Convergent ablation measurements with gas-filled rugby hohlraum on OMEGA

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Abstract. Convergent ablation experiments with gas-filled rugby hohlraum were performed for the first time on the OMEGA laser facility. A time resolved 1D streaked radiography of capsule implosion is acquired in the direction perpendicular to hohlraum axis, whereas a 2D gated radiography is acquired at the same time along the hohlraum axis on a x-ray framing camera. The implosion trajectory has been measured for various kinds of uniformly doped ablators, including germanium-doped and silicon-doped polymers (CH), at two different doping fraction (2 % and 4 % at.). Our experiments aimed also at measuring the implosion performance of laminated capsules. A laminated ablator is constituted by thin alternate layers of un-doped and doped CH. It has been previously shown in planar geometry that laminated ablators could mitigate Rayleigh Taylor growth at ablation front. Our results confirm that the implosion of a capsule constituted with a uniform or laminated ablator behaves similarly, in accordance with post-shot simulations performed with the CEA hydrocode FC12.

1. Introduction
In indirect-drive inertial confinement fusion (ICF) [1,2], a cryogenic deuterium-tritium target is imploded to high density and temperature using thermal x-ray. To ignite the fuel from the central hot spot generated at implosion stagnation an high implosion velocity \( V_{\text{fuel}} \geq 370 \text{ km.s}^{-1} \) is requested. Recent experiments performed on the National Ignition Facility have achieved \( V_{\text{fuel}} \geq 350 \text{ km.s}^{-1} \) at the price of a record laser shot (520 TW, 1.86 MJ laser pulse) [3]. Additional research and alternative paths are therefore actively pursued to achieve high implosion velocity at lower laser energy. Ablators more efficient than plastic provide one way to optimize implosion performances [4]. Beryllium is a well-known candidate [5] but it implies new safety rules for the facility. High Density Carbon (HDC) has been therefore tested on a few NIF shots and has performed very close to 1D predictions, approaching implosion velocity of \( 400 \text{ km.s}^{-1} \) [6]. An HDC capsule is the current record holder for neutron production in a non-cryogenic layered implosion with a yield of \( 1.6 \times 10^{15} \) neutrons.

The other way to increase implosion velocity for a given laser energy is to improve the hohlraum coupling efficiency. Wall losses could be reduced using higher opacity wall material such as depleted uranium [7], or also by changing the hohlraum internal shape to reduce its area as suggested with rugby hohlraums [8,9]. The baseline design for implosion experiments with the Laser MegaJoule (LMJ) relies in fact on a rugby-shaped hohlraum [10], which presents significant advantages in terms of LPI mitigation, coupling efficiency and symmetry control with a 1/2-1/2 energy balance [11]. The increased x-ray flux on capsule in rugby hohlraum compared to a classical cylindrical hohlraum was confirmed at OMEGA scale by enhanced...
nuclear performances [12–14]. Rugby hohlraum implosions experiments are currently conducted on NIF [15,16]. Here we present the first convergent ablation measurements [17] for gas-filled rugby hohlraum implosion experiments performed on the OMEGA laser facility.

2. Experimental configuration
A schematics of the experimental configuration is shown on Fig. 1a). The rugby hohlraum (spherical internal shape) is aligned along a pentagonal axis of the OMEGA target chamber and filled with 1 atm methane at room temperature. The primary diagnostic to assess the implosion velocity, key metric for implosion performance, is the SSC-A x-ray streak camera with a 20x magnification and a 10 μm imaging slit. A typical streaked radiograph is shown on Fig. 1b). The limb of the shell is well defined and its position versus time could be extracted. Typical internal capsule diameter is 550 μm with ablator thickness in the range from 30 to 55 μm. For radiography access two slots were made of either side of the hohlraum. One slot is covered by a 6 μm thick vanadium backlighter foil, whereas a 50 μm CH foil is glued on the opposite slot. Due to the presence of these lateral slots the hohlraum is driven by 36 beams (instead of 40) arranged in three cones (21°, 42° and 59°) on each Laser-Entrance-Hole. Beams were equipped with elliptical phase plates and smoothed by spectral dispersion. Polarization smoothing was not used in this experiment. Backscattering levels were measured on 2 beams belonging to 42° and 59° cones and were found to be negligible. The laser drive (shaped pulse) was adjusted by playing with the Frequency Crystal Conversion (FCC) of the 59° beams. The x-ray flux was measured with Dante, looking at one LEH at 37° of hohlraum axis. 2 radiative drive conditions have principally been tested: a low-drive case with a peak radiative temperature at 205 eV, and a high-drive case reaching 225 eV. A second radiograph was simultaneously performed along the hohlraum axis with a titanium area backlighter. Images were recorded with an x-ray framing camera coupled to a gated microchannel plate detector. We used a magnification of 8 with 10 μm diameter pinholes for that diagnostic.

3. FCI2 Integrated simulations
We performed two-dimensional radiation-hydrodynamics simulations of hohlraum and capsule dynamics with FCI2 [18], taking into account M-band contributions determined with the Non Local Thermodynamical Equilibrium (NLTE) model Radiom [19]. Hohlraum wall deformations

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**Figure 1.** (a) Schematics of the experimental configuration. (b) Typical streaked radiography acquired on a gas-filled rugby implosion. The thin white line is the capsule limb position extracted by an automatic edge detection algorithm.
Figure 2. (a) FCI2 postprocessed radiograph. The external and internal radii are underlined in yellow. (b) Vertical lineout across the previous image. The external limb radius is defined at the position of the maximum exposure gradient.

and x-ray flux asymmetry on capsule require an Adaptative Lagrangian Eulerian (ALE) mesh for the whole integrated simulation. As shown on Fig.1b) for a germanium-doped CH ablator (2 \% atomic fraction and 50 \( \mu \text{m} \) initial thickness) the external limb position (thin white line) of the ablator could easily be extracted from experimental radiographs by detection of the maximum slope of the exposure. Detection of the internal limb is more challenging due to backlighter profile and photocathode non-uniformities, as well as spatial resolution of the x-ray camera. The same analysis procedure is applied on postprocessed FCI2 radiographs, as explained on Fig.2. Experimental and postprocessed radiographs are therefore compared directly without Abel inversion and the subsequent hypothesis on the density and opacity profiles of the ablated plasma [17]. This is the most straightforward and robust method to compare simulations and experiments. In the remaining of the article we will refer to the limb radius and velocity (\( V_{\text{limb}} \)) as our implosion metrics.

4. Comparison of laminated and uniformly doped ablators

These experiments aimed first at comparing the implosion performance of uniformly doped and laminated capsules [20]. A laminated ablator is constituted by thin alternate layers of un-doped and (here) germanium-doped CH. The figure 3a) presents a pre-shot radiography of a laminated capsule, on which the thin layers (1 \( \mu \text{m} \) each) of doped and un-doped material are clearly visible. The germanium-doped CH layers of the laminated ablator were at 3.7 (\( \pm 0.1 \)) \% at. fraction. The corresponding uniformly doped CH capsules were doped at 2.4 (\( \pm 0.1 \)) \% at. fraction, so that the mean doping fraction of the 55 \( \mu \text{m} \) thick ablator were equivalent in both cases. It has been experimentally demonstrated in planar geometry that laminated ablators could mitigate Rayleigh Taylor instabilities at ablation front due to a transverse diffusive mechanism [20, 21]. However laminated capsules have never been fabricated and tested before those shots. Implosion trajectory for laminated and uniformly doped capsules are shown on Fig. 3b). First of all streaked and gated radiographs are in accordance demonstrating the good level of x-ray drive uniformity on capsule. Then the main result is that there is no detectable discrepancies between laminated and homogeneous ablators which implode in accordance with FCI2 simulations. This
Figure 3. (a) Cross-section of a laminated capsule. (b) Comparison of capsule trajectory for laminated and uniformly doped ablators. The square points represents the measurements acquired on the 2D gated radiography on axis.

corroborates the trajectory measurements already acquired for planar samples [21]. A definitive answer regarding the stabilizing effect of laminated ablator on hydrodynamic instabilities in convergent geometry needs yet to be given via a serie of high nuclear performance implosions [13].

5. Comparison of germanium and silicon-doped polymers

We focus in that section of the relative implosion performances of CHGe and CHSi capsules. It has in fact been emphasized that Si-doped ablators are more efficient than Ge-doped ones at NIF scale [22]. A larger database has been acquired in our experiments, as parametric variations have been made under low-drive and high-drive conditions for both ablators, at two different doping fraction (2 % and 4 % at.) and for various ablator thicknesses. A detailed comparative study will be presented elsewhere [23]. We only present here the general trends. Fig.4 presents typical outer limb trajectory and velocity as a function of time in the case of a silicon-doped (4 % at.) CH capsule with an initial ablator thickness of 55 $\mu$m. The maximum drive temperature was 225 eV in that case. A reasonable good agreement is found for the experimental and postprocessed trajectories, even if simulations predict an earlier final convergence x-ray bang time [13]. The final outer limb velocities are in accordance within the error bars of the measurements, with $V_{\limb}^{max} = 200 \pm 20$ km.s$^{-1}$. Regarding ablator efficiency conclusions should be drawn carefully due to fluctuations in density and capsule external diameter for different production batches. Fig.5 compares in a low drive case (205 eV) the performances of CHSi and CHGe capsules (doped at 4 % at.) having the same external diameter, thus receiving the same x-ray drive. The CHSi capsule (initial thickness 55 $\mu$m) has 13 % more mass than CHGe (45 $\mu$m) thick for the same external capsule diameter. The silicon-doped capsule seems performs slightly better than the germanium-doped reaching a maximum limb velocity of 120 km.s$^{-1}$, versus 100 km.s$^{-1}$.
Figure 4. (a) Ablator outer limb radius versus time in the case of of CHSi capsule doped at 4% at. fraction. The initial ablator thickness is 55 μm. The long dashed black lines represent the results of FCI2 postshot simulations. (b) Experimental and simulated outer limb velocities $V_{\text{limb}}$ as a function of time.

Figure 5. (a) Trajectories and (b) outer limb velocities $V_{\text{limb}}$ as a function of time for CHSI and CHGe capsules with the same initial external diameter.

6. Conclusions
Since the last IFSA [14], CEA has pursued gas-filled rugby hohlraum experiments on the OMEGA Laser Facility in preparation for LMJ and has improved the level of precision of its experiments. The first convergent ablation experiments in gas-filled rugby-hohlraum were performed in a double axis radiography configuration, with a transverse streaked radiography (aka ConA) and an axial time-resolved radiography (aka 2D ConA) recorded simultaneously on the same shot. Various kinds of ablators have been tested with this new commissioned platform.
We have verify that laminated ablator capsules performs similarly as uniformly doped capsules, as expected from homogenization principle. CHGe and CHSi ablators were compared for 2 doping fraction (2 and 4 % atomic) and 2 different drive conditions. The resulting implosion velocities span the range in between 150 and 300 km.s$^{-1}$. The general tendency is that the simulated trajectories converges slightly more early than the experimental radiographs, which is consistent with the late bang times (200 to 300 ps) measured in rugby implosion experiments on OMEGA. However the final limb velocity does not show an important velocity deficit as observed in NIF implosions [22]. CHSi is performing slightly better than CHGe, as found at NIF scale [22]. This rich implosion database will be used to benchmark FCI2 simulations of germanium and silicon doped ablators and to test the rocket model [24] in the high ablation regime limit.

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