Numerical evaluation of the impact of laser preheat on interface structure and instability

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This paper presents a computational study of the impact of preheating, in advance of shock heating, on a structured interface and on the subsequent postshock instability evolution. The study was performed by applying a method, described previously, of evaluating radiative effects using a multidimensional, front-tracking hydrodynamic code with input from a one-dimensional, radiation-hydrodynamic code. The method is general and could be applied to a range of laser-driven shock experiments. Results of simulations are shown for both high and low levels of preheat, conducted using a robust front-tracking algorithm in the presence of a radiation energy source. In the low-preheat case, which represents the minimum to be anticipated in laboratory experiments, some impact of preheat on both preshock conditions and postshock evolution are observed. In the high-preheat case, which represents one potential result of preheating by increased radiation and/or energetic electrons, the preheat alters the spectral content of the interface structure. In this case, before the shock reaches the interface, higher-order harmonic modes are induced, the interface position is shifted, and the perturbation amplitude is reduced. Furthermore, the postshock evolution of the interface is affected by the amount of preheat and by whether radiative heating after the laser pulse is also included. Such a numerical assessment of preheating can be important to the design and analysis of laboratory experiments. The initial conditions for the interaction of any shock wave with structures in the target may be altered by the presence of preheating. This poses a challenge to the laser experimental study of fluid mixing. Numerical simulations can serve as a useful tool to guide decisions regarding control and/or measurement of this effect. © 2007 American Institute of Physics.

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I. INTRODUCTION

Laser experiments at high-energy density nearly always involve the generation of a shock wave in the material struck by the laser, as is discussed in Chap. 8 of Drake.\textsuperscript{1} In many such experiments, one is interested in the long-term behavior of a structured system through which the shock wave initially passes. This is the case in experiments for laser-fusion,\textsuperscript{2} for equation of state studies, for fundamental hydrodynamics,\textsuperscript{3} and for laboratory astrophysics.\textsuperscript{4} A detailed and complete understanding of any such experiments must include an understanding of the initial conditions throughout the laser target before the shock wave arrives. This might seem to require knowing only the target materials and their geometry, but there is always in addition the possibility that energy is deposited throughout the target in advance of the shock wave, by deeply penetrating photons or particles. Such deep heating is known as \textit{preheat}. Preheat is of specific concern to laser-fusion studies. (See Chap. 11 of Lindl,\textsuperscript{2} Chap. 9 of Drake,\textsuperscript{1} or Yaakobi \textit{et al.}\textsuperscript{5}) More generally, however, it is of concern to every laser-driven experiment involving a shock wave. In order to fully understand any such experiment, one must address the issue of what role preheat may play.

The specific experiments that motivate the present work are laboratory astrophysics experiments intended to be well-scaled reproductions of certain aspects of supernova explosions. There has been a sequence of such experiments during recent years, involving a steady increase in experimental sophistication.\textsuperscript{6-17} Motivated by the challenges of understanding the supernova explosion SN1987A, and specifically of the early emergence of material from deep within this star,\textsuperscript{18,19} these experiments drive a very strong blast wave (a shock front, followed by a rarefaction) through an interface where the density drops significantly. This produces a system that is a well-scaled model of a very small segment of SN1987A at the hydrogen-helium interface in the star.\textsuperscript{20-22} At such interfaces, which in the star are transition zones across which the dominant elements change and the density drops more rapidly, the shock wave produces the Richtmeyer-Meshkov (RM) instability\textsuperscript{23,24} while the deceleration created by the rarefaction drives the Rayleigh-Taylor (RT) instability.\textsuperscript{25,26} The combination of these instabilities at the
interfaces throughout the star has the potential to transport some material from deep within the star to its outer layers. The interface between layers in the experiment is structured to seed, in a known manner, these instabilities. Preheat has the potential to alter this structure before the shock arrives, which motivates the present study. Some preliminary work to develop measurements relevant to this issue has also been reported.  

Some other related work is worth mentioning here. One paper reports an experiment addressing the coupling of two structured interfaces through which a shock wave passes. Another paper reports an experiment addressing the behavior of the instabilities in a spherically expanding target with a single, structured interface. This latter paper included a description of the experiment, of its results, and of simulations using the codes used in the present work. The output of the simulations was in good agreement with the experimental results.

We now return to the issue of preheat, which is our focus here. In the specific experiments of interest, the interaction of the laser beams and the target material can produce energetic photons and/or energetic electrons, either of which can in turn penetrate the target and "preheat" its interior. Once the interface in the experimental system is heated, the material there will begin to move. This motion in turn will alter the initial conditions for the development of instabilities at the interface. The profile of the interface may change, and structure in the velocity of the interface may also be present.

We have previously reported the development of a method that can be used to evaluate the effects of radiative preheat. This paper will be referred to below as paper I. The method combines the output of the one-dimensional (1D) radiation-hydrodynamic code HYADES with the 2D or 3D purely hydrodynamic, front-tracking code FronTier. HYADES is a Lagrangian code with laser propagation and absorption physics, multigroup flux-limited diffusive radiation heat transfer based on average-atom opacities, tabular equation of state using SESAME tables, and single-group, flux-limited, diffusive electron heat conduction. Front-tracking as implemented in the code FronTier includes the ability to handle multidimensional wave interactions in both two and three space dimensions and is based on a composite algorithm that combines shock capturing on a spatial grid with a specialized treatment of the flow near the tracked fronts.

Our algorithm couples these codes as follows. The radiation-hydrodynamic code is used to evaluate the deposition of energy in the target by the laser beam, the initial formation and propagation of a shock wave, and the transport of radiation throughout the target. Once the laser pulse ends, which is well before the shock wave reaches the interface of interest, the evolution of the target becomes almost purely hydrodynamic. At this time, the data are interpolated onto a front-tracking grid as the initial data for the FronTier simulation. However, after this time there remains some transport of energy by radiation, and the effect of this energy transport on the interface is not necessarily negligible. We addressed this by adding an energy source term to the energy equation in FronTier. This couples the radiative heating from the radiation-hydrodynamic code into the system while also following the development of structure on the two-dimensional interface. For a detailed description of the front-tracking algorithm and its radiation coupling, we refer the reader to Zhang et al. and Glimm et al. In the following, we will describe simulations including this coupling term as having "late radiative heating."

The method just described provides a means of evaluating preheat by photons. However, the uncertain presence and magnitude of the preheating by suprathermal electrons creates challenges in attempting to evaluate the full effects of preheat. (The suprathermal electrons are those produced by nonlinear processes whose density in phase space is above that corresponding to an assumed Maxwellian distribution of thermal electrons produced by laser heating and subsequent energy transport.) The reader might suppose that one could apply some established models or estimates of the source of such electrons to a transport calculation, in order to determine how much heating would result. However, this is not possible because neither understanding nor data support even factor-of-2 estimates of the energy flux of such suprathermal electrons. A number of physical mechanisms can produce energetic electrons during laser-plasma interactions. These are discussed in Chaps. 6, 7, 9, and 11 of the book by Krueer, yet none of them can be accurately modeled in the present simulation codes. Observationally, in experiments using high-Z cavities irradiated with light of 1.05 μm wavelength, several tens of percent of the laser energy was inferred to have been converted into suprathermal electrons (see Chap. 11 of Lindl). In experiments in which gold targets were irradiated with light of 0.53 μm wavelength, several percent of the laser energy was inferred to have been converted into suprathermal electrons, and attributed to Stimulated Raman Scattering. In experiments in which gold targets were irradiated with light of 0.35 μm wavelength, >0.1% of the laser energy was inferred to have been converted into suprathermal electrons, and attributed to Two-Plasmon Decay. All these experiments found evidence of a very rapid increase in the production of suprathermal electrons as a function of laser irradiance, for irradiances of order those of interest here. It is beyond the scope of the present paper to thoroughly review all the evidence relating to the various possible nonlinear processes that may produce suprathermal electrons. It is clear in summary that the magnitude these processes reach is sensitive, in ways that are not yet well understood, to the details of the laser irradiation and the plasma conditions, including their time dependences. Thus, one cannot be completely certain of the magnitude of preheat by suprathermal electrons. Even so, there is enough evidence to assess the likely order of magnitude of the suprathermal electron production in typical experimental cases.

The additional question to be asked in any specific experimental case then is whether to invest the considerable expense involved in measuring the level of preheat. Very few such measurements exist to date. The measurement of most relevance here, using a somewhat higher laser irradiance (1.5 × 10^15 W/cm^2 as opposed to just below 10^15 W/cm^2 in the experiment of interest here), found that 0.3% of the laser energy was deposited in a 40-μm-thick
vanadium sample by electrons of energy >50 keV. It is not known what fraction of the electron energy in this experiment was transmitted through the vanadium. One cannot directly apply these results to the experiments of interest here, whose 150 μm of plastic affects the electron transport differently from 40 μm of vanadium. Simple estimates, using the specific heat of plastic having singly ionized atoms, show that preheat temperatures of order 10 eV could be produced if 0.5% of the laser energy (of 10^6 J/cm^2) was deposited uniformly in the 150-μm-thick plastic layer of the target of interest. This fraction (0.5%) is on the high side of the plausible range based on the previous experiments, but is well within the range of possibility. However, the resulting exact value of 10 eV is not important here. What is important is that this is two orders of magnitude higher than the value we obtain, and discuss below, due to the radiation alone. For the experiments of specific interest here, this makes it worthwhile to assess in some way the impact of such a large difference in temperature on the evolution of the plasma in advance of the shock, to determine how important it is to invest in measurements of preheat.

We were thus led to the need to identify a method by which we could make this assessment. One has no viable choice other than to do this in some artificial way. In some prior work, such as that of Remington et al., an assessment of preheating effects was made by artificially increasing the source of high-energy x rays that irradiated the target surface. For the present study, we chose to model the potential effect of suprathermal-electron preheat by simulating a plastic layer that included a bromine dopant. This produced a hotter plasma on the laser-irradiated surface and more bremsstrahlung emission, causing heating of the plastic near the interface to temperatures of order 10 eV. This allows us to assess the qualitative potential for preheat to alter the target behavior, so as to learn how important measurements of preheat, and perhaps the reduction of it, may be in such experiments. It also models a specific case that might be measured in experiments, which would provide an integrated test of these simulations. In the following, we evaluate the effects of preheat on the structure at the interface in the experiments of interest, considering both the case in which the preheat is purely radiative, produced by modeling of the nominal target structure, and the case of increased preheat using radiation caused by bromine doping as a surrogate for hot-electron production.

The paper is organized as follows. In Sec. II, we describe the parameters of the experiments of interest, the 1D simulations, and the comparison of the two codes in 1D. In Sec. III, we discuss the extension of the simulations into two dimensions and show the results of the simulations while the shock front is approaching the interface. The influence of preheat on the amplitude and spectral content of the interface profile is analyzed. Section IV investigates the effect of preheat on the postshock evolution of structure at the interface. A final section contains conclusions and discussion.

II. THE EXPERIMENT AND THE SIMULATIONS

The experiments of interest here are in planar geometry, and are discussed in more detail elsewhere. Impulsive laser ablation at an irradiance that is typically 6.4×10^{14} W/cm^2, of 1 ns duration and 0.35 μm wavelength, creates a blast wave in a 150-μm-thick layer of plastic. The blast wave crosses an interface into a low-density layer of carbon foam, initiating the unstable dynamics described above. The foam is 0.1 g/cm^2 in the present calculations; some experiments used this value while others used 0.05 g/cm^2 foam, but this difference is not significant. The heating of the plastic at the interface drives the dynamics of interest here. In the experiments, the entire layer of plastic was polyimide (C_{22}H_{10}O_{5}N_{2} at 1.41 g/cm^3) in some locations. In other locations, the lasers struck a 75-μm-thick polyimide layer which was followed by a 75-μm-thick layer of brominated plastic (C_{508}H_{357}Br_{24} at 1.42 g/cm^3). These latter locations are our focus here, as the diagnostics detect the structure of the brominated plastic surface.

We simulated the first phase of these experiments with the HYADES code, described above. The simulations used a flux limiter of 0.05 for the electron heat transport. This provides a heat flux consistent, within a factor of 2, of that found by more accurate calculations of heat transport using Fokker-Planck methods, as is discussed in Chap. 10 of Kruer. Thirty photon groups were used for the multigroup radiation transport calculation, from 1 to 30 keV. These were distributed to have equal energy content for an exponential photon distribution, as is standard. Tabular equations of state were incorporated in the specific simulations whose results are used here. However, for these dominantly low-Z ionized plasmas, one obtains very similar results using ideal-gas models with plausible polytropic indices. The laser irradiance used in the HYADES simulations was 4.2×10^{14} W/cm^2, which is the value needed in the 1D code to match the observed time dependence of the interface and shock positions. This is lower than the actual irradiance because of radial electron heat transport. The data regarding the positions show <10% scatter, and the comparison establishes the laser irradiance needed to reproduce the data to 10%. The fact that the data are reproduced implies that the correct amount of mass has been ablated from the target and that the correct impulse has been delivered to it, with accuracies not much worse than 10%. Even so, this does not guarantee that other quantities are calculated to this accuracy. Given the uncertainties in the equations of state, the uncertainties in the photon-group opacities from the average-atom model, the fundamentally nonlocal nature of electron heat transport, among other issues, the physical parameters found by any code of this type that has not been “tuned” based on data from relevant experiments have a typical uncertainty of a factor of 2 in the regime of interest here. In the present case, the evaluation of heating at the interface in the target might be more accurate than this, because the laser irradiance has been adjusted to match the data as just described, the source of radiation is bremsstrahlung, which is well understood, and the opacities throughout most of the target are close to their cold values for the radiation energies of inter-
est. Unfortunately, the evaluation of uncertainties is not an established science for this type of code, which simulates multiple nonlinear physical mechanisms using approximate physical models. The typical value of the uncertainty indicated above reflects the 25 years of experience of one of the authors (R.P.D.) with similar codes. Returning to the context established in the previous section, factor-of-2 variations in the heating near the interface are not fundamentally important here, because we are primarily concerned with the potential effects of a variation of two orders of magnitude in such heating.

For the present study, we simulated two variations on the target structure. In one case, which we will designate the “low-preheat” case, the laser strikes a 75-µm-thick polyimide layer, which is followed by a 75-µm-thick layer of brominated plastic. This corresponds to the layer of material that is diagnosed by radiography in the actual experiment, but includes only the radiative preheat and not any hot-electron preheat that may be present. The radiative preheating near the interface will be larger in this layer than in those regions where the target is entirely composed of polyimide, because the brominated plastic has a larger x-ray opacity and thus is more absorptive. The simulation finds heating of the interface to approximately 0.1 eV, negligible ionization, and interface motion of 2 µm by 2.2 ns, just before the shock reaches the interface. We show below that such small heating and motion would not produce major effects. In the second case, which we will designate as the “high-preheat” case, the target is entirely composed of the brominated plastic. As described above, the radiation from the laser-irradiated, brominated plastic in this case is intended to be a surrogate for the production of energetic electrons by the laser-plasma interactions. In this case, the simulation finds heating of the interface to approximately 10 eV and interface motion of ~30 µm by 2.4 ns, which is the time when the shock is approaching the (moving) interface. For each of the two cases, *Frontier* simulations were run with and without late radiative heating. We note that simulations without late radiative heating are not equivalent to simulations without any radiation, because the HYADES simulations include the effects of radiation throughout the system for the first ns.

In all cases, we simulated the behavior of a modulated target, in which the surface of the plastic is sinusoidally perturbed with a peak-to-valley amplitude of 5 µm and a wavelength of 50 µm. To map the one-dimensional output onto this two-dimensional initial condition, we identified an interface corresponding to a cosine wave centered at the 1D interface location. This created regions up to 2.5 µm in extent where foam needed to be replaced with plastic or vice versa. We established the properties in the new material by applying the values of the 1D data at the 1D interface to this new material. This is appropriate because the gradients in the physical parameters correspond to very small variations in their absolute values over this distance. In all cases, the foam extended to the interface from above. This is appropriate at the modulated surface, as this type of foam is a spongy material that is pressed against the plastic in assembling the target. The foam distributes the resulting density perturbation over a large volume at small amplitude. The method used here makes it practical to obtain enough lateral resolution to

![FIG. 1. HYADES output at 1 ns as initial condition for Frontier for the high-preheat case.](image)
quantify the evolution of the spectral content of the interface profile. (In contrast, in paper I we used a sequence of six distinct 1D simulations to define the modulations corresponding to the interface. This produced results that are the same qualitatively and similar numerically to those from the approach used here, but without enough resolution to determine the spectral content.)

The initiation and early-time one-dimensional response of the system were discussed in paper I. The HYADES input for the high-preheat case at time 1 ns is shown in Fig. 1, reproduced from that work. In the low-preheat case, the input is similar except that there is a much smaller spike in the velocity at the interface and the radiative heating is also much smaller. The *FronTier* simulation is conducted from time 1 to 2.4 ns with the input from HYADES. By 2.4 ns, the radiative heat transfer has become negligible in all cases. In the high-preheat case, shown in paper I, we found that the interface has moved 30 \mu m at 2.4 ns when the shock is yet to reach the interface. At this time, the interface has a velocity approaching 20 km/s.

Figure 2 shows, for the low-preheat case, the comparison of density, pressure, and velocity from the two codes for times 1, 1.6, and 2.2 ns. Reasonable agreement between *FronTier* and HYADES is obtained. The last time shown (2.2 ns) is just before the shock breaks through the heavy fluid into the light. The initial density ratio between the plastic and the foam is 14.2:1 at the interface, which is located at 0.015 cm. In the figure, the laser is incident from the left. The density profile in the plastic evolves from a shock wave at 1 ns to a planar blast wave (a shock front followed by a rarefaction) later in time. In all cases, the shock front is the first abrupt decrease in density as one scans from left to right. The shock strength (the pressure ratio) is 500, which is much stronger than the shock strength of 10 in the high-preheat simulations. The shock front and also the falloff behind it move through the denser plastic fluid toward the interface at the boundary of the plastic with the less dense foam. (From the perspective of the RT and RM instabilities, one identifies the “interface” as the location of maximum density gradient near the plastic-foam boundary.) This interface fails to move on the scale visible in this plot. However, the dense material does begin to rarefy near the interface. As the leading edge of this material expands, its density drops below that of the foam. This material pushes the adjacent foam rightward, producing a small density increase in the foam, moving at a velocity on the scale of 10^5 cm/s. We evaluate the impact of these effects on the structure and later evolution of the interface in the next two sections. (We note that the simulation for the low-preheat case shown here is nearly identical to that for the high-preheat case, with the sole difference being in the nature of the first layer of material. Although there is little evident difference, the low-preheat simulation whose results are shown in paper I differed in several ways from the high-preheat simulation.)

### III. TWO-DIMENSIONAL BEHAVIOR AS THE SHOCK APPROACHES THE INTERFACE

In this section, we describe the results of the 2D simulations during the period until 2.5 ns, which is approximately...
the time when the shock reaches the interface. The \textit{FronTier} simulations for this purpose were carried out for a 330\text{\,mm} long and 50\text{\,mm} wide rectangular tube in planar geometry. Figures 3 and 4 show density contour plots from the front-tracking simulations during this period for the low-preheat and high-preheat cases, respectively. Both these examples are from simulations with late radiative heating. In both cases, the shocked plastic is a red color and the shock progresses upward in time. The unshocked foam is a blue color. Density contour plots for the low-preheat case are shown in Fig. 3, at times 1, 1.6, and 2.2 ns. At time 2.2 ns (about 0.1 ns before the shock reaches the interface), one can see the localized increase in foam density discussed in the previous paragraph, appearing in green in the figure. There is no other change that can be readily observed from this type of display.

Density contour plots for the high-preheat case are shown in Fig. 4 for times 1, 1.6, 2, 2.3, and 2.5 ns, which correspond to 1.6, 1, 0.6, 0.3, and 0.1 ns before the shock hits the interface. The disturbance in the foam has now evolved into a weak shock wave, and has become much more pronounced. We observe that there is significant pre-shock interface motion, as expected based on the 1D case discussed in paper I. In addition, the structure of the interface is clearly altered by the preheating. These effects are enhanced because the local heating is proportional to local opacity, and so is much larger in the dense (and brominated) material than in the much less dense (and C) foam. Motion occurs when the heated, dense material pushes against the foam, leading to some expansion of the dense material near its edge and to some response in the foam. Here our main concern is to determine changes in shape of the interface (both spectrum and amplitude) due to the preheat.

Figures 5 and 6 show, for the low-preheat and high-preheat cases, respectively, profiles of the interface at several times from the simulations just discussed. In the low-preheat case of Fig. 5, one can see that the changes in the shape of the interface, while not zero, remain quite small. In particular, they are small compared to the uncertainty of manufacturing of real targets. For the high-preheat case, Fig. 6 shows the front profiles at times 1, 1.6, 2, 2.3, and 2.5 ns with fitted cosine waves shown as dashed lines. First, we see that the interface was driven upward by 25–30\text{\,mm} during the preheat period. Second, the interface develops some degree of deviation from a pure cosine wave during the course of evolution. Finally, the interface is significantly flatted at \(t=2.5\text{\,ns}\), which is about 0.1 ns before the shock reaches it.
In order to study the evolution of the interface structure in more detail, we use Fourier analysis to generate the spectrum corresponding to the interface profile. We can write the interface profile as

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left( a_n \cos \frac{2\pi}{L} n x + b_n \sin \frac{2\pi}{L} n x \right),$$

where $L = 5 \times 10^{-3}$ cm is the domain width. Using a discrete Fast Fourier Transformation, we obtain a cosine spectrum with coefficients $a_n$ ($n=1,2,3,\ldots$) and with all the sine coefficients $b_n=0$. The results are plotted in Fig. 7 for $t=1.6$ and 2.5 ns. We see that the number of nonzero interface spectrum modes grows with time. By the time of 2.5 ns, the interface has eight modes ($a_n \neq 0$ for $n=1,2,\ldots,8$). In other words, the initial, single-mode perturbation evolves to a multimode interface. Therefore, preheat can alter the interface structure by inducing higher-order harmonic modes. This preshock hydrodynamic change due to the presence of preheat will have a significant impact on the later-time, postshock, interface instability (see Sec. IV).

We now turn to the effect of the preheat on the perturbation amplitude. We define the dimensionless amplitude to be the ratio of the time-dependent amplitude to the initial amplitude. Figure 8 plots the evolution of the dimensionless amplitude for two simulations with initial amplitudes of 5 and 10 $\mu$m. We see the dimensionless amplitudes increase from 1 to 1.4 ns and then decrease by 2.5 ns. The value at 2.5 ns is approximately 35% for the 5 $\mu$m case and 40% for the 10 $\mu$m case. We also see that the dimensionless amplitude during the course of the evolution is very similar for both initial amplitudes. It thus appears that the dimensionless amplitude is not strongly sensitive to the initial amplitude over this range.

We are also interested in whether the interface shape has changed in the low-preheat case. The amplitude of the interface modulation is plotted as a function of time in Fig. 9, during the preshock phase. We see that the amplitude increases by about 0.9% of the initial amplitude. We also evaluated the change in the spectral content for the low-preheat case. We performed a Fourier series expansion (1) for interfaces at times 1.6 and 2.2 ns. We do not see any spectral change of the interface structure at time 1.6 ns. At time 2.2 ns, we obtain cosine amplitudes $a_1 = 0.000\ 251$, $a_2 = 0.000\ 001$, and $a_3 = 0.000\ 001$ ($a_n = 0$ for $n > 3$ and $b_n = 0$ for all $n$). Thus, some higher modes have been excited, albeit with small amplitude.

IV. LONGER-TERM EFFECTS ON INTERFACE STRUCTURE

In this section, we show the longer-term effects on the interface structure that evolve from the altered initial conditions produced by preheat. We compare the four cases de-
scribed in Sec. II, that is, the low-preheat and high-preheat cases, each with and without late radiative heating. The FronTier simulations for this purpose were carried out for a 1000 \(\mu\)m long and 50 \(\mu\)m wide rectangular tube in planar geometry, working from the initial conditions described above.

For the low-preheat case, Fig. 10 shows the comparison with and without late radiative heating. The figure shows the postshock interface evolution by displaying contour plots of density at times 1, 6, 8, 12, and 16 ns. In each case, one sees a “spike” of denser material penetrate upward into the shocked foam, as expected due to the action of the RM and RT instabilities. We see that the mean interface positions, the amplitudes of the perturbation, and the transmitted shock positions are very similar in the two simulations. One slight difference is that the bubble-edge positions near the boundaries at times 12 and 16 ns are slightly higher in the simulation with late radiative heating. In addition, the simulation with late radiative heating shows development of a secondary structure on the interface, which starts at the shoulder of the spike at 6 ns and becomes more significant near its lower neck at 12 and 16 ns.

For the high-preheat case, Fig. 11 shows the comparison with and without late radiative heating. The figure shows the postshock interface evolution by displaying contour plots of the density side by side at times 1, 2, 3, 4, 5, 6, 7, 8, and 9 ns. We see the mean interface positions in the simulation with late radiative heating are higher than those in the simulation without late radiative heating. The amplitude and growth rate are plotted in Fig. 12, from which we make several observations. The perturbation amplitude in each simulation reaches its maximum around 8 ns. The maximum amplitude in the simulation with late radiative heating is about 3.1 \(\times 10^{-3}\) cm, which is 25% higher than the maximum amplitude of 2.5 \(\times 10^{-3}\) cm in the other case. The rate of amplitude growth is also a bit higher in the simulation with late radiative heating. It is clear from the comparison of the two cases in Fig. 11, and from the comparison with Fig. 10, that increased preheat alters the instability development at later times. This occurs due to heating during the laser pulse, as illustrated by the case without late radiative heating (which might be the best surrogate for the effect of hot electrons, whose source ends when the laser pulse does). In addition, the effect on instability development is increased if late radiative heating is actually present after the laser pulse.

V. CONCLUSIONS

In the present paper, we have applied a general methodology using computer models to study the impact of preheat on the structure and evolution of an unstable interface in laser-driven shock experiments. While our specific motivation is certain laser astrophysics experiments, preheat may be an issue for many laser experiments. Our simulations are carried out by using a radiation-coupled, front-tracking algorithm, which can effectively track the evolution of interfaces in the presence of continuing radiative heating. We find that preheat at the level of 10 eV, which might be produced by hot electrons, can shift the position of the interface between denser and less dense materials and also can alter the inter-
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face structure including its spectrum and amplitude. In the specific high-preheat case evaluated here, the interface perturbation was gradually flatted during the preheating. By the time the shock front was near interface, the amplitude was reduced to 35–40% of its initial value. A Fourier analysis of the interface profile showed that higher harmonics modes were induced during the preheating, so that the initial single-mode perturbation evolved to a multimode perturbation. We showed that such preheat-induced interface changes have a significant effect on the structure produced later in time by interface instabilities. In contrast, preheat at the level of 0.1 eV, which is expected due to radiative effects alone, has much smaller effects. Some changes in the initial interface position and shape remain, but these are small enough that their effects would be very difficult to detect. In this case, we do observe the appearance of secondary interface structures at later times. Thus, it may be that the detailed structure of the spikes produced in experiments is to some degree a diagnostic of preheat. However, this might also be problematic given the well known variation in such details among different simulation codes.

Since preheat can have a significant impact on both pre-shock interfacial conditions and postshock interface evolution, as demonstrated in the high-preheat case, knowledge (and ideally control) of preheat is essential in laser experiments. To achieve the simplest possible experiment, minimization or elimination of preheat is clearly desirable as shown by the low preheat study. We have demonstrated here that one can conduct a preliminary numerical assessment of preheat effects before actual laser experiments are conducted. Such numerical estimates or predictions of preheat effects may be useful in designing experimental targets since many sets of simulations can be carried out before an appropriate set of parameters is chosen for an experiment.

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