On a statistical scattering model to explain capsule implosion asymmetry in vacuum hohlraums with radiation temperatures of order 100eV

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Abstract. We apply a statistical scattering model of laser ray propagation to obtain improved agreement with measurements for capsule emission symmetry in one of three sets of experiments. Linearized post-processing of the simulations for amplification of a variety of plasma instabilities, coupled with an accounting for intensity seed perturbations in the laser beams suggests that thermal filamentation can cause the density fluctuations. Although this mechanism does not appear to be significant in the remaining two series, its identification adds to the knowledge base in the use of symmetry capsules to measure hohlraum drive asymmetry.

1. Introduction
Researchers from Los Alamos National Laboratory have conducted shot sequences on symmetry capsules in hohlraums at the LLE facility of the University of Rochester to probe contributions to symmetry behavior of NIF capsules due to the first of four pulses in the NIF ignition profile[1]. The concept of symmetry capsules has been elucidated in an earlier paper [2]. The capsule and hohlraum dimensions were scaled to 0.7 of NIF scale 1 size. The hohlraum temperatures were designed to be about 100eV, approximately the temperature for the NIF hohlraum during the first pulse.

The characteristic geometry for the individual shots is shown in Figure 1; for simplicity we consider one half of the total hohlraum, and assume reflection symmetry around the z=0 plane. Up to three cones of beams were incident through the laser entry hole (LEH) at each end of the hohlraum. All shot series were primarily concerned with the predictability of capsule symmetry at peak emission.

A limited number of random phase plates were available for the first set of shots; since it appeared likely that it would be hardest to control the cone 1 beams, which penetrated furthest into the hohlraum, the phase plates were put on these beams. For the latter two shot sets, random phase plates were available for all cones. Other differences between the original and the latter shots were pulse-width (3ns FWHM for the original series vs. 1ns FWHM for the latter series) and hohlraum temperature (lower for the original series because the available beam energies were approximately 270 J/beam instead of 500 J/beam).
In the absence of azimuthal variation around the hohlraum symmetry (z) axis, the capsule shape for any emission intensity at the time of peak total emission can be expressed as 
\[ a_0 + \sum_{n=1} P_{2n} (\cos \theta) \],
where \( P_{2n} \) is the Legendre polynomial of order \( 2n \) and \( \theta \) is the angle between the line from the capsule origin to the contour point and the symmetry axis. For \( a_2/a_0 > 0 \), the capsule is prolate. The differences in \( a_2/a_0 \) between experimental and simulational results were initially significantly greater for the original series.

In this paper we present and provide justification for a model of statistical scattering of laser rays, which brings the simulational results for the original shot series into substantially better agreement with experiment. We then assess the impact of this model on the latter two shot series.

2. Comparison of experiments and simulations for the original shot series
The targets for this series were CH shells, nominally 15\( \mu \)m thick and 1400\( \mu \)m in diameter. Figure 2 summarizes the results for a pointing scan consisting of three shots with the intersection of the central ray of the 42° cone (2) with the z-axis successively at -500\( \mu \)m, -250\( \mu \)m, and +500\( \mu \)m with respect to the intersection of the z-axis and the LEH plane. (The geometry for -250\( \mu \)m displacement is shown in Figure 1; cones 1 and 3 make angles of 21° and 58° with the negative z-axis.) Values for \( a_2/a_0 \) and \( a_4/a_0 \) for the image 30% contour are plotted vs. z-axis – cone2 intersection location in microns.

In addition to calculations with standard Lasnex modeling, simulations were also done with a statistical laser ray scattering model (also available in Lasnex) based on the assumption of a scattering length due to unresolvable small-scale fluctuations in the electron density \( n_e \). The scattering length has the form:
\[ L_s = L_0 (n_e/n_{crit}), n_{e < cut-off}, L_s = 0, \text{ otherwise.} \]
The value for \( L_0 = 10^{-7}\text{ cm} \) provides a reasonably close match to the experimental data. \( n_{cut-off} (= 10^{19}\text{ cm}^{-3}) \) was selected to avoid spurious low electron density interactions; for our case \( n_{crit} \) is the critical electron density for 3\( Z \) light.

The usage of \( L_0 = 10^{-7}\text{ cm} \) instead of the more plausible \( L_0 = 10^{-4}\text{ cm} \) is only significant for electron densities between \( 10^{19} \) and \( 10^{20}\text{ cm}^{-3} \) (where the resulting values for \( L_s \) are more physically reasonable), but this has the effect of greatly increasing the size of the region of significant ray scattering. Higher densities are spatially close to the region of significant absorption, so the effect of \( L_0 \) variation on the energy deposition location due to the scattering from them is small.

Experimental values are connected by the black lines. Results for standard calculations, are linked by green lines, and results including statistical scattering are joined by magenta lines. Solid lines connect values for \( a_2/a_0 \), and dashed lines are appropriate to \( a_4/a_0 \). Experimental emission images are in color, and simulated emission images with statistical scattering are shaded in grey.

Considering the plots for \( a_2/a_0 \) and \( a_4/a_0 \) separately, it is clear that the agreement between simulation and experiment is significantly improved by the addition of the statistical scattering model to the simulations.

3. Physical basis for the application of the statistical scattering theory
Plasma instabilities can possibly amplify seed perturbations due to intensity fluctuations in the incident laser beams to produce plasma density microstructure for beam scattering. Since the beams in cones 2 and 3 do not pass through phase plates, they are more likely to contribute to instability growth than smoothed beams with speckle structure. The NEWLIP code [3] has been used to obtain linear calculations of the integrated gain exponent \( G \) for various instabilities along an averaged laser ray trajectory for the beams in each cone. Spatial gains obtained by Krue [4] were used for the filamentation processes. A set of results for the 42 degree cone with pointing at -250\( \mu \)m is shown in Figures 3a-3c. Instability growth within the hohlraum, e.g. within the gold plasma ablated from the hohlraum walls, appears to be dominated by thermal filamentation.
For purposes of an estimate, the size of seed perturbations in intensity can be found from laser intensity plots, which are provided on the University of Rochester LLE web-site [5]. Figure 4 is the plot for a beam with pulse shape, energy, and defocus at the hohlraum side wall, similar to those in the experiment. Using IDL to Fourier transform the beam in two-dimensions and then taking a diagonal cut of the resulting image, one readily obtains Figure 5 as a representation for the variation of intensity fluctuations as a function of spatial wave number (normalized to \( k_0 \), the wave number for 3\( \omega \) light). Normalizing to the amplitude of the uniform (\( k=0 \)) mode (\( \approx 10^{4.33} \)), one finds that \( 3.e-5 \leq \delta I/I_0 \leq 3.e-2 \), where \( \delta I \) is the intensity seed amplitude and \( I_0 \) is the mean intensity.

From Figure 3a, we note that the estimated values of amplified perturbations (\( \eta = e^{G} \delta I/I_0 \)) are readily greater than unity; i.e. for \( G=15 \) and \( \delta I/I_0 = 3.e-5 \), \( \eta \approx 10 \). Hence it is plausible for this set of shots, that thermal filamentation instability can produce substantial fluctuations for beam scattering. It is also possible that structuring of cone1 beams could derive from cone2, because, as shown in Figure 1, the deposition regions for the two cones tend to overlap on the hohlraum side wall.

For thermal filamentation the fractional electron density fluctuations, \( \frac{\delta n}{n} \), and intensity fluctuations, \( \frac{\delta I}{I} \), are related by [4]:

\[
\frac{\delta n}{n} = \frac{1}{2} c_T e (\frac{\delta I}{I}) \left( \frac{2 n_c}{T_e} \right) (n_c/ke)^2,
\]

with \( T_e, n_c, e, \) respectively the electron temperature, electron-ion collision frequency and electron thermal velocity. For \( I = 10^{14} \text{W/cm}^2 \), and \( T_e = 600 \text{ev} \), with \( \lambda \) in microns, this becomes [6]:

\[
\frac{\delta n}{n} \approx 2.75 \times 10^{-4} \lambda^2 (\frac{\delta I}{I}) (n/10^{21})^2,
\]

from which at \( k/k_0 = 0.01 \), and \( n=10^{21} \text{cm}^{-3} \), \( \frac{\delta n}{n} \approx 0.3 \frac{\delta I}{I} \).

### 4. The effect of statistical scattering through thermal filamentation on capsule emission symmetry for the latter two shot series

The laser intensities at the hohlraum side wall in these two series are within about a factor of 2 of those in the first series. With phase plates, a number of factors should act to decrease the magnitude of density fluctuations: 1. transfer of beam energy from larger to smaller wavelengths, which have lower intrinsic instability growth rates, 2. weaker linear coupling of the resulting intensity fluctuations to density fluctuations, 3. creation of speckles in the direction of light propagation to limit coherent filamentation growth lengths. Hence it is not surprising that simulation results are closer to experiment for these series.

For the second series, which did not use cone 1 beams, the calculated \( \alpha_2/\alpha_0 \) values for the pointing scan agreed with experiment to within 0.02. For the third series, which included beams at all three cone angles, for CH capsules with oblate observed shape (\( \alpha_2/\alpha_0 < 0 \)), the calculated values were typically high by \( \approx 0.25 \), still a relatively small fraction of the discrepancy with standard Lasnex modeling for the original series.

![Fig. 1 Original shot series: region boundaries and beam cones at t=0.](image)

![Fig. 2 Graphical summary of pointing scan results for the initial shot series.](image)
Figure 3 Total gain exponent $G$ for instabilities at selected times after the start of the laser pulse: red-0.7ns, green-1.2ns, blue-1.7ns, cyan-2.2ns, magenta-2.7ns. Abscissae are either wave number $k$ normalized to $k_0$, the wave number for $3\omega$ light or wavelength $\lambda$. Instabilities are: a) thermal filamentation, b) ponderomotive filamentation, c) backward stimulated Brillouin scattering. The peak $G$ value for backward stimulated Raman scattering (not included) is 0.6.

Figure 4. Relative intensity plot for a beam similar to the beams in cones 2 and 3.

Figure 5. Plot of $\log_{10}[F(k)]$ vs $k/k_0$, for the beam of Fig. 4. Here $F(k)$ denotes the Fourier amplitude of the intensity perturbation at magnitude $k$ for wave vectors in the diagonal direction.

References
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