

Capsule Ablator Inflight Performance Measurements Via Streaked Radiography Of ICF Implosions On The NIF*

E L Dewald^{1,3}, R Tommasini¹, A Mackinnon¹, A MacPhee¹, N Meezan¹, R Olson², D Hicks¹, S LePape¹, N Izumi¹, K Fournier¹, M A Barrios¹, S Ross¹, A Pak¹, T Döppner¹, D Kalantar¹, K Opachich¹, R Rygg¹, D Bradley¹, P Bell¹, A Hamza¹, B Dzenitis¹, O L Landen¹, B MacGowan¹, K LaFortune¹, C Widmayer¹, B Van Wonterghem¹, J Kilkenny¹, M J Edwards¹, J Atherton¹, E I Moses¹

¹Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550 USA

²Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

³E-mail: dewald3@llnl.gov

Abstract. Streaked 1-dimensional (slit imaging) radiography of 1.1 mm radius capsules in ignition hohlraums was recently introduced on the National Ignition Facility (NIF) and gives an inflight continuous record of capsule ablator implosion velocities, shell thickness and remaining mass in the last 3-5 ns before peak implosion time. The high quality data delivers good accuracy in implosion metrics that meets our requirements for ignition and agrees with recently introduced 2-dimensional pinhole radiography. Calculations match measured trajectory across various capsule designs and laser drives when the peak laser power is reduced by 20%. Furthermore, calculations matching measured trajectories give also good agreement in ablator shell thickness and remaining mass.

1. Introduction

In the indirect drive approach to inertial confinement fusion (ICF) employed on the National Ignition Facility (NIF), laser energy is converted into thermal x-rays that ablatively drive the implosion of a spherical capsule containing a deuterium-tritium (DT) fuel layer [1]. The resulting kinetic energy delivered to the fuel has to be high enough to overcome the heat lost by conduction and radiation while maintaining a relatively low fuel adiabat prior to implosion stagnation. Specifically the ignition threshold factor (ITF) [2] that quantifies the quality of an implosion relative to achieving ignition, scales as implosion velocity to the 7th power. However, as the rocket equation and earlier data show [3,4], increasing velocity leads to decreasing remaining ablator mass and greater undesirable sensitivity to feed-through of ablation front instabilities. In our quest for ignition and high gain, as we experimentally optimize the capsule, hohlraum and laser pulse designs [5], it is hence important to measure accurately the implosion velocity and ablator remaining mass. In addition, in the absence of a direct observation of the fuel, a precise measure of the ablator thickness is required to validate the ablator drive, compression and coupling to the DT fuel.

2. Experimental setup

Convergent Ablator (ConA) experiments measure inflight capsule ablator performance using 1-d slit radiography as shown in Figure 1a. Typically these experiments employ gas filled (DHe3) capsule



surrogates that have slightly thicker ablators to compensate for the missing DT fuel payload or use low yield THD layered capsules.

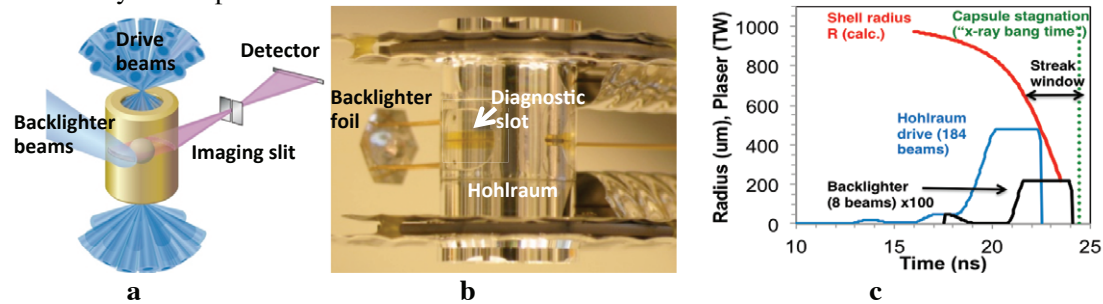


Figure 1. (a) ConA experimental arrangement, (b) picture of the target and (c) typical time history of a ConA measurement.

Eight laser beams (two 50° quads) of the 192 NIF beams are diverted towards a backlighter foil, mounted 6-12 mm away from the capsule center (Fig. 1b) to radiograph the capsule. Areal radiography is performed through two 0.1 mm tall and 2.4 mm wide diagnostic slots cut out in the high-Z hohlraum and filled with 100 μ m thick high-density carbon (HDC) that ensure minimal distortion of the hohlraum drive. The other 184 laser beams heat the hohlraum and drive the capsule implosion, whereas some beams have modified pulse shape to compensate for the missing backlighters when compared to full 192 beams DT implosions. Figure 1c superimposes the calculated time history of the ablator center of mass (CoM) trajectory on the hohlraum laser power and the backlighter pulses. The 2-5 ns long pulse backlighter beams generate He-alpha lines of the Zn or Ge foils ($h\nu=9-10$ keV), and are delayed to capture the ablator trajectory at radii ranging from 0.9 mm through stagnation (bang time, Fig. 1c). The ablator is imaged at the capsule waist using a 15 μ m wide slit oriented along the hohlraum axis, perpendicular to the diagnostic slots and placed 100 mm away from the capsule. Until early 2012 the measurement was performed using a 4-strip gated imager (M=9x setup) with 80 ps temporal blurring providing 4 adjustable times within a 1 ns time interval [3]. Recently we employed a x-ray streaked detector (DISC) [6] (M=12x setup) that provides reduced temporal blurring (40 ps), and at the same time captures a longer 3-5 ns continuous history of the inflight ablator.

3. Streaked data of NIF implosions

Figure 2 shows a target schematic as viewed by the detector and typical streaked images of imploding capsule ablators recorded with DISC.

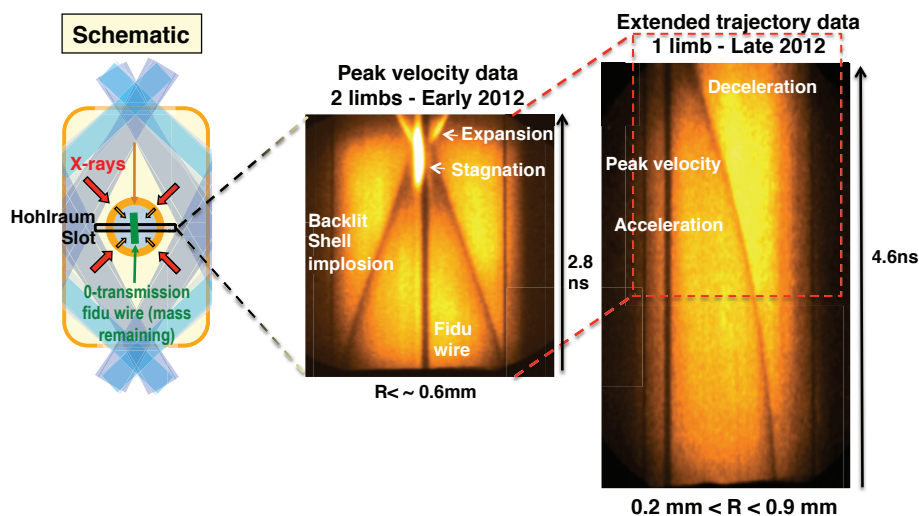


Figure 2. Target schematic and ConA data for peak velocity and extended trajectory of NIF ICF implosions (360 TW peak power/Au hohlraums).

Data shown here was recorded using gas filled, 210 μm thick CH capsules with a embedded Si doped layer (2% Si, 50 μm thick) that dominates the x-ray absorption in two distinct configurations: peak velocity and long record. Peak implosion velocity measurements, expected at a capsule radius of 0.2-0.4 mm, image both capsule limbs at the waist starting at radii > 0.6 mm, through stagnation and re-expansion. In validating our calculations we also use the expansion of the outgoing shock to constrain the energy coupled into the hot spot and remaining mass, typically in the order of 5-10 kJ [7]. Long record measurements, on the other hand, follow the trajectory of a single capsule limb over an extended range within a single experiment, at radii between 0.9 and 0.2 mm. Peak velocity data provide better statistics (2 limbs) and use a 3 ns streak record (40 ps temporal blurring), while extended record data images one limb over 5 ns to capture most of the trajectory and hence is affected by larger blurring (70 ps). The high quality streak data provides high accuracy in implosion velocity, remaining mass and shell thickness as summarized in Table 1. Besides providing a long continuous range of ablator implosion history, the accuracies of implosion metrics, inferred from data rms over the resolution element, are fairly consistent with the photon statistics, improve for streaked over gated data [3] and meet estimated requirements for ignition. Spatial blurring is reduced for streaked vs gated data due to reduced slit size and hence temporal blurring.

Table 1. ConA accuracies and requirements for ignition

	Estimated req. for ignition	Gated	Streaked peak velocity	Streaked extended trajectory
Radius range , mm		0.2-0.4	0.1-0.6	0.1-0.9
Temporal blurring, ps	< 50	80	40	70
Resolution, μm	< 20	25	17	17
Signal-to-noise /20 μm	> 10	80	35	45
Spatial blurring, all sources, μm^*	< 20	34	18	23
Velocity accy., (0.3 ns av.), %	≤ 2	5	2	3
Width accy., μm^*	≤ 4	6	3	3
Shell density, %[*]	≤ 10	15	10	9
Rem. mass/Mass($t=0$) accy, %	≤ 2	1.5	2	2

4. Streaked slit vs gated 2D ConA data comparison

In addition to streaked ConA's, we have recently developed 2D ConA backlit pinhole imaging using gated detectors [8] that provide inflight shape data, typically around 0.3 mm capsule radius.

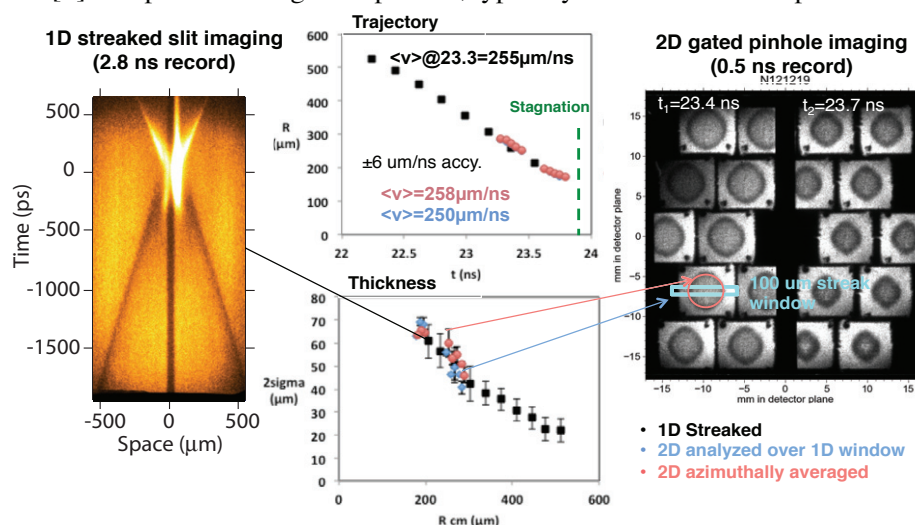


Figure 3. Comparison of 1D and 2D ConA data for similar implosions (360 TW peak laser power, 210 μm thick graded doped (Si) CH capsules).

While 2D ConA provides implosion velocity over the entire capsule rather than the waist, it requires larger diagnostic windows (hence bigger distortion on hohlraum drive), covers a shorter temporal window (~ 0.5 ns) and provides lower accuracy in velocity. A comparison of ConA and 2D ConA data for similar implosions is shown in Figure 3 for 360 TW peak power and 210 μm thick graded dopant capsules. ConA and 2D ConA results show same implosion velocities and capsule thickness within measurement uncertainty, both if the 2D analysis is performed over same 100 μm window of streaked ConA or over the azimuthal average around the capsule. This cross check validates these two measurement methods and shows that, for reasonably round implosions, streaked data is representative for the overall implosion performance around the capsule.

5. Data comparison to simulations and discussion

We compare our data with HYDRA calculations that are employed to optimize our implosions towards ignition. Good agreement in trajectory is obtained when the peak laser power (Fig. 1c) is reduced by 20%. Figure 4 shows a comparison between a measured and a simulated streaked radiograph processed from post-shot simulations.

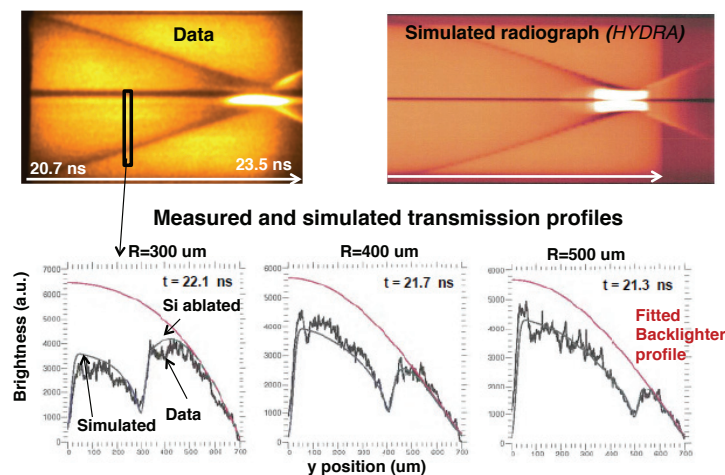


Figure 4 Measured and simulated radiographs and corresponding spatial lineouts (360 TW power, 210 μm thick CH capsule with Si doped layer).

Furthermore, once we match the measured trajectory we observe good agreement in the transmission profiles [9], even at $R=0.3$ mm, when ablation burns into the doped layer, and therefore in capsule thickness and remaining ablator mass. The drive reduction is due to an overestimate in the calculated radiation drive at the capsule as confirmed by View Factor experiments [10] that measure independently the x-ray drive through the hohlraum laser entrance hole and the drive as seen by the capsule. As it will be shown in future work, a similar drive reduction is required to match the data across various laser powers, capsule and ICF designs.

*This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

6. References

- [1] Haan S et.al, *Phys. Plasmas* **18**, 051001 (2011).
- [2] Edwards M J et. al., *Phys. Plasmas* **20**, 070501 (2013).
- [3] Hicks D et al, *Phys. Plasmas* **19**, 122702 (2012).
- [4] Meezan N et al *Phys. Plasmas* **20**, 056311 (2013).
- [5] O.L. Landen et. al., *Phys. Plasmas* **18**, 051002 (2011).
- [6] Opachich K et al., *Rev. Sci. Instrum.* **83**, 125105 (2012).
- [7] Pak A, *Phys. Plasmas* **20**, 056315 (2013).
- [8] Rygg R et al, O.Mo_A7, presented at IFSA 2013.
- [9] Olson R et al., *Rev. Sci. Instrum.* **83**, 10D310 (2012).
- [10] Schneider M et al, O.Fr_A8, presented at IFSA 2013.