Numerical study of core formation of asymmetrically driven cone-guided targets

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Compression of a directly driven fast ignition cone-sphere target with a finite number of laser beams is numerically studied using a three-dimensional hydrodynamics code IMPACT-3D. The formation of a dense plasma core is simulated for 12-, 9-, 6-, and 4-beam configurations of the GEKKO XII laser. The complex 3D shapes of the cores are analyzed by elucidating synthetic 2D x-ray radiographic images in two orthogonal directions. The simulated x-ray images show significant differences in the core shape between the two viewing directions and rotation of the stagnating core axis in the top view for the axisymmetric 9- and 6-beam configurations. Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4996256]

In cone-guided Fast Ignition (FI),\textsuperscript{1–4} a spherical target with a re-entrant metal cone is irradiated by a number of high-power laser beams to create a high density fuel core, and subsequently, an additional ignition laser is injected into the cone for rapid core heating. The separation of the compression from the ignition phase could potentially lead to a high fusion gain with less compression driver energies. The purpose of the cone is to maintain a clear plasma-free beam path to the closest to the core. However, it breaks the symmetry of the spherical implosion, requiring a non-spherical symmetric beam configuration, a 2D or 3D hydrodynamics modeling, and benchmarking of the simulations. Recently, flash x-ray radiography\textsuperscript{5,6} has been applied to cone-FI targets driven by 9 of 12 beams\textsuperscript{1,7} of the GEKKO XII (GXII) laser\textsuperscript{8} at the Institute of Laser Engineering (ILE) and 54 of 60 beams\textsuperscript{4,9} of the OMEGA laser\textsuperscript{10} at the Laboratory for Laser Energetics (LLE). The measured areal densities along a single diagnostic line of sight agree with axisymmetric 2D simulations, but the details of the core shape and the size of the dense core are not reproduced by the simulations.\textsuperscript{5,6}

The Fast Ignition Realization Experiment (FIREX) project\textsuperscript{11} at ILE has been dedicated to develop a concept of Magnetic-field-assist Fast Ignition.\textsuperscript{12} As an experimental testbed, a solid deuterated plastic (CD) sphere has been used because of the reproducibility of compressed cores and its insusceptibility to hydrodynamic instabilities. In this concept, an external magnetic field is applied to a cone-sphere target to guide a beam of relativistic electrons generated inside the cone tip to the core, enhancing the coupling efficiency. The magnetic field is generated by irradiating a metal capacitor\textsuperscript{13,14} with 3 beams, while a dense core is formed by 9 GXII drive beams at the frequency-doubled 532 nm wavelength (2\(\omega\)). Currently, optimum laser conditions for the B-field generation are an open question in terms of total laser energy, incident laser intensity, and laser wavelength. On GXII, a simultaneous use of beams at different wavelengths imposes the system at risk due to different focal lengths at the fundamental wavelength of 1064 nm (1\(\omega\)) and 2\(\omega\) beams. When a capacitor coil is irradiated by 3 beams at 1\(\omega\), the ports of the opposing three beams configured at 2\(\omega\) must be blocked, which leaves 6 beams for the drive. Although compression of magnetized fast ignition targets has been simulated with a 2D radiation-magnetohydrodynamics code,\textsuperscript{12} effects of drive beam configurations and the number of beams on fuel compression have not been investigated.

In this letter, we present a simulation study of dense core plasma formation by asymmetrically driven cone-sphere targets. Using a three-dimensional pure hydrodynamics code IMPACT-3D,\textsuperscript{15} simulations of target compression including the exact beam port locations of the GXII laser and the target orientation are performed for a solid CD sphere driven by 12 beams and cone-solid-CD sphere targets compressed by 9, 6, and 4 beams of the GXII laser. The core characteristics for the different numbers of beams are evaluated by comparing synthetic 2D x-ray radiographic images calculated by post-processing the 3D core plasmas in two orthogonal directions perpendicular to the cone. The main focus of this letter is to study variations of core formation by changing the number of drive beams and not to accurately simulate core parameters with each drive configuration because the code does not include laser absorption and ablation physics. Realistic simulations of a fast ignition target with the 3D code and comparisons to measurements are beyond the scope of this paper. The work presented here could impact not only cone-guided FI research but also high energy density plasma experiments using cone-in-shell targets such as shock timing measurements\textsuperscript{16} and spherical Rayleigh-Taylor growth experiments.\textsuperscript{17}

The ILE at Osaka University houses two high-power laser systems: kilo-joule nanosecond laser GXII and picosecond Petawatt laser LFEX (Laser for Fast Ignition Experiment).\textsuperscript{18} The GXII system has 12 laser beams in a dodecahedron.
orientation. Each beam delivers \( \sim 300 \) J at \( 2 \omega \) in a \( \sim 1.3 \) ns Gaussian pulse (FWHM). The newly constructed LFEX laser system consisting of a bundle of four beams, each with an energy of 500 J, delivers two Petawatt peak powers on the target in a \( \sim 1.5 \) picosecond pulse duration. The primary use of the LFEX laser includes FI core heating,\(^{2}\) generation of bright backlighter x-ray sources,\(^{6}\) and charged particle acceleration.\(^{19}\)

A cone-sphere target consists of a 200 \( \mu \)m diameter solid CD sphere attached to the tip of a Gold cone. The Au cone has an inner tip diameter of 100 \( \mu \)m, an opening angle of 45°, and a wall thickness of 7–17 \( \mu \)m. Figure 1 shows model views of a cone-sphere target illuminated by 9 GXII beams. The target is set in the equatorial plane, and the center of the sphere is at the origin (0, 0, 0). The opening of the cone is pointed to \( (\theta, \phi) = (90^\circ, 0^\circ) \), where \( \theta \) is a polar angle and \( \phi \) is an azimuthal angle in spherical coordinates. Figures 1(b)–1(d) show the side view (90°, 90°), front view (90°, 180°), and top view (0°, 0°) of the model. A 9-beam configuration uses beams of B1, B2, B4, B7, B8, B9, B10, B11, and B12, whereas the rest of the three beams (B3, B5, and B6, not shown in Fig. 1) are either turned off or used for magnetic field generation. As described before, when those beams are converted to 1\( \omega \), the opposing three beams (B1, B2, and B8) at 2\( \omega \) are unavailable to drive the target, limiting the drive beams to be 6 (B4, B7, B9, B10, B11, and 12) as shown in Fig. 1(c) without B1, B2, and B8. Four beam implosions were performed in the previous implosion experiments.\(^{8,20,21}\) Here, a 4-beam compression [B4, B9, B10, and B11, see in Figs. 1(c) and 1(d)] is simulated to study the influence of B7 and B12 beams by comparing the 6 and 4 beam configurations. The angle between the B7–B12 beam axis and an axis normal to the cone is 10.8°.

IMPACT-3D is a three-dimensional pure fluid code that solves the set of inviscid compressible fluid Euler equations in 3-D Cartesian coordinates with no singular point at the origin. This allows for simulating target compression and asymmetric plasma flow passing through the origin including drive nonuniformities due to a finite number of drive beams and/or beam-power imbalance and target offsets. The code uses the ideal gas equation of state to close the equation set. No radiation transport is included. Since no laser absorption and ablation models are included in the code, hydrodynamic motions (i.e., target compression) are calculated based on a given initial pressure that is determined as follows. First, CD sphere compression is simulated with a 1D radiation-hydrodynamics code Helios\(^{22}\) at a 2.7 TW peak power equivalent to the 12-beam uniform illumination. Figure 2(a) shows the simulated radius-time diagram along with a 1.3 ns Gaussian laser pulse. The 1D simulation predicts compression of the outer surface of the sphere starting at \( \sim 2.2 \) ns and a peak density of \( \sim 15 \) g/cm\(^3\) at 3.9 ns. Second, a 2D raytracing calculation\(^{23}\) is performed to calculate a laser absorption profile by a single beam irradiating on a 200 \( \mu \)m diameter sphere surrounded by a 35 \( \mu \)m scale-length, blow-off plasma from the 1D simulation at 2.2 ns. The beam has a spatial Gaussian profile of 120 \( \mu \)m diameter (FWHM). Then, the absorption profile is used as a pressure perturbation profile. For multiple beam drives, the profile is duplicated and overlapped on the sphere surface. Figure 2(b) shows a pressure perturbation for the 12-beam drive. For a 12-beam 3D hydrodynamic simulation, a pressure of 60 Mbar for a single beam is chosen to reproduce the 1D-predicted peak density. This generates a pressure variation due to beam overlapping from the maximum pressure of 65 Mbar to the minimum of 35 Mbar between the beams. The details of the raytracing calculation are presented in Ref. 23. The 3D simulations are initiated with this pressure distribution at 2.2 ns with a 101 \( \times \) 101 mesh cell and a mesh size of 3 \( \mu \)m. In this study, the spatial beam profile is fixed for the sake of simplicity. It is noted that the temporal evolution of simulated target compression between the pressure-driven IMPACT-3D and the radiation-hydrodynamics simulations is fairly different even

![FIG. 1. Model views of a cone-sphere target with 9 drive beams. (a) Overview of the target and beams in the view of B1 and (b) side view (90°, 90°), perpendicular to the cone along the direction of B12. The laser intensity pattern of B12 is shown on the sphere. (c) Front view (90°, 180°). (d) Top view (0°, 0°). Only two beams (B7 and B12) in the plane of the cone axis are shown.](image-url)
though the final peak core density and the peak compression time match in the simulations. The laser-generated pressure increases with the laser intensity in time. The Helios simulation shows $\sim 2$ Mbar at 2.2 ns and 200 Mbar at 3.5 ns before the shock coalesces at the center, strongly compressing the sphere towards the laser peak as shown in Fig. 2(a). In contrast, the pressure applied in IMPACT-3D is an instantaneous pulse and has no temporal dependence. The initial pressure is the maximum and decreases as the shock propagates. Consequently, the compression of the sphere by this pressure gradient is rather constant in time. Thus, the core profiles in those two simulations largely deviate from one another at times much earlier or later than the peak compression, but the simulation results near peak compression are expected to be similar.

Figures 2(c)–2(r) show 3D simulations of compression of a CD sphere by 12 beams and cone-sphere targets by 9, 6, and 4 beams. The target parameters are identical to the experiment. The cone is treated as a rigid material. Simulations with and without a cone show no differences in core characteristics because no radiation and laser interaction with the cone are included. With the 12-beam drive, a relatively round core is formed with the peak density above 10 g/cm$^3$ at $\sim 4.0$ ns. In the cone-sphere compression with 9, 6, and 4 beams, overall shapes of the core are no longer round. The peak density for the 9-beam drive reaches $\sim 8$ g/cm$^3$ at 4.0 ns as shown in Fig. 2(i), but no high density regions above 7 g/cm$^3$ are created by 6 and 4 beams. The peak core densities for the different drives are compared later.

The complex 3D structures of the simulated cores are difficult to quantitatively compare for different drive beams. Using a radiation transport atomic physics code Spect3D,$^{24}$ synthetic 2D x-ray radiographic images of the core plasmas are calculated in X (side) and Z (top) directions as shown in Fig. 3. Both lines of sight are perpendicular to the cone that is aligned along the Y axis. In 2D axisymmetric simulations along the cone axis, these views in X and Z directions are assumed to be the same. Thus, any differences observed in the two images reflect asymmetry of the core characteristics. Transmission of time-resolved core images is computed using 4.51 keV (Ti K$\alpha$) x-rays since they were used in the radiography experiment performed on GXII.$^6$

**FIG. 2.** (a) A radius vs time diagram of a 200 $\mu$m CD sphere compression simulated with a 1D Helios code. A 1.3 ns Gaussian laser pulse is also shown. (b) A pressure perturbation on the target surface for the 12-beam irradiation. IMPACT-3D results: (c)–(f) Time evolution of a CD sphere driven by 12 beams and cone-sphere targets by (g)–(j) 9 beams, (k)–(n) 6 beams, and (o)–(r) 4 beams. Density contours above 1 g/cm$^3$ are shown. A quarter of the sphere is cut away.

**FIG. 3.** A 3D density contour of a compressed cone-sphere target with the 6 drive beams and directions of a monochromatic backlighter in X and Z.
Figure 4 shows calculated transmission of a solid sphere driven by 12 beams. No noticeable differences in the core shape or transmission are observed between the two orthogonal views in the series of the images. This confirms symmetric core formation with 12 beams under the assumption of the ideal laser and target conditions (i.e., no beam-power imbalance, target offset, and surface roughness). Figure 5 shows calculated transmission of a cone-sphere target driven by 9 beams. A dense core is formed on the axis of the cone at \(Z = 0\) in the side view shown in Figs. 5(a)–5(d). Since there is no pressure applied on the core from the cone side, the dense plasma is created slightly away from the cone and moves toward the cone tip at later times. Axisymmetric 2D cone-in-shell simulations reported previously show similar core shapes and motions. Different from the side view, the core plasma seen in the top view is asymmetric to the cone axis and slightly rotated in the clockwise direction as shown in Figs. 5(e)–5(h). Because of the tilted axis, the dense region of the core plasma moves toward an edge of the cone tip, while the angle of the axis is maintained. The peak core density is qualitatively the same in both directions; however, the shape of the core clearly depends on viewing directions along the polar angle, showing strong asymmetry of the dense core that cannot be simulated with axisymmetric 2D codes. The simulation results of the 6-beam compression show similar trends as the 9-beam drive, namely, axisymmetric core shape in the side view and a tilted core in the top view as shown in Fig. 6. In the 6-beam configuration, there is no pressure applied from the opposite side of the cone, which leads to a cigar-like shape of the core. It is clearly seen that two high-density islands are formed at 3.70 ns and merged together later. The compression of the core is weaker than that with 9-beam drive. The peak compression time of the 6-beam driven core is delayed to \(\approx 3.30\) ns from \(\approx 4.00\) ns for the 12- and 9-beam drives. In Fig. 7, the shape of the core driven by 4 beams appears to be symmetric to the cone axis within the same viewing directions. This indicates that the rotation of the core axis is attributed to the B7 and B12 beams, which can be visually confirmed by comparing the beam axis in Fig. 1(d) and the transmission images in Figs. 6 and 7. The peak compression for the 4-beam drive is further delayed to 4.55 ns.

Figure 8 shows comparisons of areal densities \((\rho L)\) and peak densities for all the drive beams considered. The time histories of \(\rho L\) are calculated by first integrating the mass density of the 3D core profiles along each direction in X and Z to produce 2D areal density maps. Then, the maximum \(\rho L\) within a \(100 \times 100 \, \mu m^2\) area at the origin is found at each time step to extract the time history of the areal densities. This allows us to directly compare the core compressibility for the different drives without considering the changes in the core shape. The peak \(\rho L\) for the 9-beam drive decreases by \(\approx 25\%\) compared to the 12-beam case in Fig. 8(a). The difference in \(\rho L\) between the side and top views is within 6% throughout the compression process. The peak \(\rho L\) decreases further to \(\approx 50\%\), and the difference is up to 17% with 6 beams. The target compression by 4 beams is higher than that with 6 beams in the side view, but almost no compression is observed in the top view, indicating that a pancake-shaped core is formed with the maximum \(\rho L\) difference of 55%.
between the two views. Figure 8(d) shows the time history of the peak core densities. Upon comparison of the 6- and 4-beam drives, it is found that cores with the peak densities of ~8 and ~4 g/cm³ are formed. The higher ρL with 4 beams in one direction can be explained by a lower peak density (ρ), but a longer integration length (L) in the case of the 4-beam drive compared to 6 beams.

Our results have revealed two important findings that cannot be obtained with axisymmetric simulation codes. First, the variation in ρL between the top and side views perpendicular to the cone inherently exists in the non-symmetric GXII beam irradiation (i.e., 9-, 6-, and 4-beam configurations). The ρL difference is only ~6% for the 9-beam drive but could be larger once actual beam-power imbalance and other experimental factors are included. It is therefore important to take the exact beam and diagnostic locations into consideration for areal density analyses in both simulations and experiments. Second, the tilted core axis and the resultant 3D core motion found for the 9 and 6 beam configurations could affect cone-tip breakout measurements and an optimum injection timing of a FI ignitor laser.

In conclusion, the three-dimensional hydrodynamic simulations of a directly driven cone-CD sphere by various numbers of GXII beams are presented. The simulations show that the 12-beam drive produces the symmetric shape of a compressed core in the directions of the top and side views as expected; however, the core shapes and areal densities are significantly different for the non-symmetrical drives. The differences in areal densities between the top and side views diverge up to 55% as the number of drive beams decreases to 4. It is found that the axis of the compressed cores for 9 and 6 GXII beam drives is tilted with respect to the axis of the cone, which could affect cone-tip breakout measurements and an optimum injection timing of a FI ignitor laser.

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FIG. 8. Comparisons of areal densities (ρL in the side and top view directions for (a) 9-beam drive, (b) 6-beam drive, and (c) 4-beam drive along with ρL for the 12-beam drive. (d) Time histories of peak mass density.

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