Progress of Indirect Drive Inertial Confinement Fusion in the US

John Kline
For Indirect Drive Working group
27th IAEA FES meeting
Gandhinagar, India
Oct. 22nd, 2018

Hohlraum Target

Capsule

Laser Pulse

Adiabat:
\[ \alpha = \text{DT ice internal energy/ Fermi energy} \]
@ 1000 g/cc
This work represents a large cross laboratory team effort!

S. H. Batha,¹ L. R. Benedetti,² D. Bennett,² S. Bhandarkar,² L. F. Berzak Hopkins,² J. Biener,² M. M. Biener², R. Bionta,² E. Bond,² D. Bradley,² P. A. Bradely,¹ T. Braun,² D. A. Callahan,² J. Caggiano,² T. Cardenas,¹ C. Cerjan,² B. Cagadas,² D. Clark,² C. Castro,² W. S. Daughton,¹ E. L. Dewald,² T. Döppner,² L. Divol,² E. S. Dodd,¹ R. Dyka-Spears,² M. Eckart,² D. Edgell,⁴ M. Farrell,³ J. Field,² F. Fierro,¹ D. N. Fittinghoff,² M. Gatu Johnson,⁵ S. Johnson,² G. Grim,² N. Guler,¹ S. Haan,² B. M. Haines,¹ C. E. Hamilton,¹ A. V. Hamza,² E. P. Hartouni,² B. Haines,¹ R. Hatarik,² K. Henderson,¹ H. W. Herrmann,¹ D. Hinkel,² D. Ho,² M. Hohenberger,² D. Hoover,³ H. Huang,³ M. L. Hoppe,³ O. A. Hurricane,² N. Izumi,² O. S. Jones,² S. Khan,² B. J. Kozioziemski,² C. Kong,² J. Kroll,² G. A. Kyrala,¹ R. J. Leeper,¹ S. LePape,² E. Loomis,¹ T. Ma,² A. J. Mackinnon,² A. G. MacPhee,² S. MacLaren,² L. Masse,² J. McNaney,² N. B. Meezan,² J. F. Merrill,¹ E. C. Merritt,¹ J. L. Milovich,² D. S. Montgomery,¹ J. Moody,² A. Nikroo,² J. Oertel,¹ R. E. Olson,¹ A. Pak,² S. Palaniyappan,¹ P. Patel,² B. M. Patterson,¹ T. S. Perry,¹ R. R. Peterson,¹ E. Piceno,² J. E. Ralph,² B. R. Randolph,¹ N. Rice,³ H. F. Robey,² J. S. Ross,² J. R. Rygg,⁴ M. R. Sacks,¹ J. Sauppe,¹ J. Salmonson,² D. Sayre,² J. D. Sater,² J. Sauppe, M. Schneider,² M. Schoff,³ D. W. Schmidt,¹ S. Sepke,² R. Seugling,² R. C. Shah,⁴ M. Stadermann,² W. Stoeffl,² D. J. Strozzi,² R. Tipton,² C. Thomas,² RPJ Town,² P. L. Volegov,¹ C. Walters,² M. Wang,² C. Wilde,¹ C. Wilson,¹ E. Woerner,² C. Yeamans,² S. A. Yi,¹ B. Yoxall,² A. B. Zylstra,¹ J. Kilkenny,² O. L. Landen,² W. Hsing,² and M. J. Edwards²

¹Los Alamos National Laboratory, Los Alamos, NM, USA
²Lawrence Livermore National Laboratory, Livermore, CA, USA
³General Atomics, San Diego, CA, USA
⁴Laboratory for Laser Energetics, Rochester, NY, USA
⁵Massachusetts Institute of Technology, Boston, MA, USA
We’ve increased the energy delivery to the hot-spot by \(\sim 5x\), stagnation pressures by \(\sim 3x\), and fusion yields by \(\sim 21x\) since the National Ignition Campaign which ended in 2012.

- Low gas filled hohlraums with low LPI use x ray drive more effectively: improved symmetry & more energy coupled to the hot spot
- 3D effects still significantly degrading performance: symmetry and hydro-instability
- We plan to use our advances in understanding to optimize performance both in implosion quality and increased scale
Low adiabat ($\alpha_{if} \sim 1.6$) implosions in high gas-fill hohlraums resulted in implosions far from the ignition regime

- Optimized high yield designs
- First attempts at ignition scale targets
- No validation data
Mid-adiabat ($\alpha_{if} \sim 1.8-2.8$) implosions approached the ignition regime, but symmetry control limited with high (and no) gas-fills.

- X beam Transfer
- Backscatter

\[ T_{Brxk} \text{(keV)} \]

- $Y \sim 25 \text{ kJ}$
- $E_{th} \sim 4-5 \text{ kJ}$
- $Y_{if}/Y_{th} \sim 2.2x$
- $P \sim 220 \text{ Gbar}$

**NIF Data: 2010-2015**
Low gas-fill hohlraum designs brought the ICF program closer to the ignition regime than any previous designs.
Moving forward both implosion quality and increasing capsule size will be used to improve performance.

Quality axis represents progress towards 1D like implosions for fixed laser conditions.

Hydro-scaling axis simply increases size of capsule without improvements in quality.

Hydrodynamic scaling

\[ \text{No alpha} \]

\[ \text{Yield} \sim \text{Scale}^{4.5} \]

1D

\[ V_{\text{Ablation}}^{4/5} \times \int \text{Scale}^{8} \times \int \text{Adiabat}^{2} \times [\text{Mix} < 1] [\text{Shape} < 1] \]

3D
While symmetry control has much improved with low gas filled hohlraums, residual asymmetries still exist.

A comprehensive understanding of the shape of both the hot spot and cold fuel are needed.
An empirical understanding consistent with simulations has been developed for low gas fill hohlraums\(^1\).

\[ \sqrt{\frac{I_{\text{picket}} t_{\text{pulse}} r_{\text{cap}}}{\rho_{\text{fill}} R_{\text{Hohl}}^2}} \]

HDC capsule experiments demonstrated control of symmetry throughout the implosion

Examination of hot spot versus laser energy shows more efficient coupling for sub scale HDC capsules
Efforts are underway to address remaining residual asymmetries

- Random P1 and semi-random m1 asymmetries persist
- Bulk hotspot flow (nToF), low fuel rr regions (FNADs and nToF) and fluence compensated downscattered neutron images all correlate in direction of mode 1
- Peak power laser imbalances
- SBS variations
- Bulk flow velocity sensitivity to drive mode 1 consistent with simulations, though much scatter
- Residual sensitivities to foot and Au bubble imbalances
- Maximum yield envelope follows expected bulk flow velocity sensitivity, and drops current yields up to 1.5x
Address hydrodynamic instabilities near stagnation

Feature driven mix: Capsule support / fill tube, perforating shell, mix – needs to be better quantified

Ice compression less than expected

Native mix: Fuel appears less compressed than predicted by ~10-20% – not yet understood

Understand magnitude and impact of hydrodynamic instabilities near stagnation
Measurements show smaller fill tubes reduced perturbations and produced an increase in implosion performance

A performance increase was observed for 5 um fill tube leading to the development of a 2 um fill tube is underway and will be tested soon
High Resolution Velocimetry (OHRV) measurements show velocity structure of the shock front released

Experiment

Nano-crystalline HDC capsules are under development

GDP 2.2 Mbar

HDC 10 Mbar*

Ali et al, sub PRL 2017

*Design pressure 12+ Mbar
We want to maximize the energy available for heating and compressing the DT fuel.

Three scaling options:

- Bigger Capsule in current hohlraum
- Bigger Capsule in new hohlraum
- Bigger Capsule in bigger hohlraum

Increases in NIF power/energy:

Advances in understanding optics damage and mitigation enable more energy/power.

Demonstrated 2.15 MJ in July.
Initial experiments with the I-raum\textsuperscript{1} and variation of the gas fill pressure show promise

\[ \frac{E_{\text{picket outer}}}{A_{\text{outer}} \rho_{\text{fill}}} = \frac{\tau}{r_{\text{cap}}} \frac{r_{\text{cap}}}{R_{\text{hohl}} R_{\text{hohl}}} \]

## Improving our modeling and uncertainty quantification requires advances in diagnostics capabilities

<table>
<thead>
<tr>
<th>Area</th>
<th>Knowledge Gap</th>
<th>Diagnostic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot spot shape</td>
<td>Shape changes / fill tube jet&lt;br&gt;Time resolved Shape &gt; 1e16n&lt;br&gt;Improved x-ray imaging&lt;br&gt;3D, n emitting shape</td>
<td>DIXI equatorial&lt;br&gt;Polar DIXI / Single line of sight&lt;br&gt;Penumbral imaging / KBO&lt;br&gt;NIS-3 primary image</td>
</tr>
<tr>
<td>Fuel</td>
<td>Is fuel Isotropic&lt;br&gt;Fuel Shape vs time&lt;br&gt;3D fuel shape</td>
<td>More real time NADS&lt;br&gt;Compton Imaging&lt;br&gt;NIS-3 downscatter</td>
</tr>
<tr>
<td>Shell</td>
<td>Shape at Bangtime&lt;br&gt;Shape near Bangtime</td>
<td>$\gamma$ imaging of 4.4MeV carbon&lt;br&gt;CBI + SLOS</td>
</tr>
<tr>
<td>Hot Spot Te</td>
<td>Te&lt;br&gt;Te (t)&lt;br&gt;Te (r,t)&lt;br&gt;Burn quenching</td>
<td>Penumbral + Edge filter / Conspec&lt;br&gt;SPIDER with edge filters&lt;br&gt;Toroidal / Wolter Crystal / SLOS&lt;br&gt;GCD + Dilation PMT</td>
</tr>
<tr>
<td>Hohlraum</td>
<td>Morphology of Au Bubble&lt;br&gt;Better Modeling of Hohlraums</td>
<td>Gated LEH imager&lt;br&gt;Optical Thomson Scattering</td>
</tr>
</tbody>
</table>
LANL has invested in improvements to the xRage Eularian AMR code expanding simulations capabilities

3D simulations of the fill tube

Code comparison for fill tubes

Multiple simulations tools provide insight using different computational algorithms helping to get to the underlying physics.
Preview of IAEA FES 2020:

- Continued improvement in implosion performance
- Computational/empirical tools to quantify boundaries for low LPI
- Stagnation campaign to evaluate residual low/high mode asymmetries
- Next generation hohlraum designs to drive larger capsules
- Tools to assess hydro-instabilities at higher convergence
- Ranking of ablator performance
- Cross code comparisons with data to evaluate hydro stability
We’ve increased the energy delivery to the hot-spot by ~5x, stagnation pressures by ~3x, and fusion yields by ~21x since the National Ignition Campaign which ended in 2012.

- Low gas filled hohlraums with low LPI use x ray drive more effectively: improved symmetry & more energy coupled to the hot spot.

- 3D effects still significantly degrading performance: symmetry and hydro-instability.

- We plan to use our advances in understanding to optimize performance both in implosion quality and increased scale.
Efforts are also underway to find alternatives to the tent

Alt-tent (tetra-cage from LEH)