Hohlraum Symmetry Experiments with Multiple Beam Cones on the Omega Laser Facility

T. J. Murphy, J. M. Wallace, N. D. Delamater, Cris W. Barnes, P. Gobby, A. A. Hauer, E. Lindman, G. Magelssen, J. B. Moore, J. A. Oertel, and R. Watt
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

O. L. Landen, P. Amendt, M. Cable, C. Decker, B. A. Hammel, J. A. Koch, L. J. Suter, R. E. Turner, and R. J. Wallace
Lawrence Livermore National Laboratory, Livermore, California 94550

F. J. Marshall, D. Bradley, R. S. Craxton, R. Keck, J. P. Knauer, R. Kremens, and J. D. Schnittman
Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14627
(Received 14 January 1998)

Symmetry experiments have been performed on the Omega laser facility using cylindrical hohlraum targets with as many as 40 beams arranged into multiple beam cones. These experiments constitute a first step in the development of "beam phasing" in which beams are arranged into multiple beam cones, forming multiple rings of beam spots on the inner surface of a cylindrical hohlraum, and demonstrate the ability to model hohlraums incorporating multiple beam cones and to tune the time-integrated capsule flux asymmetry by adjustment of the beam pointing. [S0031-9007(98)06471-0]

PACS numbers: 52.40.Nk, 52.50.Jm, 52.58.Ns

The goal of the inertial confinement fusion program (ICF) [1] is to implode a deuterium-and-tritium-filled capsule to a sufficiently high density and temperature that the thermonuclear fuel is ignited; this requires the areal density (ρR) of the fuel to be sufficiently large to stop the alpha particles formed in the deuterium-tritium reaction so that their energy is deposited in the fuel allowing the fusion reaction to propagate. The energy-efficient accomplishment of this will require a spherically symmetric capsule implosion and thus a highly symmetric "drive" around the capsule for the entire duration of the implosion, with a time-averaged flux asymmetry on the capsule no greater than 1% and with time-dependent swings no larger than 5%–10% [2]. Excessive time-dependent asymmetry can reduce the efficiency of the implosion process by producing nonradial flows that prevent the attainment of ignition [3,4].

In the indirect-drive approach to laser-driven ICF, the capsule is placed inside a radiation case (hohlraum) made from a high-Z material, typically gold. The laser beams enter the cavity through laser entrance holes (LEHs) and strike the walls where they are absorbed and converted into x rays. The radiation then isotropizes through repeated absorption and reemission. In addition, emission asymmetries from the wall are reduced on the capsule in a manner that depends on the case-to-capsule radius ratio [5].

Symmetric moderate-convergence implosions have been achieved at the ten-beam Nova laser facility using two symmetrically positioned irradiation rings on the inside of a cylindrical hohlraum using cones of five beams each [6]. (In this Letter, a "cone" of beams refers to a group of laser beams at a given angle from the hohlraum axis; a "ring" refers to the pattern those beams create on the hohlraum wall.) A flux pattern is produced around the capsule with a low *time-integrated* asymmetry [7]. The time-averaged P_2 (second-order Legendre polynomial) component to the flux, ideally the lowest-order mode contributing to the asymmetry, is minimized by adjusting the pointing or distance between the rings. Flux asymmetry has been measured by imaging the core of an imploded capsule [7] and comparing the observation with simulations [8], by measuring the reemitted flux from a nonimploding sphere at the center of the hohlraum [9], and by imaging the shock front in a backlit, low-density foam sphere [10].

For the achievement of ignition, both *time-integrated* and *time-dependent* asymmetry must be controlled. The method proposed for the National Ignition Facility [11] is the use of multiple, independently pointed beam cones which can have different temporal intensity profiles (pulse shapes) in order to allow time-dependent control of flux asymmetry. In this Letter, hohlraum experiments and corresponding numerical simulations using the two-dimensional radiation-hydrodynamics code LASNEX [12] are described in which multiple beam cones are used in a cylindrical hohlraum for the first time. The beam cones are pointed in such a way as to produce one or two rings of beams on each end of the hohlraum. Symmetry is characterized by the shape of the imploded core of capsules designed for such purposes [7]. In addition to providing information on symmetry with multiple rings of beams, these experiments serve to test the ability of modeling codes to predict results from not only the Nova laser facility [13], to which they have been extensively benchmarked [8], but also from the recently upgraded

 0031-9007/98/81(1)/108(4)$15.00

Omega laser [14], to which they have not previously been applied.

The targets (Fig. 1) consisted of thin-wall hohlraums [15,16] with 2100 to 2500 μm inside length and 1600 μm inside diameter, and with 1200-μm-diameter LEHs. The walls were made of 2-μm-thick gold backed by 100 μm of epoxy for structural support. This design allowed imaging of the imploded core without the need to drill a diagnostic hole in the side of the hohlraum; in addition, the laser deposition region could be viewed by imaging the hard x rays (>5 keV) produced at the conversion region (Fig. 2). The use of thin walls also reduced the amount of high-Z debris introduced into the Omega target chamber. Plastic capsules placed at the center of the hohlraum had a nominal outside diameter of 550 μm and a wall thickness of 55 μm, and were filled with 50 atm of D_2 gas and 0.1 atm of Ar. The Ar allowed imaging of the x-ray emission from the imploded fuel.

Up to 40 of the 60 Omega laser beams were used for these experiments [17], arranged in three beam cones on each side of the hohlraum, consisting of five, five, and ten beams in each cone, respectively, centered on a pentagonal diagnostic port. The half angles of the beams cones are 21.42°, 42.02°, and 58.85° (Fig. 1).

The position of the beams, referred to as "beam pointing," is specified by the distance from the center of the hohlraum to the point where the beams cross the hohlraum axis. The focusing of the beams along their axis is referenced to that crossing point. The defocus for these experiments was set to give about 8×10^{14} W/cm^2 on the hohlraum wall.

These experiments were performed using a 1-ns flat-top laser pulse with 500 J per beam delivered to the target. The root mean square deviation from the mean of the beam energies was about 8%, as these experiments preceded efforts at achieving better beam balance on Omega. X-ray drive measurements were performed and showed good agreement with simulations [18].

The core images were obtained with gated x-ray pinhole cameras similar to those previously described in the literature [19–21]. The cameras had an integration time of 50 ps, were operated at a magnification of 12×, and utilized 10-μm-diameter pinholes. Since the core was imaged through the gold wall, the image was primarily due to ~5-keV x rays and represented the hottest part of the fuel. Each image is analyzed by evaluating the shape of the contour of 50% maximum emission, and is parametrized by the ratio of the radius of the contour perpendicular to the hohlraum axis a to that parallel to the hohlraum axis b. This quantity is referred to as the distortion and is written a/b. The Omega port geometry is such that no two ports are at right angles to each other. Thus, with the framing cameras in use on Omega at the time, it was not possible to obtain an image perpendicular to the hohlraum axis. Instead, images were obtained 79° from the hohlraum axis. The distortions were corrected using an ellipsoid model. An ellipsoid with axes of length a, a, and b (where b is defined as being along the hohlraum axis) will have an apparent distortion $[a/b]_{\mathrm{ap}}$, when viewed at an angle to the hohlraum axis of θ, of [22]

$$[a/b]_{\mathrm{ap}} = \frac{[a/b]}{\sqrt{\sin^2\theta + [a/b]^2\cos^2\theta}}, \qquad (1)$$

so that, for $\theta = 0°$, $[a/b]_{\mathrm{ap}} = 1$, and, for $\theta = 90°$, $[a/b]_{\mathrm{ap}} = [a/b]$. This correction increases with increasing deviation of $[a/b]$ from unity, but amounted to only about 20% for the largest $[a/b]$ measured in these experiments.

The experiments were simulated on an individual basis with fully integrated, two-dimensional LASNEX calculations [8,23]. The simulations employed the established procedure [8,23] of representing the target by an azimuthally symmetric computational surrogate. The rings of beams were treated as continuous, having the width of the physical beam diameters, and an azimuthally averaged intensity, smaller than the intensity of the

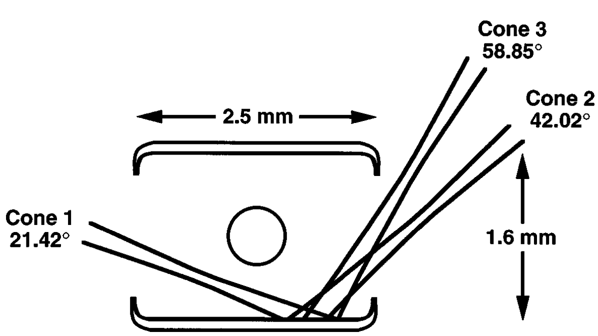

FIG. 1. Target design and typical beam pointing for the indirect-drive symmetry experiments on Omega.

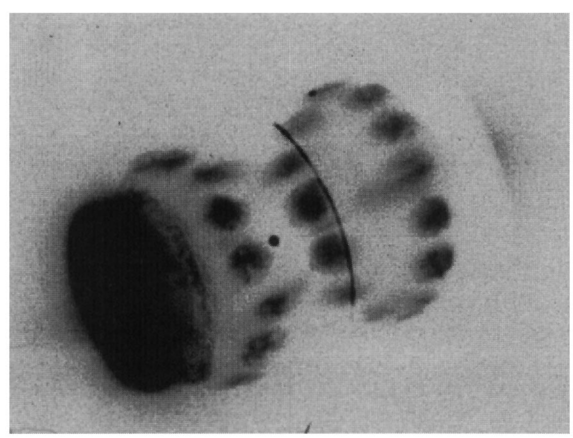

FIG. 2. X-ray pinhole camera image of a thin-wall hohlraum implosion target. The core of the imploded capsule at the center of the hohlraum is clearly seen, as are the joint in the hohlraum midplane made when mounting the capsule, the beam spots, and one laser entrance hole on the left.

individual physical beams. The simulations incorporated the temporal laser power measured on a single Omega beam. The measured laser energy delivered to each target was, likewise, used in the simulation of that experiment. A semi-Eulerian rezoning procedure was employed periodically in the simulation to maintain an orderly mesh in the Au blowoff region, which eventually encompassed most of the hohlraum interior. The new feature of the computations, unique to these applications, was the incorporation of multiple laser beam sources. Similar techniques have been used for NIF target performance predictions [2], but these, of course, cannot be compared to experiments before the construction of the NIF facility is completed. The simulations were run through capsule stagnation time. A postprocessor was used to simulate the transmission of the hard component of the capsule-stagnation x-ray pulse outward through the thin Au hohlraum walls (and the epoxy support structure) to a specified "detector" location. A computational image of the imploded core, spatially smoothed to account for the finite resolution of the framing camera data, was obtained and used to provide the distortion for comparison with the experiment at the time of peak x-ray emission. For these experiments with the relatively short 1-ns laser pulse, only a modest amount of laser spot motion, about 150 μm in the axial direction, was predicted, explaining the clear definition of the spots in the time-integrated image of Fig. 2.

In the first experiment (the upper scan in Fig. 3), the beams were pointed to give a single ring of 15 beams on each end of the hohlraum so as to approximate a Nova symmetry scan [7,16]. Cone 3 was pointed to cross the hohlraum axis 50 μm inside the LEH, and cone 2 was pointed 300 μm farther out. The beam pointing and hohlraum length were varied together to maintain

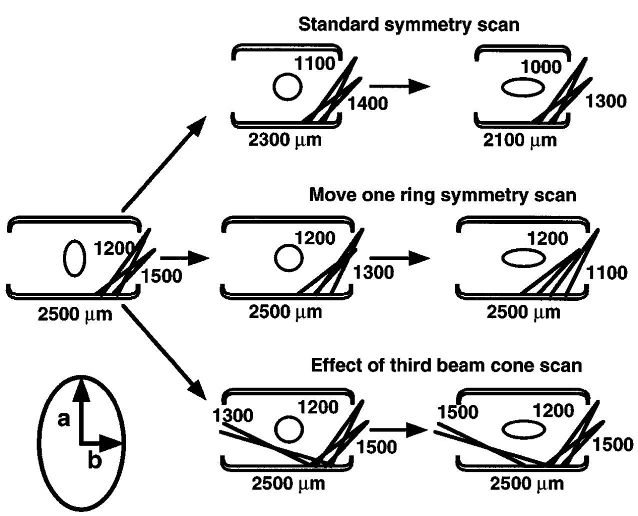

FIG. 3. Schematic showing the three types of symmetry scan performed in this experiment and the expected effect on the shape of the imploded core.

this relationship. Three different hohlraum lengths and beam pointings were used in the scan. The measured distortions are in agreement with the LASNEX simulations [Fig. 4(a)], and the slope is similar to Nova results for 1-ns square-pulse indirect drive implosions, with the distortion doubling for each $\sim$100 μm change in beam pointing. The simulations describe the Omega results with similar precision as has been seen for Nova experiments.

In the next scan (middle scan in Fig. 3), beam cone 3 was held fixed at a pointing of 1200 μm. This required that the hohlraum length also be held fixed at 2500 μm to avoid having beams hit wall material outside the LEH on the way in. The pointing of beam cone 2 was then varied from 1100 to 1500 μm. Again, the simulations of distortion [Fig. 4(b)] are in agreement with the experiment in most cases, especially for pointing giving nearly round implosion images ($[a/b] \sim 1$). The sensitivity to changing the pointing of cone 2 only is, as expected, less than the sensitivity of moving cones 2 and 3 together.

In the third scan, beam cone 1 was added at two different pointings. Because of its small angle with respect to the hohlraum axis, cone 1 struck the hohlraum on the opposite side from which it entered, and the spot motion for cone 1 should be much greater than for cones 2 or 3, and should be in the opposite direction. The addition of cone 1 might therefore have been expected to reduce the distortion of the capsule by compensating for the spot motion of the other beam cones. In experiment and detailed simulations, the distortion is not reduced to the extent expected from this simple model [Fig. 4(c)]. Simulations imply that, due to its low angle, beam cone 1 is not being absorbed at the wall to the same extent as cones 2 and 3 and that laser energy is being reflected onto the end cap of the hohlraum where it is absorbed, adding drive to the poles of the capsule. For NIF, the larger scale lengths are expected to mitigate this problem.

Neutron yields were measured on all of the implosion experiments. The yields were found to be consistent with yields for similar ten-beam Nova experiments. Further, the dependence of yield on implosion symmetry was also found to be similar, in agreement with simulation results.

In summary, a series of hohlraum symmetry experiments with multiple beam cones pointed to give multiple rings of laser deposition regions have been carried out on the Omega laser facility. They are in agreement with simulations performed using the LASNEX code and provide confirmation of an important aspect of the beam-phasing concept. They show that capsule implosion symmetry can be controlled with a multiple-cone irradiation geometry, just as with the simpler single cone per side configuration used on Nova. At the same time, the experiments broaden our general knowledge of ICF hohlraums with the investigation of a qualitatively new laser beam configuration and give us more confidence in predictions of ignition on NIF.

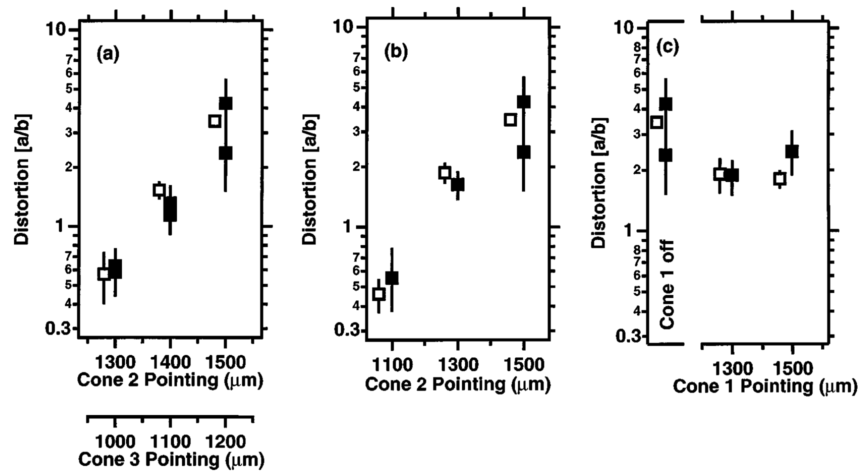

FIG. 4. Distortion as a function of beam pointing for the experiment (a) in which beam cones 2 and 3 formed a single ring on each side of the hohlraum, (b) in which the pointing of cone 2 was varied while that of cone 3 remained fixed at 1200 μm, and (c) in which cone 1 was added while cones 2 and 3 remained fixed at 1500 and 1200 μm, respectively. The uncertainty in the data (solid symbols) is determined by analyzing multiple images and contours on the same experiment, and that from simulations (open symbols, offset to the left for clarity) represents the range of calculations obtained from the LLNL and LANL versions of LASNEX.

The authors thank the Omega Operations crew, especially S. Loucks, G. Pien, and S. Morse, for developing the techniques necessary for the performance of these experiments. Target fabrication efforts by teams from Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and General Atomics are gratefully acknowledged. This work was performed under the auspices of the U.S. DOE by Los Alamos National Laboratory under Contract No. W-7405-Eng-36, by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48, and by the Laboratory for Laser Energetics under Cooperative Agreement No. DE-FC03-92SF19460.

[1] John Lindl, Phys. Plasmas **2**, 3933 (1995).
[2] S. W. Haan *et al.,* Phys. Plasmas **2**, 2480 (1995).
[3] Stephan E. Bodner, Comments Plasma Phys. Controlled Fusion **16**, 351 (1995).
[4] John D. Lindl, Comments Plasma Phys. Controlled Fusion **17**, 221 (1996); **17**, 307 (1996).
[5] D. W. Phillion and S. M. Pollaine, Phys. Plasmas **1**, 2963 (1994).
[6] M. D. Cable *et al.,* Phys. Rev. Lett. **73**, 2316 (1994).
[7] A. Hauer *et al.,* Rev. Sci. Instrum. **66**, 672 (1995).
[8] L. J. Suter *et al.,* Phys. Rev. Lett. **73**, 2328 (1994).
[9] N. D. Delamater, G. R. Magelssen, and A. A. Hauer, Phys. Rev. E **53**, 5240 (1996).
[10] P. Amendt *et al.,* Phys. Plasmas **4**, 1862 (1997).
[11] See National Technical Information Service Document No. UCRL-LR-105821-95-2 [J. A. Paisner, J. D. Boyes, S. A. Kumpan, and M. Sorem, ICF Quarterly **5**, 110 (1995)]. Copies may be ordered from the National Technical Information Service, Springfield, Virginia 22161.
[12] G. Zimmerman and W. Kruer, Comments Plasma Phys. Controlled Fusion **2**, 51 (1975).
[13] E. M. Campbell, Laser Part. Beams **9**, 209 (1991).
[14] T. R. Boehly *et al.,* Opt. Commun. **133**, 495 (1997).
[15] D. A. Baker *et al.,* Bull. Am. Phys. Soc. **38**, 2083 (1993).
[16] N. D. Delamater *et al.,* Phys. Plasmas **3**, 1721 (1996).
[17] T. J. Murphy *et al.,* Phys. Plasmas **5**, 1960 (1998).
[18] C. Decker *et al.,* Phys. Rev. Lett. **79**, 1491 (1997).
[19] J. A. Oertel, R. E. Chrien, and J. M. Mack, in *Proceedings of the Fourteenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research Held by the International Atomic Energy Agency,* Würzburg, Germany, 30 September–7 October 1992 (International Atomic Energy Agency, Vienna, 1993), Vol. 3, pp. 45–49.
[20] D. K. Bradley *et al.,* Rev. Sci. Instrum. **66**, 716 (1995).
[21] K. S. Budil *et al.,* Rev. Sci. Instrum. **67**, 485 (1996).
[22] J. Koch (private communication).
[23] R. A. Kopp, in Proceedings of the 1991 Topical Conference on the Physics of Radiatively Driven ICF Targets, Los Alamos, 28 January–1 February 1991 (unpublished).