Expected Variation in Radiative Shock Behavior due to Experimental Laser Beam Variability

E. M. Rutter1 • M. J. Grosskopf1 • C. C. Kuranz1 • F. W. Doss1 • B. Torralva1 • R. P. Drake1

Abstract High-energy-density lasers are used to create radiative shocks which are abundant in astrophysical phenomena such as supernova remnants. Natural variation in the laser-driven radiative shock experiments, such as the exact placement of each laser beam, may affect the velocity of the radiative shocks as well as general shock behavior. Analysis of experimental variabilities and uncertainties was performed which included a Latin hypercube sampling of beam pointing and target alignment errors to investigate laser spot uniformity.

Keywords Radiative Shocks, Radiation Hydrodynamics, Laboratory Astrophysics

1 Introduction

Radiative shocks are a specific type of radiation hydrodynamic system, mainly shockwaves that are hot enough that the energy loss from the shocked matter via radiation is approaching the incoming thermal energy flux. Radiative shocks are abundant in astrophysical phenomena including supernova remnants. These shocks can be scaled in order to be reproduced and studied in laboratory settings using high-energy-density facilities and millimeter-scale targets containing beryllium and xenon gas (Reighard 2006). Diagnostic tools can image these radiative shocks, using x-rays, so one can further understand their behavior in terms of velocity and shock location. However, using high-energy-density facilities is costly, and often a lot can be learned from simulating experiments.

The University of Michigan’s Center for Radiative Shock Hydrodynamics (CRASH) is developing an adaptive mesh refinement (AMR) radiation hydrodynamics code, which will be able to model radiative shocks, among other astrophysically relevant radiation hydrodynamic systems. However, at the present moment, CRASH does not model the energy deposition of the laser, therefore another code, Hyades, is used in order to model laser driven experiments like ours. Hyades is a 1D or 2D Lagrangian Radiation Hydrodynamics code containing a laser package (Larsen and Lane 1994) whose results are passed to CRASH as initial conditions.

In addition to input from Hyades, results from radiative shock experiments (Reighard 2003; Doss 2009) performed on the Omega Laser at the Laboratory for Laser Energetics (LLE) at the University of Rochester (Boehly 1995) are used to improve the predictive capability of the CRASH code. As with many simulations, there are discrepancies between the experimental data and the simulation results. Naturally, there are experimental variabilities, including exact placement of each laser beam, which can affect the behavior of the radiative shocks. An analysis of these experimental variabilities, using a statistical method called latin hypercube sampling, was performed to analyze expected variation in shock behavior they produce. The things that vary include the properties of the laser beam envelope, the accuracy of positioning the target in the Omega chamber, and the variation between the target specification and the target as built. Consequences of these variations include oblique or crooked shocks and slower, weaker shocks. If the shocks were slow enough, they would not be radia-
Laser Beams

The initial CRASH radiative shock problem is displayed in Fig 1. There is a 2.5mm, 20-micron thick disc of beryllium at 1.8 g/cm$^3$ density one end of a tube filled with xenon at 1.1 atmospheres of pressure at density 0.0065 g/cm$^3$. The 550-micron diameter polyimide tube of density 1.15 g/cm$^3$ is 4.5 mm long. There is a gold foil on the non-irradiating side of the beryllium and an acrylic shield behind that. A 1ns square laser pulse of ten laser beams delivering a total of 3800 J of nominal laser energy, although it varies with a standard deviation of 2% (Doss 2010).

As can be expected, there are pointing errors within each of the ten lasers used to create the radiative shocks. As the targets are extremely small, sub-millimeter, even miniscule errors may greatly affect shock behavior. The Omega facility at LLE cites errors within approximately 25 microns on average with extreme cases being as large as, or larger than, 50 microns for each beam. For the Latin hypercube, explained below, one needs to create a statistical function representing the range of errors. Therefore, a normal distribution with a mean of zero and a standard deviation of 25 microns was chosen to represent the function of errors per beam in the $x$, $y$, and $z$ directions. This represents errors more extreme than we expect to encounter in actual experiments.

Two different specific sets of laser beams are examined here. These two sets, referred to as October 2008 and December 2009, were used to perform the experiment just described on the Omega laser at LLE. The two separate combinations of beams were chosen because each experiment required different diagnostic tools located in different angular positions in the target chamber, which necessitated using different laser beams. Each group of ten laser beams created a different distribution of beam angles with the target. The October 2008 beam configuration features two beams at 10.32 degrees, three beams at 31.69 degrees, four beams at 42.25 degrees and one beam at 50.51 degrees. The December 2009 beam profile is generated by one beam at 10.62 degrees, two beams at 20.7 degrees, three beams at 31.0 degrees, two beams at 39.8 degrees and two beams at 51.1 degrees. These two cases are compared below to a nominal case, in which ten laser beams irradiate a target at 0 degrees. Both the individual beams and the envelopes composed of ten beams turn out to be well described by a Super-Gaussian equation:

$$y = a \exp \left(-\frac{(x - c)^2}{b^2}\right)^d \quad (1)$$

where $a$ is the maximum laser irradiance, $b$ is the location of the center of the Super-Gaussian, $c$ is related to the spread (full-width half-maximum), and $d$ is the Super-Gaussian power. A Super-Gaussian function is almost identical to the Gaussian function, except the power is not restricted to 2. Higher powers imply a steeper, thinner, more square-shaped profiles. For the individual beams, the distributed phase plates on Omega create a spot size of 820 microns diameter at half-intensity, with a Super-Gaussian power of 4.7.

Another experimental error affecting the beam envelopes is the target alignment. The targets are aligned
Fig. 2 Surface plot of beam profiles with a spot-size inset. The smaller circle in the inset represents the 500-micron radius where most of the beam profile resides

within the Omega laser chamber to the location where the laser beams are pointed with high accuracy. Thus, an error in target alignment will cause uncertainty in the experimental data collected and this process seeks to find what degree of uncertainty. The errors for target alignment, as observed in our previous data, are assumed to follow a uniform distribution with a maximum error of 6 degrees for both target theta and phi positioning. Note these errors are the combination of target fabrication errors as well as alignment errors within the Omega chamber. These errors in target alignment also may affect diagnostic measurements, although these are not the subject of the present study.

Target fabrication for these experiments are performed at the University of Michigan and metrology is performed to analyze the errors in target properties. One property that varies is the angle that the beryllium disk is attached to the polyimide tube, which are ideally perpendicular. As the glue thickness joining the disk and tube is difficult to control, it is possible the glue layer is thicker on one side, angling the drive disk. This inclination would cause a crooked shock to be launched into the xenon. As the fabrication team has gained experience and developed new fabrication techniques, target fabrication errors have grown smaller. Thus, the assumption that combined target fabrication errors and placement errors reaching six degrees models the worst-case scenarios occurring in the past. Current angular errors for combined target alignment and fabrication errors average 1–2 degrees in the theta and phi directions taken from previous experiments.

In order to accurately model the beam pointing errors, a sample space of errors must be constructed. A latin hypercube is an efficient method of accurately sampling parameter spaces. It aims to generate plausible values for multiple parameters with less computation. It is a multi-dimensional sampling process meaning that it is possible to perform statistical analysis on all thirty-two variables at the same time. Many studies use latin hypercubes in order to determine a fairly even spread over parameter space without extraneous computing cost.

To construct the latin hypercube, the first step is to choose the total number of desired sample points. We chose 27 points because it was large enough to cover our sample space, and our resources permitted larger selection. From here, the sample space of each of the 32 variables (x, y, and z errors for each of the ten individual laser beams, target theta and target phi positioning) described above is divided into 27 equally-probable subspaces. Within these subspaces a sample point is selected. The latin hypercube is now ready to be generated.

The latin hypercube will return 27 sets of values, each containing one sample point for each of the 32 variables. Each set of values depends on the previously selected values. For the first set, a random subspace is chosen for each of the variables. For subsequent sets, previously chosen subspaces are not eligible to be selected again. By pre-selecting subspaces of equally probable values, there is a guarantee that the latin hypercube sampling is representative of the variability, as opposed to a random sampling which could leave out large areas. Thus, latin hypercubes are especially useful when varying large amounts of variables, as we are doing here.

Each of the 32 functions described above is used to create a 32-dimension latin hypercube. The selected values are then used to generate a beam profile. The program used to generate the beam profiles is an IDL-written program called Illumine, distributed to us via S. G. Glendinning. This program is specifically used for generating beam profiles for the Omega laser at LLE. It intakes desired beam numbers, as labeled at the Omega laser, and target positioning. There is an option of changing beam positioning in each of the x, y, and z directions for any Omega laser beam. It outputs a contour plot or the laser spot size as well as an array containing information about the irradiance. The center of the laser spot outputted from Illumine is not located in the center.

3 Analysis of Beam Envelope Variations

After Illumine calculates the laser beam spot sizes, it outputs an irradiance map of the beam envelope produced by a specific combination of beams. The data generated in one case are displayed on a 3D surface plot
Fig. 3  The Super-Gaussian fitted to the October 2008 beams. The Super-Gaussian very accurately fits to the data points for the laser irradiance in Fig. 2. Fig 2 displays the October 2008 beams. This surface plot is the combination of the ten beams over the 2.5 mm diameter target size. Much of the beam spot is located within a 500-micron radius circle. The inset of Fig 2 features the actual output of Illumine, a contour spot size of the laser. The radius is 1.25 mm and it is easy to see that much of the beam does not even register significant energy outside of the 500-micron radius. In order to accurately understand the shape of the beam envelope, we took two cross sections of the 3D profile, along arbitrary x and y axes as seen in Fig 2. From these two cross-sections through the center of the beam, the locations, shapes, and aspect ratios of each of the 27 beam profiles, for each of the October 2008 and December 2009 cases, at full-width half-max, 90% laser beam strength and 5% laser beam strengths are calculated. We used these measurements to determine the spot size of the beam envelope, as well as how circular the spot is. These measurements control whether an uneven shock may be driven through the xenon. Each cross-section was also fitted with a Super-Gaussian curve to determine the power, as illustrated in Fig 3. Fig 3 shows that the October 2008 beams are well fitted to a Super-Gaussian curve. The power of the Super-Gaussian is important because it is one of the main features used to define the laser beam envelope for our simulations.

Once all the features were noted, the mean and standard deviation of each feature across the 27 runs for a given set of beams was calculated to determine a likely distribution of the laser beams for each of the December 2009 and October 2008 beam sets. Fig 4 displays the comparison of the same cross-section through the nominal case, the December 2009, and the October 2008 beams in black, dotted, and dashed, lines respectively. The nominal case, of 10 beams at a 0 degree angle, is not possible at Omega, but is the profile used for simulations without angled beams. As can be seen in the graphs, although the differences are not extreme, there are noticeable differences. The magnified portion more noticeably displays these differences. The nominal beam envelope forms a more slender, steeper Super-Gaussian curve, which creates a more square pulse. The October 2008 beam envelope is furthest from the nominal case. In addition, the nominal beam profile also reaches a higher irradiance maximum.

The properties of the super-Gaussian fit also vary among the cases. The full-width half-max of the beam envelope was near 820 microns for both the October 2008 and December 2009 beams, as well as for the nominal case. There was a slightly elliptical shape to the October 2008 laser beam envelope, with an aspect ratio of 1.037 and a standard deviation of 0.0064, as compared with the more circular December 2009 aspect ratio of 1.005 with a standard deviation of 0.0039. The October 2008 and December 2009 beam configurations have aspect ratios differing by 3.2%. The aspect ratio was determined by comparing the diameters at the full-width half-max for both cross-sections. The power of the super-Gaussian fit was closer to 4.0 than to the 4.7 of the nominal case, for both the October 2008 and December 2009 beams.

4 Impact of Beam Envelope Variations in Laser-Plasma Simulations

Once these data were collected, they were used to generate a beam profile to use in simulations with Hyades. Hyades is a 1 or 2 dimensional Lagrangian Radiation Hydrodynamics code that models laser deposition with multi-group radiation transportation and uses tabular
or ideal gas equations of state. The simulations containing new beams were both run to 1ns at which point the laser pulse ends and the results from Hyades are used to initialize CRASH. Thus, we are interested to ascertain whether there are significant consequences in using a more experimentally accurate beam profile. We cannot, however, assess the implications of the anticipated offset of the target axis relative to the center of the beam profile on tilting of the shock, because Hyades is only a 2D code.

Three simulations were run; the nominal case, an October 2008 case using the average of the parameters found in the latin-hypercube study, and a similarly averaged December 2009 case. The features that are interesting in radiative shocks include the shock position and the profiles of pressure and density. In order to find the shock position, it is necessary to observe the pressure and locate the largest drop in pressure, representing the shock front. Fig 5 shows the output from 2D Hyades (h2d) for the October 2008 beams, which is a 2 dimensional density plot where there is increased density near shock location is (just before 0.07 cm). Since the shock is now in the xenon, located below 0.03 cm in the z direction, it is easily visible as the higher density portion. As it is difficult to compare many two-dimensional images, horizontal 1-D profiles are taken from h2d and compared as one-dimensional graphs.

Fig 6 side-by-side graphs show these results at three different time points, .25 nanoseconds, .5 nanoseconds, and 1 nanosecond. The black line, dotted line, and dashed line represent the nominal beams, the December 2009 averaged beams, and the October 2008 averaged beams, respectively. Notice that the shapes and positions of the graphs, at all three times are extremely similar. In fact, viewing the graphs, it does not appear there are any differences, it is only when the values of pressures and densities are examined that any conclusions can be drawn. The differences in maximum pressure and density are minimal: at 1 nanosecond, maximum density exhibits a difference of +1.25% compared to the nominal beams. The maximum pressure at 1 nanosecond showed a -4.21% difference from the nominal beams. The densities and pressures retain similar shapes and locations at the hand-off time for CRASH.

5 Conclusions

In an effort to determine the cause of the differences between theoretical simulations and experimental data of laboratory-produced radiative shocks, a latin hypercube analysis was performed on laser beam pointing errors and target alignment errors. The resulting average beam profiles were implemented into the Hyades code and the output at the moment when the results are transferred to the CRASH code was analyzed. Although the beam profiles corresponding to the experimental variability exhibited differences from a nominal, normal-induced case in terms of Super-Gaussian power, spot size, and eccentricity, the simulations of the radiative shock did not show these same differences. Despite
using errors far more extreme than those we would encounter in an actual experiment, the pressures, densities, and locations of the radiative shock had negligible differences, which increased only slightly as the simulation time increased. Now that it is understood that variations in the actual laser beam profile are not responsible for experimental errors, further studies will be performed to determine the cause of experimental errors in an effort to understand the differences between simulation and experiment. Once the ability to model laser deposition in 3D becomes available, it will be important to evaluate the impact of off-center beam nad target alignment on the target dynamics.

Acknowledgements The authors would like to acknowledge and thank the target fabrication team at University of Michigan and Steve Stagnitto and the technical staff at LLE. This research was supported by the Predictive Sciences Academic Alliances Program in NNSA-ASC under grant number DE-FC52-08NA28616.

References


This manuscript was prepared with the AAS LATEX macros v5.2.