Modeling and Interpretation of Nova's Symmetry Scaling Data Base

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Our 2D LASNEX simulations of Nova's nine symmetry scaling data bases reproduce the fundamental features seen in the experiments. In particular, we predict how we must change Nova's beam pointing in order to achieve best symmetry with various pulse shapes. This need to change pointing with different pulse shapes is the result of a bulk-plasma-induced migration of the laser deposition/x-ray production region. We have observed and modeled this migration.

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Understanding and controlling capsule implosion symmetry is a key requirement for inertial confinement fusion (ICF). For more than a decade it has been recognized that the fundamental asymmetry for the indirect drive approach to ICF is a long-wavelength pole-waist radiation flux variation, which varies like the P_2 Legendre polynomial [1]. Examination of our ability to understand and control the time integrated P_2 asymmetry has been the subject of a number of scaling experiments over the past seven years. These experiments confirm that the long-wavelength mode dominates while shorter-wavelength modes seem heavily damped [2,3]. They also show that the P_2 mode can be systematically varied from shot to shot by changing the beam pointing (Fig. 1 shows how we measure beam pointing) and that approximately spherical implosions, with inferred P_2 flux nonuniformities of $<\sim 2\%$, can be produced with the appropriate pointing [3]. We find that pointing Nova's beams so they strike the *Hohlraum* wall closer to the midplane tends to make a more prolate implosion, while pointing them further away from the midplane makes a more oblate implosion. Recently, we have carried out a number of quantitative symmetry studies [3]. The basic procedure of these experiments has been the same; for a given pulse shape and *Hohlraum*-type, we generate a symmetry scaling by carrying out shots in which we vary the beam pointing while observing the resulting shapes of the capsules' self-emission flash produced at stagnation.

Since 1990, we have produced nine different symmetry scaling databases with the Nova laser, using three pulse shapes and two classes of *Hohlraums*. We have done three scalings with 1 ns wide, flattop pulses; five scalings with a 26 kJ, 2.2 ns, shaped pulse which had 3:1 power ratio between the foot of the pulse and the peak ("ps22"); and one scaling with a 27 kJ, 3.2 ns, 8:1 power ratio, shaped pulse ("ps23"). We have used these pulse shapes to irradiate two classes of *Hohlraums*, pure gold *Hohlraums* and lined *Hohlraums*. Lined *Hohlraums* are gold *Hohlraums* which are lined, on the inside, with a thin layer of either low-Z material (e.g., CH) or mid-Z material (e.g., Ni). We investigated lined *Hohlraums*, because we believe something like a liner is necessary at larger, ignition scales. For ignition *Hohlraums*, we calculate that pure gold designs will fill with high-Z plasma. This causes the laser absorption region to move almost to the laser entrance hole, producing an unacceptably large radiation flux asymmetry on the capsule. Liners are one way to eliminate this effect by replacing the high-Z blowoff with low- or mid-Z blowoff.

With 1 ns flattops we have shot both pure gold and Ni-lined (1500 Å) gold *Hohlraums* fixed in length at 2700 μm. We have also shot pure gold *Hohlraums* where we varied the length of the *Hohlraum* with the pointing so that the beams always cross in the plane of the laser entrance hole (LEH). We have done five scalings with ps22: fixed length gold and Ni-lined gold *Hohlraums* and variable length pure gold, Ni-lined gold, and CH-lined (0.75 μm) gold *Hohlraums*. Our ps23 series used pure Au *Hohlraums* which were open cylinders.

Our most detailed modeling of these experiments is done with our two-dimensional numerical simulation code, LASNEX [4]. Figure 1 is a cut-away picture, at

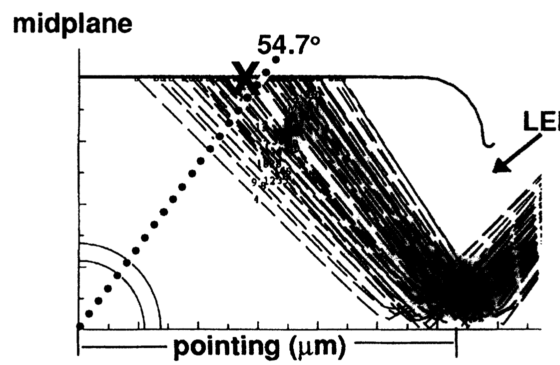

FIG. 1. Cut away at $t = 0$ from a two-dimensional simulation of a *Hohlraum* containing a pure plastic capsule with a realistic representation of Nova's beams. The calculation is cylindrically symmetric around the horizontal axis and left-right symmetric across the midplane. The beams enter through LEH's at the ends of the *Hohlraum*. "Pointing" is the distance between the midplane and where the beams "cross" (i.e., the reflection off the horizontal, rotational axis of symmetry).

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$t = 0$, from a simulation of a *Hohlraum* containing a pure plastic capsule which is irradiated by a "realistic" two-dimensional representation of a three-dimensional Nova laser beam [5]. The wall materials, laser power vs time, etc., of a given simulation are our best estimate of what was used in the experiments we are trying to model. To model a given scaling we carry out a number of simulations with different beam pointings. At stagnation our simulated capsules, like real capsules, produce a burst of x rays which can be imaged. A post processor simulates the actual x-ray diagnostics, producing synthetic images which vary with pointing from oblate to prolate, like the experiment's. The ratio of the image's FWHM perpendicular to the polar axis to the FWHM along the polar axis is the "distortion," a quantity we vary with pointing and compare with experiment.

Our calculations start of fully Lagrangian (matter is fixed in the zones of a moving mesh). Later in time, after a considerable amount of blowoff has filled the *Hohlraum,* we perform a major rezone and change the numerical scheme. The main part of the *Hohlraum* has become Eulerian (matter flows through a fixed mesh), allowing the calculation to run inspite of the larger sheer flows. Most of the capsule, however, remains Lagrangian, the accepted procedure for modeling nearly spherical implosions. We interface the Eulerian and Lagrangian regions with a stretching region that maintains equal-ratio zoning, a hybrid mesh that has matter flowing through it while moving slowly. Using three numerical schemes in the same calculation allow us to simulate both the main *Hohlraum* and the capsule with the most appropriate numerical technique.

A series shot using gold *Hohlraums* lined with 1500 Å of nickel provides an example of how we model a given scaling. The *Hohlraums* were 1600 μm in diameter with 1200 μm diameter laser entrance holes. In this series, the *Hohlraum* length was varied with pointing such that the beams always crossed in the plane of the LEH. We did this to keep laser entrance hole effects approximately the same for all pointings. The capsules in this series had a nominal inner diameter of 440 μm and a plastic wall that was 55 μm thick [6]. They were filled with 50 atm of DD doped with ~0.1% atomic fraction of Ar. We irradiated these targets with ps22. The key observations from this (and all other) scaling series are the self-emission x-ray images from the imploded capsule. Our x-ray diagnostics are both time resolved (~100 ps frame time) and time integrated cameras which are filtered to measure emission >3 keV, where the Ar fuel dopant's emission dominates.

Figure 2 displays the results of this experimental scaling and compares it to our modeling. The solid circles are distortions (ratios of the FWHM's of the x-ray images) from our experiments, as a function of beam pointing. The horizontal error bar shows an estimated ±50 μm systematic uncertainty in the absolute pointing of the beams (the relative shot-to-shot pointing jitter is believed to be considerably smaller than this). The modeling's

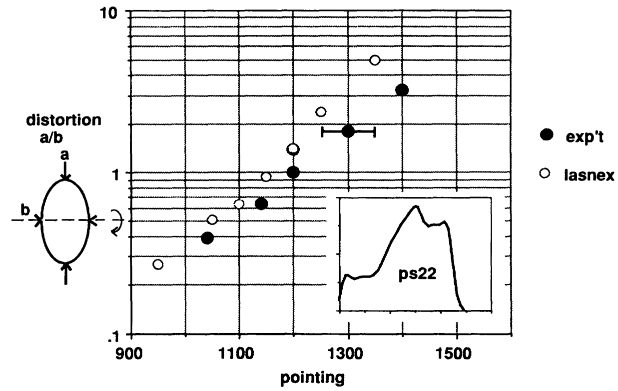

FIG. 2. Capsule image distortion vs pointing from a series using Ni-lined *Hohlraums* irradiated by ps22. Inset: relative laser power vs time for ps22.

distortions are the open circles. Both experiment and modeling agree that we can control Nova symmetry by varying the beam pointing. Modeling and experiment also produce about the same "pointing of best symmetry." For this ps22 series it is ~1200 ± 50 μm in experiment and ~1150 μm in simulation.

The pointing of best symmetry will change as we vary the pulse shape. For example, another scaling series used fixed length (2700 μm), nickel-lined Au *Hohlraums* irradiated with 1 ns flattop pulses. Again, in this series, both modeling and experiment agreed that we can control Nova symmetry by varying the beam pointing. However, for this pulse shape the pointing of best symmetry is about 100 μm outward from the best pointing found in the ps22 series, described above. For this 1 ns experiment, the pointing of best symmetry is ~1320 ± 50 μm in experiment and ~1250 μm in simulations.

We have simulated, with LASNEX calculations, all nine of our symmetry scaling databases. Figure 3 summarizes our ability to estimate the pointing of best symmetry over this wide range of situations. It plots the pointing of best symmetry inferred from experiment against the pointing of best symmetry inferred from our LASNEX simulations. Overall, we find the agreement to be very satisfactory. The vertical error bars in this plot indicate only the uncertainty in the pointing of best symmetry extracted from each experimental data set, using the "nominal" pointing. They do not include the systematic uncertainty in Nova's absolute pointing ~50 μm, which would allow all the points to be moved, as a group, either to the up (towards poorer agreement) or to the down (better agreement). Regardless of systematic differences, the most significant and apparent feature of the plot is this: *the longer the pulse shape, the further in we must point the beams to get good symmetry.*

We believe that the reason for this is found in the basic principles of symmetry scaling in Nova-type *Hohlraums.* First, there are hot, laser produced emission rings which migrate towards smaller polar angle (when viewed from

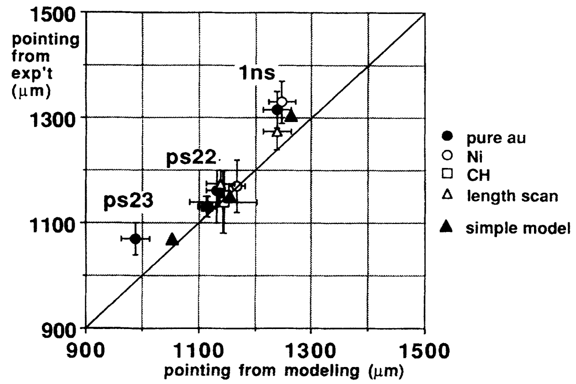

FIG. 3. Pointing of best symmetry in experiment vs pointing of best symmetry from our modeling. The longer the pulse shape, the further in we must move the beams to get good symmetry.

the capsule position) because of bulk plasma evolution. We refer to this migration as "spot motion." Second, there is also an "optimal" polar angle for the rings, where pole flux equals equator flux (~48° for these *Hohlraums*). Third, to get good symmetry we must point the beams so the emission rings pass through 48° when we deliver about $\sim\frac{1}{2}$ of a shape's useful energy. Since spot velocity is weakly dependent on laser intensity, we move the beams further inward with longer pulses.

In our simulations there are three components to spot motion. First, dense plasma evolution from the cylindrical walls causes the laser deposition region to move inward and, because of the beam geometry, towards the LEH. Second is a refractive component off plasma which accumulates on axis. Finally, there can be a low intensity volume emission when gold blowoff fills the *Hohlraum*, pulling the average center of emissivity further down from the walls. In our simulations, which use a non-LTE, average atom atomic physics model [7], the gold blowoff is optically thin to thermal radiation. Consequently, volume absorption does not paly a significant role in determining the capsule flux.

To see how spot motion can cause the scaling of Fig. 3, first recall that the fundamental asymmetry in a left-right-symmetric, Nova-like *Hohlraum* is a long-wavelength, pole-to-waist flux variation which varies like the P_2 Legendre polynomial [1]. Whether the asymmetry is pole high or equator high depends on the polar angle to the center of the laser produced, x-ray emission ring. In an idealized *Hohlraum* without laser entrance holes and with otherwise uniform walls, the drive asymmetry will clearly be pole high when the emission ring is at very small polar angle and equator high when the emission ring is near the midplane of the *Hohlraum*. Somewhere in between the pole and equator fluxes will be equal. In a spherical *Hohlraum*, the P_2 component of capsule flux vanishes when the P_2 component of the source flux is zero [1]. This occurs when the "center of emissivity" of the emission ring is at the polar angle where P_2 is zero, at 54.7°. For larger angles, the flux onto the capsule will be equator high. For smaller angles, pole high.

A laser entrance hole modifies this quantitatively, but not qualitatively. To compensate for the lack of wall radiation from the LEH, the angle to the center of emissivity in a spherical *Hohlraum* must be smaller than 54.7° for the P_2 component to vanish. Exactly how much smaller than 54.7° is a function of both the emission ring: cold-wall emission ratio and the LEH size.

For example, the angle where the P_2 component of the source vanishes is about 44° in an idealized spherical *Hohlraum*, with wall and LEH areas the same as ours and a wall albedo (which determines the emission ring: cold-wall emission ratio) of ~0.7. This albedo is typical of a rising, nanosecond scale pulse shape. In our more detailed LASNEX simulations, which include higher l-mode components, volume emission, and mode coupling due to having a sphere inside a cylinder, we find the pole-waist fluxes are balanced when the center of emissivity is at ~48°.

With this background we can simply interpret features found in our LASNEX modeling. The lines in Fig. 4 plot, from our simulations, ratios of capsule ablation pressure at the pole to that at the equator vs time in pure gold *Hohlraums* near the pointing of best symmetry for each pulse shape. Early on the ablation pressure is equator high. Late in time, the pressure is pole high. Analysis of our simulations indicates that this time dependence is mainly produced by spot motion. Figure 1 shows a laser ray plot at $t = 0$ for a ps22, pure Au *Hohlraum* simulation. The angle to the center of the beam is greater than 54.7°. Quantitative analysis shows the center of emissivity to be located at the "x" in Fig. 1 at ~57°. The simple symmetry arguments outlined above lead us to expect the drive to be equator high, as is seen in the early time ps22 curve of Fig. 4. By, say, 1.4 ns, spot motion has caused the center of emissivity to move to the "+" in

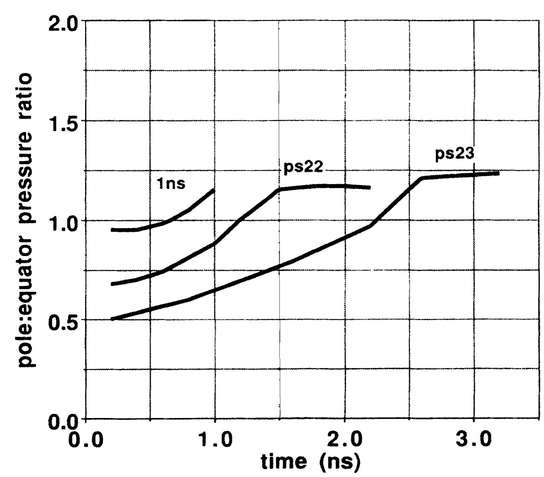

FIG. 4. Ratio of capsule ablation pressure at the pole to the ablation pressure at the equator vs time for our three pulse shapes.

Fig. 1(b) at ~44°. At this time the ablation pressure ratio has become about 10% pole high.

Spot motion, the migration of the radiation production region to smaller polar angles, causes a simulated Nova-type *Hohlraum* to have the characteristic equator-high to pole-high asymmetry swing shown in Fig. 4. For all three pulse shapes we find that near the pointing of best symmetry the center of emissivity sweeps through the "optimal angle" (where pole pressure = equator pressure, ~48° for these *Hohlraums*) when ~50% of a shape's useful energy has been delivered. This ~50% value makes sense. If the pressures were equal when a very different fraction of energy was delivered, the implosion would be dominated by pole-high or equator-high flux and be obviously distorted. Therefore, since spot velocity depends weakly on laser intensity, longer pulses need more inward pointing for best symmetry, because $t_{50\%}$, the time to deliver ~50% of the energy, is longer, leading to more spot motion.

LASNEX shows spot angular velocity to be very weakly dependent on I_{laser}. Over the first 50% of the energy, angular velocity $d\theta/dt$ of the center of emissivity in our simulations increases only as the logarithm of the laser power, closely following

$$\frac{d\theta}{dt} = 6°/\text{ns} + (3.9°/\text{ns}) \log_{10}(P_{\text{laser}}(\text{TW})).$$

We can couple this expression for spot motion with the need to have the center of emissivity at ~48°, when ~50% of the laser energy has been delivered to produce a simple expression for the pointing of best symmetry

$$P_{\text{best}} = 671\ \mu\text{m} + 800\ \mu\text{m}/\tan(48° + (d\theta/dt)t_{50\%}).$$

This expression is for our standard 800 μm radius *Hohlraums* and Nova's 50° half-cone angle. The results of this very simple model are plotted as the filled triangles in Fig. 3 and also agree well with our data base.

For a number of years we have been carrying out separate experiments to observe laser produced x-ray emission spots and their migration [8]. In these experiments we cut an 800 μm × 1200 μm rectangular observation port into the side of a *Hohlraum* through which we take time-resolved x-ray images of the opposite wall. Our field of view includes the initial spot of a beam as well as some of the surrounding region. Qualitatively, these images verify that there are spots and that they do migrate towards the laser entrance hole. We quantitatively analyze these images to find the center of emission, within the port's field of view, at various times. To compare these with simulations we quantitatively analyze LASNEX simulations of the experiment with a postprocessor that mimics the imaging diagnostic and the analysis. Figure 5 shows such a comparison. It plots the position of the center of emission for the 450 eV channel from pure Au ps22 simulations and experiments. The good comparison with LASNEX shows that we can calculate the component of spot motion observed, the component along the *Hohlraum* wall. The data from four different shots show that the motion is reproducible. Reproducible spot motion has also been indirectly corroborated by Precision Nova shots, which produced nearly identical capsule shapes and performances for 5 ps22 shots at one pointing and 4 shots at another.

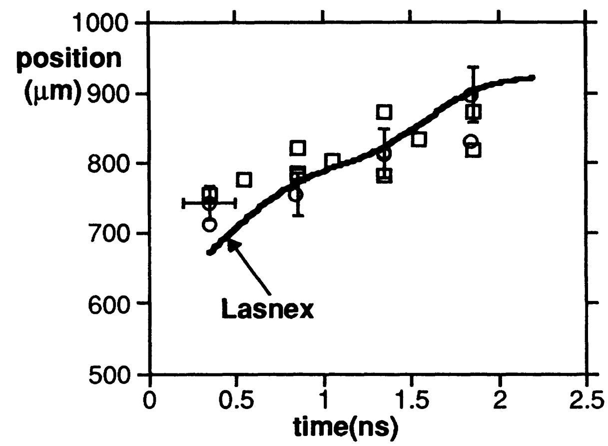

FIG. 5. Distance from the *Hohlraum* midplane to the center of emission, at $h\nu$ ~ 450 eV, vs time, in a pure gold *Hohlraum* irradiated by ps22. We observe spots which migrate about as expected from simulations.

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[1] J. Greene, Research and Development Associates (private communication), 1980; M. Murakami and K. Nishihara, Jpn. J. Appl. Phys. **25**, 242 (1986); A. Caruso, in *Inertial Confinement Fusion*, Proceedings Course and Workshop, Varenna, 1988 (Casa Editrice Composotori, Bologna, 1988), p. 139.

[2] R.E. Turner and L.J. Suter, Bull. Am. Phys. Soc. **1** (1988); Y. Kato *et al.*, in *Proceedings of the 13th International Conference Plasma Physics and Controlled Nuclear Fusion Research, Washington, DC, 1990* (International Atomic Energy Agency, Vienna, 1990).

[3] A. Hauer *et al.*, Rev. Sci. Instrum. (to be published).

[4] G. Zimmerman and W. Kruer, Comments Plasma Phys. Controlled Fusion **2**, 85 (1975).

[5] A. Friedman, in Lawrence Livermore Laboratory Laser Program Annual Report No. UCRL-50021-83, 1983, pp. 3–51.

[6] A. Burnham, J. Grenz, and E. Lilley, J. Vac. Sci. Technol. A **5** (6), p. 3417.

[7] D.E. Post, R.V. Jensen, C.B. Tarter, W.H. Grasberger, and W.A. Lokke, At. Data and Nuclear Data Tables **20**, 397 (1977); G.B. Zimmerman and R.M. More, J. Quant. Spectros. Radiat. Transfer **23**, 517 (1980).

[8] D. Ress and L.V. Powers (to be published).