High-Efficiency Rugby-Shaped Hohlraum Designs for Driving Large Gas-Filled Capsules on the NIF

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In indirect-drive inertial confinement fusion a high-*Z* enclosure (or "hohlraum") surrounds a low-*Z* capsule containing DT fuel. Laser beams irradiate the interior of the hohlraum through a pair of laser entrance holes, creating an x-ray bath that compresses the fuel to ignition conditions. The coupling of laser light to the capsule is typically ~10% in cylinder hohlraums, resulting in ~0.2 MJ absorbed energy for the ~2 MJ-scale laser at the National Ignition Facility (NIF). By contrast, a 7 mm-wide rugby-shaped Au hohlraum design is found that can accommodate ~50% larger (DT) gas-filled capsules for up to 0.5 MJ capsule absorbed energy and ⩾25% coupling efficiency. This new integrated design is made possible by using a high-density gas fill (4-8 mg/cc) that limits the fuel convergence ratio (C) to <15 while providing ~0.1 MJ of output energy. The low convergence limits the degrading effects of hohlraum drive asymmetry and hydrodynamic instability from surface roughness and target-fielding fixtures. Integrated hohlraum simulations in 2-D show good implosion symmetry with peak radiation temperatures reaching 295 eV at <1.8 MJ of laser energy and 440 TW peak power while delivering nearly 0.1MJ (compared with ⩽0.06 MJ in DT-layered implosions to date [Le Pape *et al.*, PRL **120**, 245003 (2018)]). The hohlraum design uses a shaped two-shock laser power history for compressed energy delivery and desired margin to late-time hohlraum filling (and loss of symmetry control). Confidence in this design is supported by a recent campaign on the NIF using a reverse-ramp pulse shape to drive a similar rugby hohlraum and a ~3 mm-scale Al shell [Ping *et al.*, Nature Phys. (https://doi.org/10.1038/s41567-018-0331-5). The high fuel-adiabat (α~6-7) character of the 2-shock design is tolerated due to the $\sim 3\times$ higher performance margin from the large-capsule design. This platform can be extended to include varying thicknesses of DT solid-fuel layering for increased yield (> 1 MJ), while benefitting from the favorably low *C* (<20). Further inroads into understanding ignition thresholds and the transition from volume-dominated ($-PdV$) ignition to higher-convergence hot-spot ignition could result from initially leveraging an optimized low-*C* gas-fill design.

I. INTRODUCTION

The ignition effort on the NIF has focused on cylindrical hohlraums that convert up to 2 MJ of incident laser energy to ~0.2 MJ of x rays absorbed (E_{cap}) by a ~2 mm diameter high-density carbon (HDC) ablator [see Fig. 1a][1]. The main limiting factor in fielding even larger capsules is ensuring late-time drive uniformity despite (1) closure of the laser entrance holes (LEHs), (2) potential inner-beam blockage by the so-called "Au bubble" from direct illumination of the hohlraum wall, and (3) impeded inner-beam propagation by a dense plasma feature above the capsule arising from ablator-wall stagnation. Ensuring adequate drive symmetry places a limit on the effective case-to-capsule ratio of ⩾2.4. Under these conditions the performance margin M=ITF-1, which is related to the ignition threshold factor ITF$\sim E_{cap}\alpha^{-1.9}v_{imp}^{3.58}P_{abl}^{1.16}$ [2], has only modest room to spare for accommodating any anomalously high fuel-adiabat α from preheat. Here, v_{imp} is the peak implosion speed of the fuel and remaining ablator, and P_{abl} is the peak ablation pressure at the time of peak implosion speed. There is experimental evidence that the fuel compressions are less than expected at higher laser power [3], presumably due to errors in

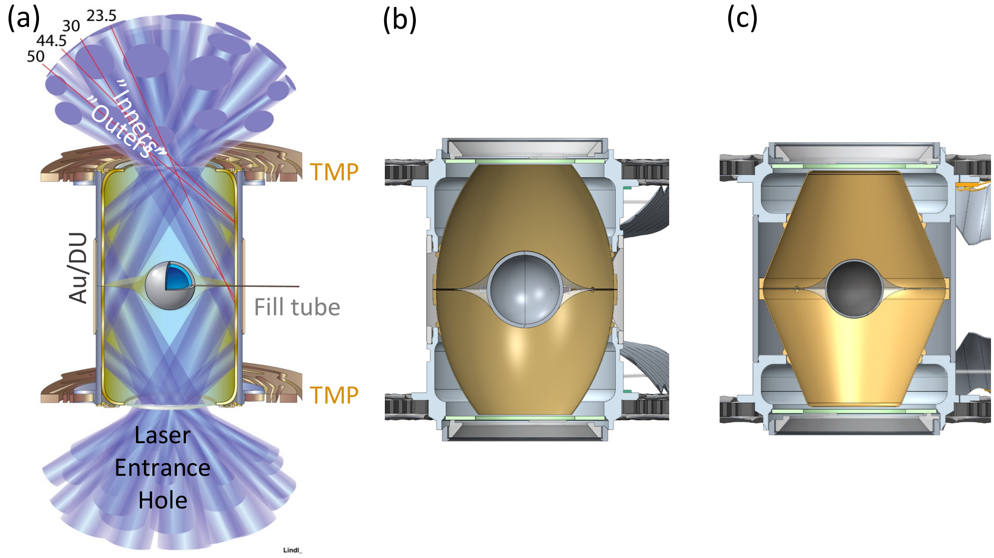

Fig. 1a-c: (a) Au or depleted uranium (DU) cylinder hohlraum with indicated thermo-mechanical packages (TMP) and inner- and outer-cone laser beams entering through pair of laser entrance holes; (b) rugby-shaped Au hohlraum with Al shell suspended by tent support; (c) Au Frustraum with 1.1 mm-radius HDC capsule.

preheat modeling. Clearly, a higher margin obtained from a higher E_{cap} could be used to offset uncertainties in preheat modeling and potentially overcome the observed deficits in areal fuel density. This paper defines a path forward to high E_{cap} with new hohlraum geometries and accessing a volume mode of ignition in contrast to hot-spot ignition.

II. ADVANCED HOHLRAUMS

The main limiting factor in achieving high E_{cap} in a cylinder is the restricted waist radius. The rugby hohlraum [4] and Frustraum [5] expand this dimension by literally "cutting corners" in a cylinder to preserve wall surface area and limit Marshak wave losses. Figures 1b-c show these two geometries with waist diameters of 7 mm as fielded. The rugby hohlraum was successfully tested with an oversized Al capsule filled with DT gas ("SYMCAP") using a reverse-ramp pulse shape [see Fig. 2a][6]. The Frustraum has recently been fielded at "sub-scale" [see Fig. 1c] for assessing laser backscatter risk, target coupling and drive symmetry. Integrated hohlraum simulations in 2-D of an ignition-scale (9 mm wide) Frustraum predict E_{cap} of ~0.5 MJ for a laser energy of 1.63 MJ [5]. Such a high coupling efficiency means more available margin to preheat modeling uncertainties for high-adiabat capsules. Such targets can be driven by a 2-shock laser pulse that also affords more control of hohlraum symmetry due to the associated short drive duration.

III. GAS-FILLED HDC CAPSULE ("SYMCAP")

The usual target surrogate for a DT-layered ignition capsule is the (~3-7 mg/cc) gas-filled capsule or "SYMCAP". These targets provide a measure of drive and symmetry that are used to tune fuel-layered targets. However, SYMCAPS have never been experimentally optimized for yield. With the possibility of absorbing ~ 0.5 MJ of x rays in an advanced hohlraum design, this target type warrants such a study to see if >0.1 MJ yield is achievable. Figure 2a shows a candidate 2-shock pulse shape for driving the HDC SYMCAP relative to the reverse-ramp previously shot for an Al SYMCAP. Figures 2b-c depict the HDC capsule inside a rugby-shaped Au hohlraum using a ^{4}He gas-fill density of 0.3 mg/cc. The capsule is driven at a peak radiation temperature of 295 eV and absorbs 0.5 MJ in separate 1-D calculations using a frequency-dependent source derived from the 2-D integrated hohlraum simulation. Figure 2d renders the simulated imploded core at the time of peak central ion temperature of ~6 keV, showing modest prolateness. The 2-D output yield is 0.099 MJ compared with 0.146 MJ in 1-D, close to the stated goal of 0.1 MJ yield.

IV. EXTENSION TO LAYERED TARGETS

The natural extension of an optimized SYMCAP at the 3 mm scale that potentially delivers ~0.1 MJ is whether introduction of a DT fuel layer between the gas volume and ablator might substantially improve yield while preserving SYMCAP functionality, e.g., high preheat margin, moderate fuel convergence, and low hydro-instability growth. Figure 3a-b compares the 1-D performance of such a layered SYMCAP and a hot-spot ignition design at a similarly large capsule scale. By virtue of the high fuel adiabat of the layered SYMCAP($\alpha \lesssim 6$) compared with the hot-spot design ($\alpha \lesssim 3$), the profiles are markedly consistent with volume ignition: strongly isobaric and high ion temperature *throughout* the fuel. Ignition is defined here as the instant when the central ion temperature reaches 12 keV, and a corresponding hot-spot radius as the contour of 1 keV. With the ion temperature above 2 keV for the layered SYMCAP, the *entire* fuel behaves as a hot spot without the

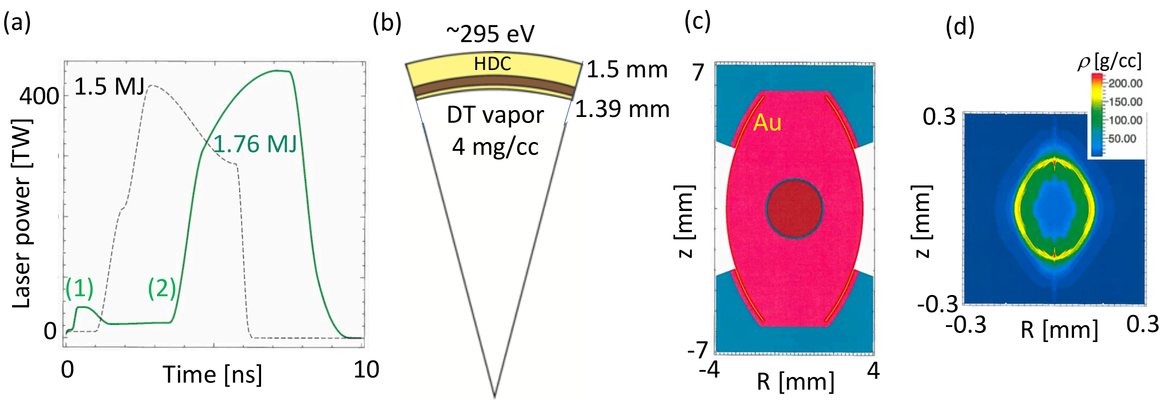

Fig. 2a-d: (a) Laser power history for reverse-ramp pulse-shape in rugby hohlaum [see Fig. 1b] (black) and proposed 2-shock SYMCAP pulse shape (green) with indicated shock launch times; (b) candidate SYMCAP dimensions; (c) initial rugby materials; (d) density of imploded SYMCAP at time of peak central ion temperature (~6 keV) with innermost blue region denoting fuel region.

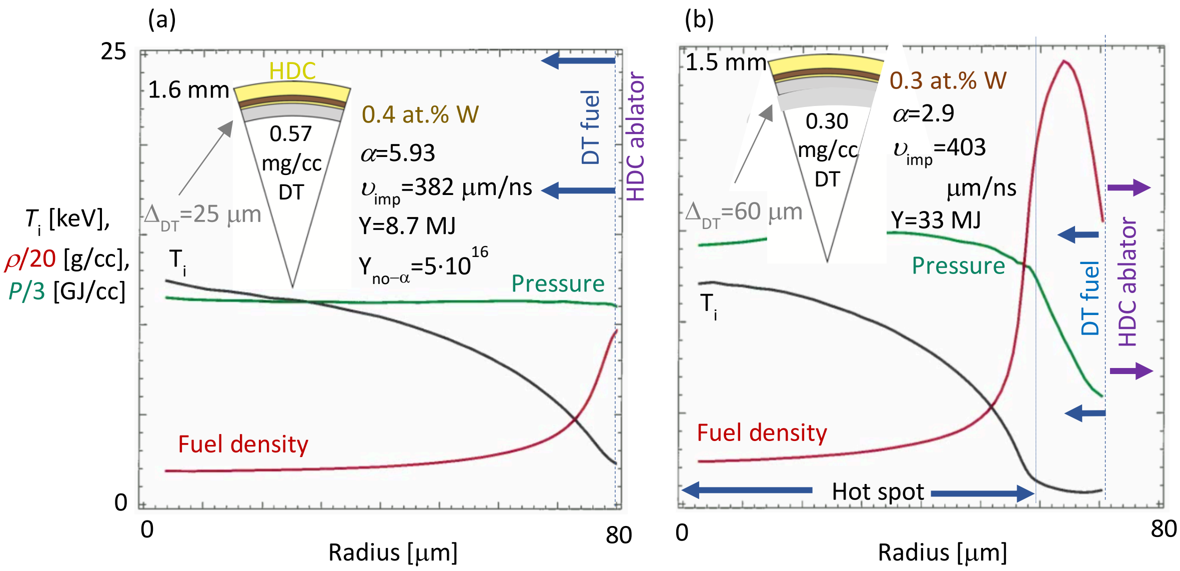

Fig. 3a-b: Fuel ion temperature (black), fuel density (red) and total pressure (green) versus radius for high-adiabat, layered SYMCAP (a) and hot-spot ignition design (b). Insets show capsule dimensions, materials and fuel layer thickness Δ_{DT}. $Y_{no\text{-}\alpha}$ refers to total output yield with alpha-heating turned off, α is the in-flight fuel adiabat, and υ_{imp} is the mass-weighted fuel speed.

feature of propagating burn into a dense, annular cold fuel region that defines hot-spot ignition. The benefits of this mode of ignition are substantial: no need to maintain a low-adiabat fuel region, reduced fuel convergence ($C \lesssim 20$) – defined as the initial capsule radius over the minimum outer fuel radius – and lessened risk of hydrodynamic instability. The cost of a volume mode of ignition is reduced yield, but much of this follows from $\cong$ $2\times$ lower fuel loading. A volume ignition mode for a single-shell target on the NIF is now made possible by the high fuel adiabats that are afforded and tolerated when the capsule can absorb nearly 0.5 MJ or more of hohlraum-generated x rays. Recent advances in hohlraum efficiency approaching 30% are the key to availing this novel design option [6].

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