

## Effect of laser illumination nonuniformity on the analysis of time-resolved x-ray measurements in uv spherical transport experiments

J. Delettrez, R. Epstein, and M. C. Richardson

*Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, New York 14623-1299*

P. A. Jaanimagi\* and B. L. Henke

*Lawrence Berkeley Laboratory, University of California, 1 Cyclotron Road, Berkeley, California 94720*

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In this paper we present measurements of thermal transport in spherical geometry made with 24 uv (351-nm) beams from the OMEGA laser system of the Laboratory for Laser Energetics of the University of Rochester. The measurements, using time-resolved x-ray spectroscopy on solid glass targets coated with varying thicknesses of plastic, provide absolute measurements of the onset times of the resonance x-ray lines of silicon. From these measurements, the scaling of the instantaneous mass-ablation rate with absorbed intensity is obtained for times before and after the peak of the laser pulse. The observed large burnthrough depths and early onsets of the x-ray lines are explained by carrying out detailed hydrodynamic-code simulations for the range of the estimated laser-intensity distribution on target which is obtained from the superposition of the equivalent target-plane intensity distribution of a single beam. We find that neglecting the effects of laser illumination nonuniformities can lead to erroneous conclusions about the heat transport. We conclude from the analysis that the experimental results can be explained by the presence of significant energy at intensities three times the nominal intensity, contained in hot spots of size less than 20  $\mu\text{m}$ . This is almost twice as much as the maximum intensity obtained from the superposition of the single-beam distribution.

### I. INTRODUCTION

Thermal transport plays a key role in direct-drive laser fusion<sup>1</sup> because it affects the efficiency of the ablation process that drives the implosion of laser driven targets. In transport experiments the thermal electron flux is not measured directly but is inferred from measurable quantities. One such quantity is the burnthrough rate of the heat front through a material that contains one or more x-ray-emitting signature layers.<sup>2-6</sup> Simulations are then carried out with a hydrodynamic code in which the thermal electron flux is characterized by the value of the flux limiter  $f$  required to replicate the experimental observations;<sup>7</sup> the flux limiter is the adjustable parameter in the definition of the free-streaming limit of the heat flux,  $Q_f = fn_e(kT_e)^{3/2}/m_e^{1/2}$ , which is the upper limit on the heat flux. Modeling of the experiments could also be carried out with Fokker-Planck codes which compute the thermal transport from the more fundamental Fokker-Planck equation (see Ref. 8 for an extensive discussion of Fokker-Planck models). Fokker-Planck codes are, however, more cumbersome and time consuming to use than flux-limited diffusion codes. Also, comparisons between Fokker-Planck calculations and flux-limited diffusion have shown that, for 351-nm laser illumination, flux-limited diffusion modeled heat transport as well as Fokker-Planck codes.<sup>9</sup> Experiments in spherical geometry have inferred various levels of flux inhibition, from as low as  $f=0.06$  with 1050-nm laser radiation,<sup>3</sup> to values of  $f>0.1$  at various laser wavelengths.<sup>2,4,6</sup> In all these experiments, the analysis of the measurements assumed that the laser-intensity distribution on the tar-

get surface did not differ appreciably from the average intensity.

In a series of transport experiments conducted at Laboratory for Laser Energetics (LLE),<sup>10</sup> experimental results were found to be incompatible with the assumption of uniform laser-intensity distribution. In these experiments, the temporal dependence of the mass-ablation rate of spherical targets irradiated with uv-laser light was measured using time-resolved x-ray spectroscopy. The estimated mass-ablation rate was found to be larger by a factor of 2 than that obtained in simulations with uninhibited heat flow, yet the scalings of the mass-ablation rate with absorbed intensity were in agreement. One of the reasons advanced for the discrepancy between experiment and simulation was that using only six beams of the OMEGA laser system at 351 nm produced a nonuniform illumination pattern on the targets.

The effect of laser illumination nonuniformity on the interpretation of thermal transport experiments has not been previously studied in detail. However, it is now clear that neglecting nonuniformity can lead to erroneous conclusions when the analysis of the thermal transport is based on spectroscopic diagnostics which usually do not incorporate high spatial resolution at the target plane. Nonuniformities in the multibeam illumination of spherical targets arise from two sources: nonuniformities in the individual beams and the result of the overlap of the individual beam distributions on the target surface.<sup>11</sup> Beam geometry and beam overlap lead to low-intensity long-wavelength variations in the intensity pattern which have little effect on transport experiments. The nonuniformities that do affect the interpretation of

transport experiments occur in the individual beams of the frequency-tripled OMEGA glass laser system and manifest themselves as small regions ( $< 20 \mu\text{m}$  in diameter in the target plane) of very high intensity or "hot spots." If the hot spots contain a sufficiently large fraction of the total energy, their presence in the intensity distribution on the surface of the target can lead to the conclusion that the heat flux inferred from spectroscopic diagnostics is larger than it would be for a given nominal intensity. Such hot spots produce stronger line emission in the case of time-integrated burnthrough experiments, or earlier emission in the case of time-resolved burnthrough experiments, than expected from nominal intensity. This effect is more pronounced for laser illumination at 351 nm than at 1060 nm because lateral thermal smoothing is not as effective at the shorter wavelength.<sup>12</sup> Illumination nonuniformity could also explain some of the discrepancies between results from various laboratories since each laser system has its own distinctive illumination pattern resulting from differences in optics and beam quality.

In this paper we present an analysis of recent time-resolved burnthrough measurements on spherical targets and discuss the effect of illumination nonuniformities on the interpretation of the results. The analysis shows that taking into account the estimated level of nonuniformity of the laser illumination can advance the onset of the x-ray signature lines by about 100 ps and also affect the temporal shape of the line emission. Intensities larger than three times the nominal intensities were required to obtain agreement between the measured and computed onset times of signature lines. We also report on measurements of the mass-ablation rate for times past the peak of the pulse when the rate had been predicted to drop rapidly.<sup>10</sup>

The measurements discussed in this paper were part of a series of transport experiments carried out at 351 nm on the 24-beam OMEGA laser system at the University of Rochester.<sup>13</sup> This system produces energies up to 2 kJ in approximately Gaussian-shaped pulses of about 600 ps full width at half maximum (FWHM) duration. The laser beams were focused eight radii behind the target; this focusing position provides the most uniform irradiation conditions from geometrical considerations.<sup>14</sup> The targets were solid glass spheres of two nominal diameters (300 and 600  $\mu\text{m}$ ) coated with 2–16  $\mu\text{m}$  of parylene [or polyparaxylylene,  $(\text{C}_8\text{H}_8)_x$ ] and suspended on submicrometer-diameter glass stalks. The nominal (average) intensities on target ranged from  $3 \times 10^{14}$  to  $1 \times 10^{15} \text{ W/cm}^2$ .

The diagnostics included an array of 20 differential plasma calorimeters and three charge collectors to characterize the absorption and the plasma blowoff, x-ray photography of the target, and time-resolved and time-integrated x-ray spectroscopy. In this paper, emphasis is placed on the analysis of the time-resolved spectroscopic results obtained from the SPEAXS instrument<sup>15</sup> in which an elliptically curved mica crystal analyzer was used to disperse the x-ray spectrum (1.5–3.2-keV range) onto the slit of an x-ray streak camera. The temporal characteristics of the burnthrough

were obtained by measuring the time of onset of the silicon  $\text{H}_\beta$  line emission for targets with varying thicknesses of  $(\text{CH})_x$ . A timing fiducial signal was generated by frequency quadrupling part of the main laser pulse obtained from mirror leakage and focusing it to a section of the photocathode consisting of a 200-Å layer of aluminum on mica.<sup>16</sup> The time of onset was defined as the time at which the intensity of a certain line emission exceeded the  $(\text{CH})_x$  continuum emission by a factor of 2.

## II. DETAILS OF THE ANALYSIS

The time-resolved spectra for two series of shots were digitized: one series at  $3 \times 10^{14} \text{ W/cm}^2$  with  $(\text{CH})_x$  thicknesses of 0, 2, 4, and 6  $\mu\text{m}$  and the other at  $1 \times 10^{15} \text{ W/cm}^2$  with  $(\text{CH})_x$  thicknesses of 0, 4, 8, and 12  $\mu\text{m}$ . Superpositions of the digitized traces for the Si  $\text{H}_\beta$  lines at each laser intensity are shown in Fig. 1. Time is measured relative to the peak of the laser pulse, as determined from the fiducial, and the vertical axis is the intensity of the line emission obtained from the measured  $D$ -log exposure curve for the streak camera recording film. The continuum emission was subtracted in order

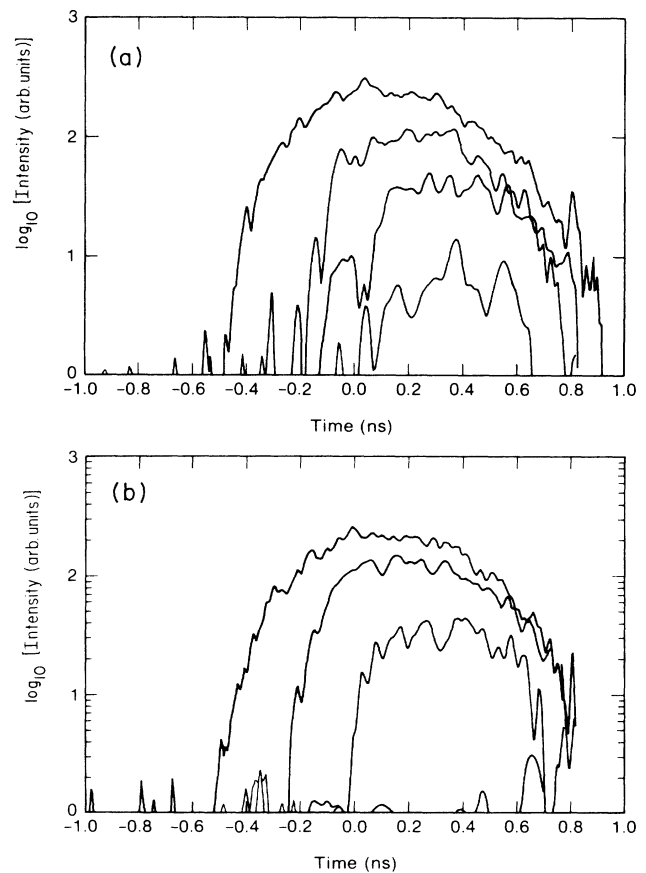


FIG. 1. Temporal emission of the Si  $\text{H}_\beta$  line from SPEAXS: (a) for 0, 2, 4, and 6  $\mu\text{m}$  of  $(\text{CH})_x$  over glass at  $3 \times 10^{14} \text{ W/cm}^2$ ; (b) for 0, 4, 8, and 12  $\mu\text{m}$  of  $(\text{CH})_x$  at  $1 \times 10^{15} \text{ W/cm}^2$ . The continuum has been subtracted.

to obtain a clearly defined onset time. In marginal burnthrough cases, such as for the  $12\text{-}\mu\text{m}(\text{CH})_x$  case in Fig. 1(b), the location of the onset of the line emission is difficult to determine from the lineout, but it can be clearly seen in the original photograph.

Simulations were performed with the one-dimensional Lagrangian hydrodynamic code LILAC (Ref. 17) which includes raytracing, Thomas-Fermi equation of state, and multigroup diffusion radiation transport. The ray tracing is carried out using the azimuthally-averaged spatial profile of a typical beam; the inverse-bremsstrahlung opacity is corrected for the Langdon effect.<sup>18</sup> The electron thermal energy was transported using a flux-limited diffusion model in which the effective flux was defined as the minimum of the diffusion flux and the free-streaming flux (the sharp cutoff method). The opacities used in the radiation transport calculation were obtained from the Los Alamos LTE (local-thermodynamic-equilibrium) astrophysical library.<sup>19</sup> A finely resolved x-ray energy grouping was used in these simulations to provide a better treatment of the x-ray line transport in the multigroup environment. The LTE line emissions presented in this paper were obtained from the energy emitted from the narrow group ( $\Delta E = 20$  eV) that contained the Si  $H_\beta$  line. Non-LTE considerations do not significantly affect the progress of the heat front through the low-Z plastic layer,<sup>20</sup> but may influence the onset of the silicon line emission. To appreciate this effect the temporal line emission was also calculated with a non-LTE postprocessor which operates from LILAC results.<sup>21</sup>

To take into account the effect of the nonuniformity of the illumination of the target by a multibeam laser system, the overall laser-intensity distribution on the target surface must be known. While it is not now possible to measure directly the intensity distribution at the target surface, one method of estimating this distribution is through the superposition of the equivalent-target-plane (ETP) intensity distributions of all the OMEGA laser beams. During this series of experiments, the illumination uniformity on target was estimated by using the measured two-dimensional ETP distribution from a single OMEGA beam as the input to a beam superposition code.<sup>11</sup> This code integrates the beam-intensity distributions from all 24 beams of OMEGA, taking into account their position and orientation and the effects of refraction.<sup>22</sup> To approximate the differences between individual beam distributions, the two-dimensional ETP distribution was randomly oriented for different beams. The illumination uniformity is then characterized by decomposing the resulting spherical distribution into a histogram, shown in Fig. 2, which gives the relative energy in each intensity group on the target surface. The inset is a shaded contour plot of the target-plane intensity distribution used. It contains several intensity hot spots about  $15\text{--}20\ \mu\text{m}$  across. The histogram shows a large peak at 1.4 times the nominal intensity,  $I_0$  ( $I_0$  is the nominal intensity defined as the peak laser power divided by the initial target area), and residual energy at 1.9  $I_0$ .

The distribution of intensities on target shown in Fig.

2 was used to estimate the temporal behavior of the x-ray line emission from the target in the presence of illumination nonuniformities. For a given target shot, LILAC simulations were performed for each of the 13 intensity distribution groups in Fig. 2. Each of these simulations produced a temporal emission of the silicon resonance lines (H- and He-like) which were then combined by weighting the emission for each intensity group by the fractional laser energy in that group.

### III. RESULTS OF THE DATA ANALYSIS

The first step in the simulations with LILAC was to adjust the flux limiter to agree at nominal intensity with the measured absorption fraction. This is in contrast with previous analyses of transport experiments<sup>2-6</sup> in which the goal had been to obtain agreement with the experimental transport data by varying the value of the flux limiter in the simulations; in most cases, agreement with the measured absorption fraction was not sought. This is not the goal in the present analysis. Fractional absorption was measured with an array of 20 calibrated differential plasma calorimeters. The approximately isotropic plasma blowoff displayed less than 10% asymmetry (standard deviation) and was accurate in absolute value to about 10%. The absorption fraction was used to adjust the flux limiter because it is an integrated measurement that depends weakly on the intensity distribution. This weak dependence was verified by comparing the absorption fraction for a simulation at nominal intensity to the weighted-average absorption fraction: the relative difference in the absorption fraction was less than 10%. The flux limiter value of 0.06 (sharp cutoff) gave the best agreement with the measured absorption fraction and was used in all simulations unless otherwise noted.

The weighted-average temporal emissions for the Si  $H_\beta$  line for the cases of Fig. 1 are shown in Fig. 3. The arrows denote the measured onset times obtained from the traces in Fig. 1. The weighted-average onset times are the same as that calculated for  $1.4I_0$  because a

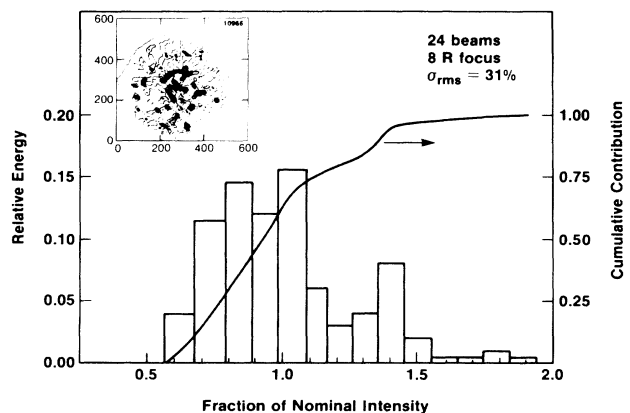


FIG. 2. Laser-intensity variation on the target surface obtained from the equivalent target-plane intensity distribution shown in the inset for 24 uv (351-nm) beam of OMEGA at 8 R (tangential) focus.

significant amount of energy is present at that intensity (see Fig. 2). For all plastic thicknesses, the calculated onset times lag the measured times. In both series, the lag increases from about 100 ps for the smallest plastic thickness (excluding zero thickness) to 200 ps for the second thickness. For the largest thicknesses of plastic, which are marginal burnthrough cases, the computed line emission is either nonexistent ( $12 \mu\text{m}$  in the high-intensity case) or much weaker than the measured line emission ( $6 \mu\text{m}$  in the low-intensity case). The effect of varying the flux limiter is illustrated in Fig. 4, where the temporal emission for a single thickness of plastic ( $4 \mu\text{m}$

at  $3 \times 10^{14} \text{ W/cm}^2$  and  $8 \mu\text{m}$  at  $1 \times 10^{15} \text{ W/cm}^2$ ) is plotted at nominal laser intensity for increasing values of the flux limiter. The shaded areas denote the measured onset times and their uncertainty. At  $3 \times 10^{14} \text{ W/cm}^2$ , increasing the flux limiter to 0.08 decreases the onset time by only about 50 ps; further increasing the flux limiter has no effect. In this case, it is not possible to simulate correctly the measured onset time even with unrestricted Spitzer heat flow. At  $1 \times 10^{15} \text{ W/cm}^2$ , the onset time is more sensitive to the flux limiter, but again, heat fluxes larger than classical Spitzer fluxes would be required to simulate the measured temporal line emission. There-

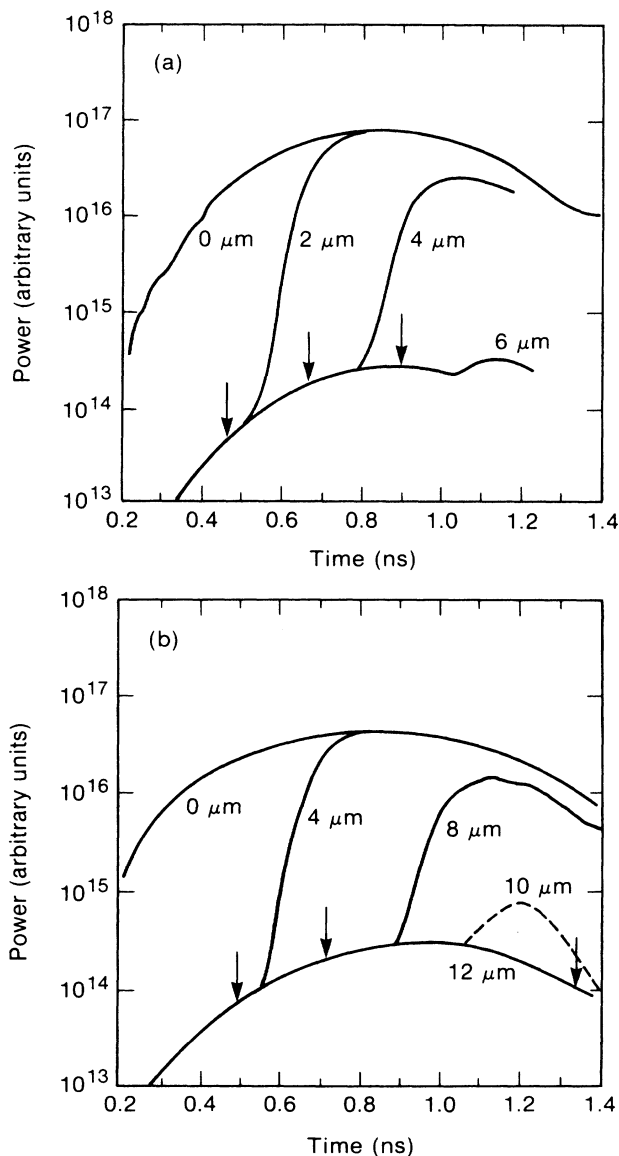


FIG. 3. Weighted-average temporal  $\text{Si H}_\beta$  emission from LILAC calculated from the intensity distribution in Fig. 2: (a)  $3 \times 10^{14} \text{ W/cm}^2$ ; arrows indicate the experimental onset times for 2, 4, and  $6 \mu\text{m}$  of  $(\text{CH})_x$ , respectively; (b)  $1 \times 10^{15} \text{ W/cm}^2$ ; arrows indicate the experimental onset times for 4, 8, and  $12 \mu\text{m}$  of  $(\text{CH})_x$ , respectively.

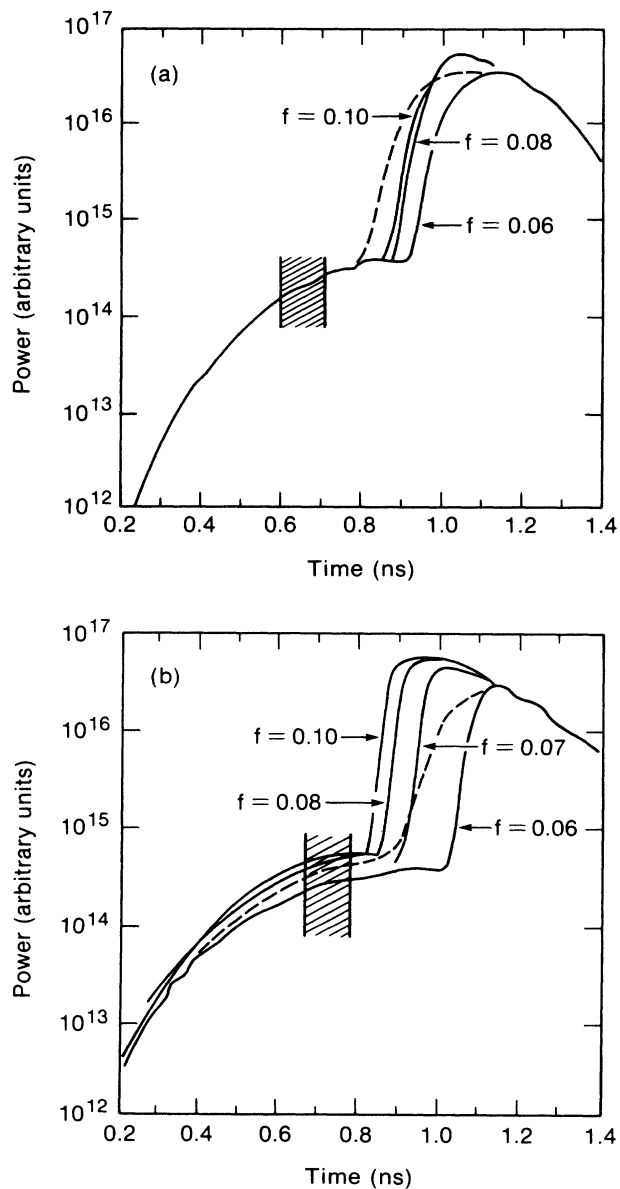


FIG. 4. Effect of varying the flux limiter on the onset of line emission and comparison between line emission at nominal intensity (solid lines) and the weighted-average line emission (dashed line): (a)  $3 \times 10^{14} \text{ W/cm}^2$  and (b)  $1 \times 10^{15} \text{ W/cm}^2$ .

fore, the experimental results can only be explained by the presence of significant energy in the laser intensity distribution at intensities larger than  $1.5I_0$ .

Based on the conclusion of Ref. 10—that absorbed intensities three times nominal would be required to match the measured mass-ablation rates with  $f=0.1$  (harmonic)—simulations were carried out for the two series of shots with incident intensities up to  $3I_0$ . The effect of varying the laser intensity from about  $0.5I_0$  to  $3I_0$  on the onset time of the Si  $H_\beta$  line is shown in Fig. 5, where the onset time relative to the peak of the pulse is plotted as a function of the laser intensity on target normalized to the nominal intensity. The shaded bands represent the measured onset time with an estimated absolute error of  $\pm 50$  ps. In both Figs. 5(a) and 5(b), for the case of the thinnest  $(CH)_x$  thickness, the heat front burns through to the glass for intensities below  $0.6I_0$ . For larger thicknesses of  $(CH)_x$ , line emission is produced only above a certain threshold intensity. Except for the two points nearest to the threshold intensity, the onset time scales as the laser intensity to some power that is different for each plastic thickness; the values of that power scaling range from 0.2–0.4. In Fig. 5, the onset times at  $1.4I_0$  reflects the same lag with respect to the measured onset times as seen in Fig. 3. For the series at  $3 \times 10^{14}$  W/cm<sup>2</sup>, the calculated onset time at  $3I_0$  agrees well with the experimental values for the three plastic thicknesses. This agreement, coupled with the fact that the onset times are not very sensitive to flux limiter values above 0.06, strongly suggests that some fraction of the incident laser energy must reside at intensities on target near  $3I_0$  in the form of small, intense hot spots. At  $1 \times 10^{15}$  W/cm<sup>2</sup>, agreement is obtained for 4  $\mu\text{m}$  and 8  $\mu\text{m}$  of plastic. For the 12- $\mu\text{m}$  plastic case, the computed time is now about 200 ps ahead of the measured time. Attempts to increase that time further would result in the disappearance of the line emission, as can be seen in Fig. 5(b). The difficulty may lie in the fact that the measured onset time may not be known accurately because the burnthrough is marginal at that plastic thickness. The argument that three times nominal intensity is required to explain the experimental results is not as straightforward at  $1 \times 10^{15}$  W/cm<sup>2</sup> as at  $3 \times 10^{14}$  W/cm<sup>2</sup> because the onset time is more sensitive to the flux limiter at the highest laser intensity; higher intensities and higher flux limiters are interchangeable in producing earlier onset times. Taken together, however, the analyses of the two series of shots strongly suggest that there is significant energy at  $3I_0$  on the target surface.

It is difficult to estimate the fraction of the energy present in the laser-intensity distribution above  $1.5I_0$ . One way is to consider the sensitivity of SPEAXS which can be estimated experimentally from the amount of absorbed energy needed to observe the onset of the Si x-ray line emission: about 2% of the total absorbed energy (20–30 J). But this is the amount of energy required to observe a signal above the noise level. The quantity of interest is the amount of energy that leads to an observable change in the onset time of the x-ray lines. This quantity could be estimated theoretically by modifying

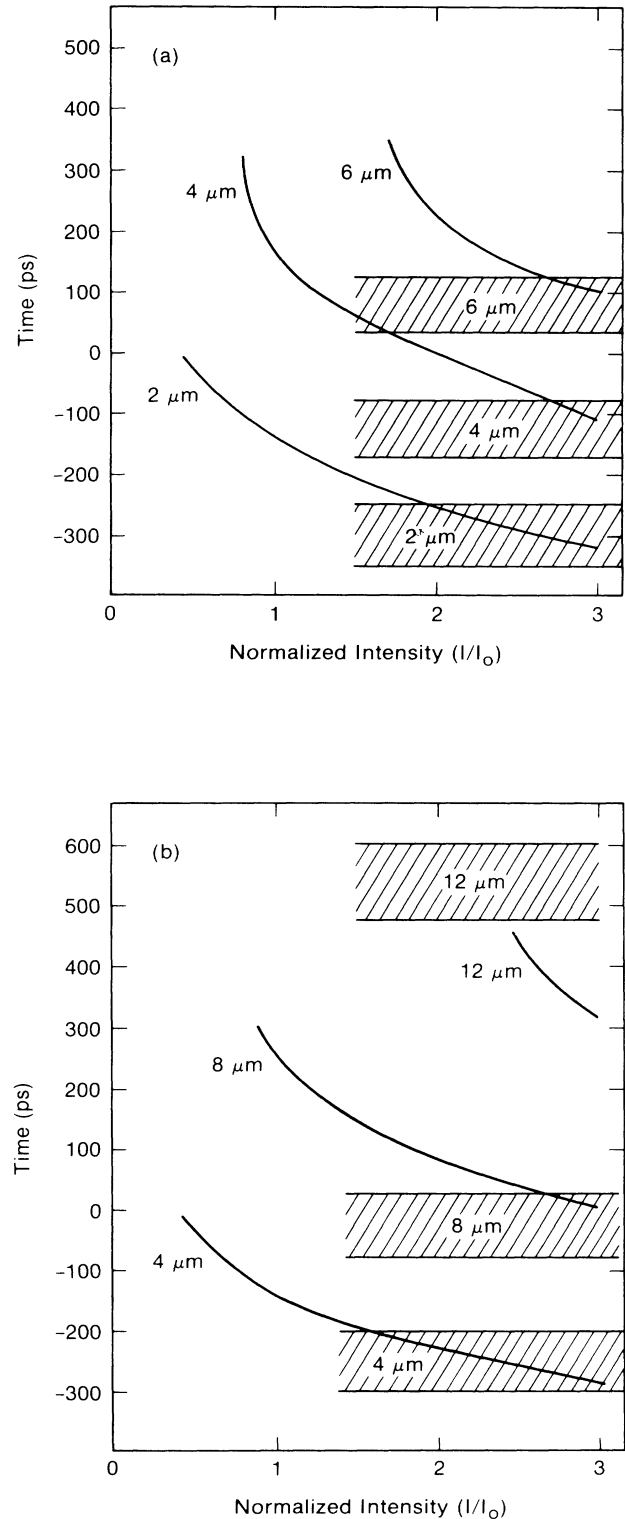


FIG. 5. Onset times from simulation (solid lines) for the Si  $H_\beta$  line as a function of the laser incident intensity normalized to the average intensity; the shaded bands are the measured onset times and their uncertainty: (a)  $3 \times 10^{14}$  W/cm<sup>2</sup> and (b)  $1 \times 10^{15}$  W/cm<sup>2</sup>.

the laser-intensity distribution of Fig. 2. The difficulty lies in how to distribute the additional energy above  $1.5I_0$ . Adding energy near  $1.5I_0$  has less of an effect than adding the same amount of energy at  $3I_0$ . This is because, near  $1.5I_0$ , the increased emission is so close to the onset of the line emission from the known intensity distribution (Fig. 2) that it is added to the existing line emission rather than to the continuum emission, ahead of the onset, as is the case at  $3I_0$ . Because the actual laser-intensity distribution between  $1.5I_0$  and  $3I_0$  is probably continuous, but not necessarily monotonically decreasing, it is not possible to get a precise estimate from theoretical considerations of the energy present in that intensity range. Reasonable estimates based on adding energy at  $1.5I_0$  and  $3I_0$  place this value at between 2% and 5% of the incident laser energy.

The method used in this paper to estimate the effect of laser illumination nonuniformity on the interpretation of transport experiments has several limitations, one of which is that it does not include the effect of thermal smoothing. However, theoretical studies<sup>12</sup> indicate that lateral heat flow contributes little to thermal smoothing for nanosecond duration 351-nm pulses on spherical targets. Another possible limitation arises from the fact that the illumination was estimated with the distribution of only a single beam of OMEGA rather than with those of all 24 beams. There was, in these experiments, wide variations in the target-plane distribution from beam to beam, due in part to the varying quality of the tripling crystal cells. The single laser beam intensity distribution used in the calculation of the intensity distribution on the target surface was obtained from an average-quality beam, not from the worst one. Finally, because the spatial resolution of the ETP distribution was limited to about  $20\ \mu\text{m}$ , the hot spots may be smaller than  $20\ \mu\text{m}$  and their intensity could possibly be larger than presently measured. Consideration of these limitations lead to the conclusion that the actual intensity distribution on target probably contains a larger fraction of the laser energy at the high intensities than in the estimated intensity distribution shown in Fig. 2.

#### IV. EFFECT OF ILLUMINATION UNIFORMITY

Figure 4 illustrates how including the illumination nonuniformity in the analysis of time-resolved spectroscopic measurements can affect conclusions regarding the thermal transport. This is seen by comparing onset times from nominal intensity simulations for varying values of the flux limiter with the weighted-average times. In Fig. 4(a), no values of the flux limiter will give the same onset time as the weighted-average onset time because the thermal transport is not sensitive to the flux limiter for  $f > 0.08$ . At  $1 \times 10^{15}\ \text{W}/\text{cm}^2$ , the weighted-average onset time is obtained for  $f = 0.07$ , not very different from the nominal value of  $f = 0.06$ . It should be noted that part of the change in the onset time is also due to the increase in the absorption fraction associated with the increase in the flux limiter. An immediate conclusion is that, in order to match computed onset times to measured onset times, simulations with nominal inten-

sity would yield larger values of the flux limiter than would be obtained when illumination nonuniformities are included; in fact, at low intensity, the heat flux would have to be larger than classical heat flux to match the measured onset times. The inclusion of illumination nonuniformity in the simulations also results in the presence of line emission that would not be produced at the nominal intensity: for example, at  $3 \times 10^{14}\ \text{W}/\text{cm}^2$  and  $6\ \mu\text{m}$  of  $(\text{CH})_x$ , line emission occurs only for laser intensities above  $1.5I_0$ . Another effect of including the illumination nonuniformity arises from the fact that the onset times are different for each of the illumination intensities on the target. While the rise time from the simulations at individual intensities is very steep, typically less than 50 ps (see Fig. 4), the weighted-average emission has a slower rise time—longer than 100 ps. This is

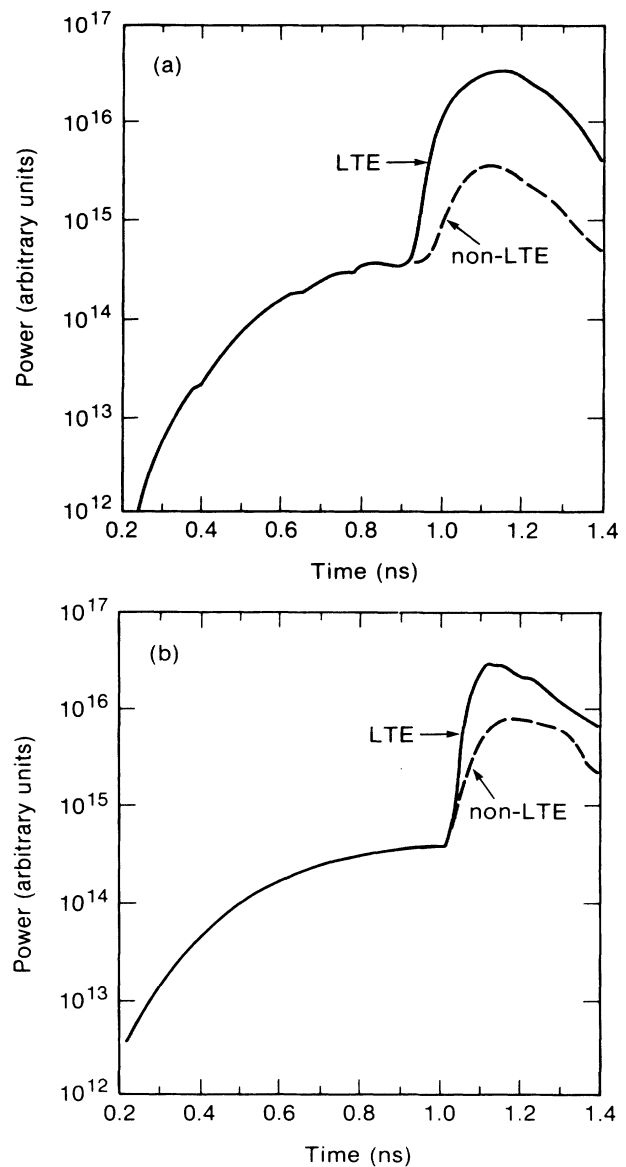


FIG. 6. Comparison between LTE (solid line) and non-LTE (dashed line) line emission for Si  $H_\beta$  (a)  $4\ \mu\text{m}$  of  $(\text{CH})_x$  at  $3 \times 10^{14}\ \text{W}/\text{cm}^2$  and (b)  $8\ \mu\text{m}$  of  $(\text{CH})_x$  at  $1 \times 10^{15}\ \text{W}/\text{cm}^2$ .

because the various illumination intensities contribute to the emission rise at different times. Thus, x-ray emission rise times, which are large in the experiment (see Fig. 1), are sensitive to the illumination uniformity: more uniform illumination will lead to steeper rise time.

The onset of calculated x-ray line emission and its rise times can also be affected by the inclusion of non-LTE atomic physics in the simulation. Because non-LTE ionization lags behind LTE ionization, one can expect the emission onset to occur later and the rise time to be longer for the non-LTE case. Simulations that included non-LTE postprocessing resulted in small differences in the line-emission onset time. In Fig. 6 are plotted the LTE and the non-LTE temporal Si  $H_\beta$  line emission for a given plastic thickness at both laser intensities. At  $3 \times 10^{14}$  W/cm<sup>2</sup>, the non-LTE onset time lags the LTE time by about 50–70 ps; at  $1 \times 10^{15}$  W/cm<sup>2</sup>, there is no lag. It is not obvious why there should be a difference between the two cases. The other differences observed were a longer rise time for the non-LTE emission and a lack of line emission for marginal burnthrough cases such as  $8 \mu\text{m}$  of  $(\text{CH})_x$  at  $3 \times 10^{14}$  W/cm<sup>2</sup>. The increase in rise time due to non-LTE is not large enough to explain the long rise times observed experimentally.

The aim of burnthrough experiments is to measure the mass-ablation rate which is an indication of the efficiency of the drive. The instantaneous mass-ablation rate is calculated<sup>10</sup> at the temporal midpoint between the onset of line emission at two plastic thicknesses using  $\dot{m} = \rho \Delta d / \Delta t$ , where  $\rho$  is the density of solid  $(\text{CH})_x$ ,  $\Delta d$  is the difference in the  $(\text{CH})_x$  thicknesses, and  $\Delta t$  is the difference in onset time. If the target were uniformly illuminated, such an analysis would give the actual drive mass-ablation rate. But when the illumination contains high-intensity hot spots, burnthrough measurements yield unreasonably large values for the mass-ablation rate because the onset time of the line emission corresponds to that of the high-intensity hot spots.<sup>10</sup> Therefore, while the absolute value of the measured mass-ablation rate reflects the level of nonuniformity, what is of interest is the scaling of the mass-ablation rate with absorbed intensity and how it compares with simulation. The predicted mass-ablation rate is obtained from LILAC simulations by following the temporal excursion of the 500-eV isotherm (500 eV is approximately the temperature required for Si  $H_\beta$  line emission). In this case, the same expression is used for calculating the mass-ablation rate except that, now,  $\Delta d$  is the excursion of the 500-eV isotherm during the interval  $\Delta t$ . Several sets of mass-ablation rates are plotted against the absorbed intensity in Fig. 7. The solid line describes the computed mass-ablation rate from the 500-eV isotherm excursion from simulations at  $3I_0$ . The discrete points are the instantaneous mass-ablation rates as calculated from the onset of line emission from experiment (solid symbols), from the weighted-average analysis (open symbols with cross), and from simulations at  $3I_0$  (open symbols). The squares were obtained from the series at  $3 \times 10^{14}$  W/cm<sup>2</sup> and the circles from the series at  $1 \times 10^{15}$  W/cm<sup>2</sup>. The dashed line has been added to show how the experimental points belong to two sets of instantaneous mass-

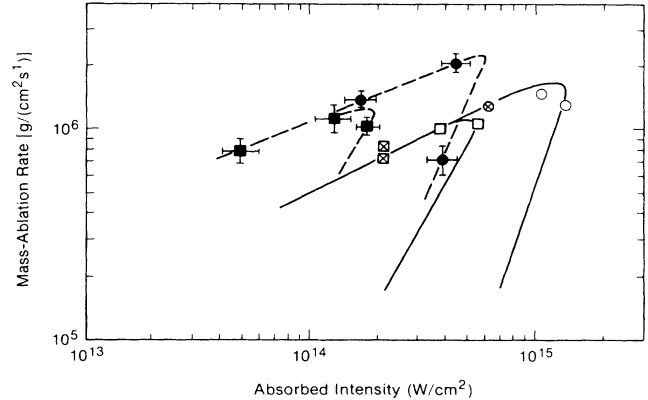


FIG. 7. Comparison between the instantaneous mass-ablation rate from experiment and simulation. The solid line is obtained from the excursion of the 500-eV isotherm in simulations at  $3I_0$ . The points are calculated from the onset times of the Si  $H_\beta$  line; the dashed lines have been added for clarity. Squares are at  $3 \times 10^{14}$  W/cm<sup>2</sup> and circles  $1 \times 10^{15}$  W/cm<sup>2</sup>; solid: experiment; open: simulation at  $3I_0$ ; cross: simulation, weighted average for the calculated laser-intensity distribution shown in Fig. 2.

ablation rate curves which parallel the solid lines of the simulation curves. On these curves the peak of the pulse occurs in the middle of the “elbow”. For the experimental points, the absorbed intensity was obtained from code simulation at nominal intensity.

The two experimental points on the downside of the dashed curve confirm the rapid decrease of the mass-ablation rate which had been predicted to occur after the peak of the pulse.<sup>10</sup> An approximate scaling of the mass-ablation rate with the instantaneous absorbed intensity ( $I_a$ ) was obtained from the rising dash line:  $\dot{m} \propto I_a^{0.43}$ ; the solid curve shows a slightly different scaling from simulation:  $\dot{m} \propto I_a^{0.53}$ . These scaling laws, but not the magnitude, are in reasonable agreement with those derived in Ref. 6 from charge collector data. Both the scaling and the magnitude of the mass-ablation rate are comparable to those obtained in the six-beam experiments.<sup>10</sup> Since the weighted-average points at  $3 \times 10^{14}$  W/cm<sup>2</sup> bracket the peak of the pulse and are very close, their value must be near to the maximum value of the weighted-average mass-ablation rate; this maximum mass-ablation rate is about two-thirds of the measured value. Only the mass-ablation rate obtained from simulations at  $3I_0$  approaches the experimental value; even there, the peak values from simulation are slightly lower than the measured values.

## V. SUMMARY

Energy transport experiments were carried out on the 24-beam OMEGA laser system at 351 nm. The laser beams were focused on spherical signature targets [glass balls or thick glass shells coated with  $(\text{CH})_x$ ] in such a way as to maximize the illumination uniformity. The temporal progress of the heat front was measured absolutely with the time-resolved x-ray spectrometer SPEAXS. Simulations of the experiment were carried

out by taking account of the nonuniformity of the laser illumination on the target surface. The 24-beam illumination was characterized by superposing the target-plane intensity distribution from one beam of OMEGA over the target surface. Weighted-average temporal profile of the line emissions were calculated from LILAC simulations at the intensities characterizing the intensity distribution on target. Inclusion of the nonuniformity advanced the onset time of the Si  $H_{\beta}$  line by about 100 ps over the time calculated with the nominal intensity. But this advance in onset time was not sufficient to obtain agreement with the measured onset time. Increasing the value of the flux limiter from 0.06 to 0.1 made little difference at  $3 \times 10^{14}$  W/cm<sup>2</sup> and not enough at  $1 \times 10^{15}$  W/cm<sup>2</sup>. The simulation intensities had to be increased to  $3I_0$  for the onset times to agree with the experiment, suggesting that significant energy (a few percents) must exist at intensities equal to or larger than three times nominal. This result indicates that the illumination nonuniformities are due to the presence of hot spots rather than to beam overlap since beam overlap cannot generate such high intensities.<sup>11</sup> The results of the transport experiment and their interpretation using simulations that included the effects of illumination nonuniformity lead to the following conclusions.

(1) The effects of illumination nonuniformity cannot be neglected in the interpretation of transport experiments in which the progress of the heat front is measured spectroscopically, both in the time-resolved and time-integrated modes. Since the onset of x-ray line emission or the burnthrough depth can be affected by varying either the flux limiter or the laser-intensity distribution on target, a full knowledge of the laser-intensity distribution at the target surface would be required to pin down the value of the flux limiter using burnthrough diagnostics. If the presence of illumination nonuniformity were neglected, a larger value of the flux limiter would be inferred than if illumination nonuniformity were taken into account.

(2) The steep falloff of the scaling of the mass-ablation rate with absorbed intensity, observed in LILAC simulations,<sup>10</sup> has been confirmed experimentally. This result indicates that a single scaling cannot be used throughout the laser pulse in the interpretation of time-integrated measurements.

(3) In the present experiments, the effect of non-LTE is small; it retards the onset of the x-ray line emission by at most 50 ps and increases slightly the rise time of that emission.

(4) To obtain estimates of the mass-ablation rate in the presence of illumination nonuniformity, it is necessary to

use diagnostics that are sensitive to the integrated or averaged intensity distribution on target. Such diagnostics include measurements of the ion blowoff distribution and of the implosion time. X-ray diagnostics of burnthrough will be a useful diagnostics when the illumination uniformity is improved (for example, through the use of better optics or incoherent illumination) or with the use of targets with high-Z dots embedded in the plastic ablator.<sup>23</sup> In dot targets, it is assumed that, if the dot is small enough, the laser intensity across the dot should not vary much. In this case, the heat transport can be characterized for one laser intensity, provided that laser intensity is known.

(5) X-ray diagnostics of targets with signature layers turn out to be good diagnostics of the illumination uniformity.

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\*Present address: Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester NY 14623-1299.

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