NIF Hohlraum Experiments at Room Temperature, a.k.a. “Warm Shots”

Anomalous Absorption Meeting
11 July 2013

D. J. Strozzi, D. E. Hinkel, J. E. Ralph, T. Ma, D. A. Callahan, J. L. Kline, J. D. Moody, O. Jones, J. R. Rygg
Why warm instead of cryogenic (cryo)?

Physics:
• San Ramon 2012 workshop: hotter hohlraum plasma could reduce inner-beam SRS
• Hohlraum gas fill affects laser propagation: higher Z absorbs more via inverse bremsstrahlung
• Only H, He, and some Ne gas fills don’t freeze in cryo conditions
• Warm shots allow range of gas fills, e.g. hydrocarbons

Practical: more shots
• Warm shots easier to field, shorter shot cycle
• Cheaper targets – no cryo hardware
Fielding warm shots

- **Hohlraum fill gas**: warm shots have 0.82 mg/cc neopentane (C$_5$H$_{12}$)
  - Same initial electron density as standard cryo fill 0.96 mg/cc He
  - Windows can’t hold same He density warm

- **Capsule fill gas**: propane (C$_3$H$_8$), or deuterated (C$_3$D$_8$) for neutrons
  - H, He diffuse through plastic at room temperature
  - Could Al-coat capsule, or continuously pump gas (T. Parham)
  - Other ablators (Be, B$_4$C, diamond) may not leak
  - More radiation, cooler hot spot, shell emission in x-ray images
We have (almost*) successfully commissioned the NIF warm hohlraum platform

2009: first two symcaps!
- Less inner SRS, more outer SBS, less pancaked at same \( \Delta \lambda \) than cryo

2012-2013 symcaps: walked up in energy/power: avoid laser SBS damage
- N121226: 821 kJ, 292 TW, \( \Delta \lambda = 1.5 \text{ Å} \) (low transfer)
  - Comparable inner SRS and outer SBS power
  - Delivered inner / total power \( \sim 1/3 \rightarrow \) large pancake
- N130125: higher power: 946 kJ, 368 TW
  - \( \Delta \lambda = 3.5 \text{ Å} \): round hotspot! This \( \Delta \lambda \) used subsequently
- N130217: extend peak power: 1.26 MJ, 362 TW
  - up-down asymmetry (potential alignment issues)
- N130405: repeat 130217, first C\(_3\)D\(_8\) capsule fill, round hotspot

2013 2D ConA’s:
- N130509: -300 um hohlraum: large in-flight diamond (\( P_4 > 0 \))
- N130627: +700 um: reduced in-flight \( P_4 \)
  - 0.5x capsule fill pressure to reduce self-emission in ConA images

* Warm keyhole shot would verify shock strengths and timings (H. Robey)
Warm shot performance different from cryo

• **Backscatter:** Warms have less inner-beam SRS, more outer-beam SBS

• **P₂ shape:** Warm hotspots are close to round with less cross-beam energy transfer

• **The P₄ question:** warm in-flight diamond shape, square hotspot
  • Lengthening hohlraum reduces in-flight diamond – both warm and cryo
  • Cryo shots have diamond in-flight and hotspot
  • Hydra simulations: both warm and cryo diamond in-flight, square hotspot

• **Nuclear:**
  • Deuterated propane C₃D₈ -> up to 2.6E11 neutrons
  • T_{ion} up to 1.7 keV
Warm laser pulse similar to cryo: picket higher by ~20% to burn through higher Z hohlraum gas

- First two shots used lower peak power or duration – avoid backscatter laser damage
- Warm trough shorter due to starting from a different comparison shot
Warm shots have less inner SRS, more outer SBS, than cryos

- Difference partly (entirely?) due to less $\Delta \lambda$ in warms
- 2009: similar changes just due to hohlraum gas composition: same pulse, same $\Delta \lambda$, just changed gas fill
Warm shots have more laser coupling than cryos

Coupling = incident - backscattered

\[ \lambda_{\text{in}} - \lambda_{\text{out}} \] [Å]

Laser Coupling [%]

- cryo
- warm
Outer beam SBS: DrD sensors show more on cone 50 than 44, and give power scaling

- DrD = drive diagnostic sensor - at least one beam in each quad
  - $3\omega$ power history - forward and backward (separated in time)
- N130125: one quad on each cone had 18% higher power: power scaling on one shot!

- Why more SBS on 50’s than 44’s?
  - 50 focal spot smaller -> higher intensity
  - Cross-beam energy transfer calculations: post-transfer power on 50’s > 44’s
  - Could be pure intensity scaling; plasma conditions may also play role
Cryo shots show some outer SBS late in time, esp. for longer pulses or high power.

Warm platform good for studying outer SBS and mitigation – cheaper, reproducible.
IN-FLIGHT SHELL SHAPE
Convergent ablator “ConA” shots: backlit radiographs of shell in-flight (before hotspot formation)

NIF chamber geometry

CH shell

X-ray
Backlighter

source

N130627 (warm 2D ConA)

Shell attenuates backlighter x-rays

Gated
X-ray
detector

Hotspot self-emission

Campaign RI:
Callahan, Moody, Kline
Platform RI:
Town, Rygg
Designer:
Strozzi, Hinkel, Callahan
Shot RI:
T. Ma, R. Rygg, M. Barrios

Objectives of the shot:
• Backlight the implosion in-flight to determine shape of warm capsule in +700 µm hohlraum
• Warm platform commissioning
• Scaling with capsule fill gas pressure -575 Au hohlraum, +700 µm, nominal LEH - Capsule: T0, graded 1x Si -15 nm tent -1.3 MJ, 370 TW into hohlraum - Ge BL - Δλ = 3.5/3.5 - Target temperature = 298 K - Capsule fill pressure = 1175 Torr

HGXD 90-78:
Backlighting of In-Flight Shell N130627 (warm 2D ConA)
Implosion symmetry expressed with Legendre modes, mut be controlled for ICF to work

NIF chamber geometry $g$

$P_2$ mode: determined by final (post-transfer, post-backscatter) laser cone fraction

$P_2 < 0$: pancake*: outers too strong

$P_2 > 0$: Sausage: inners too strong

$P_4$ mode: determined by geometry: hohlraum length, beam pointing

$P_4 < 0$: square: corners out

$P_4 > 0$: diamond: corners in

*Oblate, prolate are ancient Etruscan for pancake, sausage
In-flight shape (ConA): warms are more pancaked ($P_2<0$), slightly more diamond ($P_4>0$) than cryo

- Red: warm
- Blue: cryo

- □: $L_{hohl}$ -300 µm
- ●: $L_{hohl}$ +700 µm

- N121219: cryo -300 µm
- N130211: cryo +700 µm
- N130509: warm -300 µm
- N130627: warm +700 µm

$P_0 = \text{radius}$

- $P_2$
  - sausage
  - pancake
- $P_4$
  - diamond
  - square

- Longer hohlraum reduces $P_4$ in both warms and cryos – as Hydra predicts
- Program has adopted +700 µm as standard hohlraum

Hotspot

\[ \sim 50 \mu m \] time – bang time [ns]
N130509: warm 2D ConA, $L_{\text{hohl}}$ -300 um:
Hydra and data agree on $P_4$, so-so on $P_2$

- Hydra $P_2$ controlled by $\delta n/n$ saturation clamp in cross-beam energy transfer. Lower value would agree better with data.
- Inline Hydra model, including ion heating, under investigation. [P. Michel et al., PRL 2012]
N130509: simulations show diamond P₄ in shell density, which leads to square hotspot.

Post-shot image and density

\[ P_0 = 200 \text{ um} \]

Measured data:

\[ P_0 \text{ limb min} = 197 \text{ um} \]

In-flight density nodes plow in material, making a square hotspot.
HOTSPOT SHAPE: THE $P_4$ QUESTION
Gated x-ray movies of hotspot emission give equatorial and polar shape

NIF chamber geometry

Movie of N130405 equatorial GXD images

hotspot

Equatorial X-ray Detector

Polar X-ray Detector
Hotspot equatorial x-ray images: warm and cryo

Warm radius slightly larger: cooler hotspot, shell emission?

P₂: less transfer makes warms round

N130627: 0.5x capsule fill pressure
While there is a clear correlation between inflight and hot-spot P2 there is not for P4

Slide courtesy R. Town
Nuclear performance of warm shots is similar to cryos, with cooler hotspots - C$_3$D$_8$ fill radiates more

<table>
<thead>
<tr>
<th>Shot</th>
<th>N130627 2DConA +700 um</th>
<th>N130509 2DConA -300 um</th>
<th>N130405 symcap</th>
<th>N130211 2DconA +700 um</th>
<th>N121219 2DConA -300 um</th>
<th>N120726 symcap</th>
<th>N120705 symcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{las}}$ [MJ]</td>
<td>1.35</td>
<td>1.34</td>
<td>1.27</td>
<td>1.33</td>
<td>1.34</td>
<td>1.37</td>
<td>1.85</td>
</tr>
<tr>
<td>$T_{\text{ion DD}}$ [keV]</td>
<td>1.7</td>
<td>1.3</td>
<td>1.3</td>
<td>2.1</td>
<td>2.2</td>
<td>2.2</td>
<td>3.4</td>
</tr>
<tr>
<td>DD yield [10$^{11}$ n]</td>
<td>2.6</td>
<td>2.0</td>
<td>2.2</td>
<td>2.4</td>
<td>2.0</td>
<td>3.19</td>
<td>5.3</td>
</tr>
<tr>
<td>Yield / simulated</td>
<td>135% ! preshot</td>
<td>44%</td>
<td>71%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capsule fill pressure</td>
<td>0.5x</td>
<td>1x</td>
<td>1x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_0$ hotspot</td>
<td>0.82x</td>
<td>57.8 $\mu$m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capsule fill gas</td>
<td>C$_3$D$_8$</td>
<td>C$_3$D$_8$</td>
<td>C$_3$D$_8$</td>
<td>D-$^3$He</td>
<td>D-$^3$He</td>
<td>D-$^3$He</td>
<td>D-$^3$He</td>
</tr>
</tbody>
</table>

Good reproducibility!

- Lower capsule pressure increases yield: smaller radius, higher $T_{\text{ion}}$
Conclusion: warm hohlraum platform commissioned on NIF, ready for physics studies

- Hydrocarbon hohlraum and capsule fill – unlike H / He for cryo

- P\(_2\) shape: Warm hotspots near round w/ less cross-beam energy transfer

- Backscatter: Warms have less inner-beam SRS, more outer-beam SBS

- The P\(_4\) question: warm in-flight diamond shape, square hotspot
  - Cryo: diamond in-flight and hotspot
  - Hydra: diamond in-flight, square hotspot - warm and cryo
  - Support tent could be playing a role

- Nuclear
  - Deuterated propane: T\(_{\text{ion}}\) up to 1.7 keV

- Future
  - Different hohlraum fill to improve inner beam propagation
  - Outer SBS mitigation: Au-Boron wall, split beams in quad
  - Capsule spectroscopy - argon, krypton; needs T\(_e\) ~ 2 keV (S. Regan)
  - Test mix estimates with unknown concentrations (T. Ma)
BACKUP BELOW
Polar shape: warms much dimmer and larger $M_0$ vs cryo; “donut” shaped

- Likely due to propane ($C_3D_8$) capsule fill radiating more and cooling

<table>
<thead>
<tr>
<th>M0</th>
<th>40.30 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2/M0</td>
<td>2.26 %</td>
</tr>
<tr>
<td>M4/M0</td>
<td>4%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>M0:</th>
<th>83 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2/M0:</td>
<td>2.7%</td>
</tr>
<tr>
<td>M4/M0:</td>
<td>2.1%</td>
</tr>
</tbody>
</table>
Reducing the capsule fill pressure *increased* the yield

<table>
<thead>
<tr>
<th>Shot</th>
<th>2: N130627 2DConA +700 um</th>
<th>1: N130509 2DConA -300 um</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{las}}$ [MJ]</td>
<td>1.35</td>
<td>1.34</td>
</tr>
<tr>
<td>$T_{\text{ion DD}}$ [keV]</td>
<td>1.7 (1.31x)</td>
<td>1.3</td>
</tr>
<tr>
<td>$&lt;\sigma v&gt;_{\text{DD}}$</td>
<td>3.6x</td>
<td>1x</td>
</tr>
<tr>
<td>DD yield</td>
<td>1.3x</td>
<td>2.0E11</td>
</tr>
<tr>
<td>Yield / simulated</td>
<td>135% preshot</td>
<td>44%</td>
</tr>
<tr>
<td>Capsule fill pressure ~ $N_i$</td>
<td>0.5x</td>
<td>2350 torr</td>
</tr>
<tr>
<td>$P_0$ hotspot</td>
<td>0.82x</td>
<td>57.8 μm</td>
</tr>
<tr>
<td>Hotspot pressure = $n_i T_i$</td>
<td>1.22x</td>
<td>1x</td>
</tr>
<tr>
<td>Hotspot $n_i \sim N_i / P_0^3$</td>
<td>0.907x</td>
<td>1x</td>
</tr>
</tbody>
</table>

Shot 2: lower ion number, hotspot more converged and hotter
Net effect is higher yield

Yield increase estimate:

$$Y \propto <\sigma v>*n_i^2 * \text{Vol}$$

$$\frac{Y_2}{Y_1} = \frac{<\sigma v>_2}{<\sigma v>_1} * \left[ \frac{P_{01}}{P_{02}} \right]^3 * \left[ \frac{N_{i2}}{N_{i1}} \right]^2$$

$$\rightarrow \frac{Y_2}{Y_1} = 1.63$$

x=N130509 value
NUCLEAR PERFORMANCE
Warm reflectivity

Reflectivity

Reflectivity [%]

SRS 23
SRS 30
SBS 50

shot number

NIF-0000-00000s2.ppt

Author—NiC Review, December 2009
The $P_4$ question – warms and Hydra agree on in-flight and hotspot $P_4$, cryos do not

- Warm shots switch from in-flight diamond to hotspot square
- Cryos have diamond in-flight and in hotspot
- Hydra predicts both should behave like warms
Next warm 2D ConA: +700 um hohlraum length: in-flight $P_4$ should be much less but still $> 0$

- Warm still calculated to have positive $P_4$
  - Difference in wall motion / gold bubble (see SXI)?
  - Room for additional re-pointing of outers?

N121219: cryo +300 um
N130211: cryo +700 um
N130509: warm -300 um
Pre-shot warm +700 um
Hydra modeling of warms agrees on bang time and in-flight symmetry

<table>
<thead>
<tr>
<th>Shot</th>
<th>Hydra pre-shot*</th>
<th>N130509 Warm 2DConA</th>
<th>Hydra N130509_ps03</th>
<th>N130405 warm symcap</th>
<th>Hydra N130405_ps03</th>
</tr>
</thead>
<tbody>
<tr>
<td>($\lambda_{23}, \lambda_{30}$)$-\lambda_{out}$ [Å]</td>
<td>3.5, 3.5</td>
<td>Same</td>
<td>Same</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Xray BT [ns]</td>
<td>22.57</td>
<td>22.32</td>
<td>Data + 60ps</td>
<td>22.44</td>
<td>Data + 80ps</td>
</tr>
<tr>
<td>P0 GXD BT [um]</td>
<td>43.77</td>
<td>57.8 TI</td>
<td>51.8</td>
<td>64.4</td>
<td>49.2</td>
</tr>
<tr>
<td>P2/P0 BT [%]</td>
<td>+2.19</td>
<td>-14 TI</td>
<td>+7.8 BT</td>
<td>-6</td>
<td>+60 !!</td>
</tr>
<tr>
<td>P4/P0 BT [%]</td>
<td>-12.02</td>
<td>-10 TI</td>
<td>-21.6 BT</td>
<td>-20</td>
<td>-60</td>
</tr>
<tr>
<td>DD yield [n]</td>
<td>1.92E11</td>
<td>44% YOS</td>
<td>4.57E11</td>
<td>71% YOS</td>
<td>3.1E11</td>
</tr>
<tr>
<td>P2/P0 % @ 200 um</td>
<td>-16.8</td>
<td>-14</td>
<td>-12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P4/P0 % @ 200 um</td>
<td>+5.18</td>
<td>+11</td>
<td>+12.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Hydra predicts both warms and cryos have in-flight diamond and hot-spot square
- Warm shots behave this way
- Cryo shots have both in-flight and hot-spot diamond – disconnect with Hydra

- Warm sims:
  - Time-dependent cryo Oggie multipliers: gives slightly later BT
  - Cross-beam transfer: script w/ $dn/n = 6E-4$ saturation – lower level would make sim pancaked
  - Working on inline cross-beam and backscatter packages
Warm equatorial self-emission x-ray images

Hydra N130405_ps03 at bang time 22.52 ns

Hydra N130509_ps03 at bang time 22.38 ns

N130405 measured @ bang-time

N130509 (-300 um) Time-integrated
Warm in-flight diamond ($P_4>0$) switches to hotspot square ($P_4<0$), unlike cryos (stay diamond)

<table>
<thead>
<tr>
<th>Shot</th>
<th>N130509 Warm 2DConA</th>
<th>N121219 Cryo 2DConA</th>
<th>N130211 Cryo 2DconA</th>
<th>N130405 warm symcap</th>
<th>N120726** Cryo symcap</th>
<th>N120705 Cryo symcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{ias}$ [MJ]</td>
<td>1.34</td>
<td>1.34</td>
<td>1.33</td>
<td>1.27</td>
<td>1.37</td>
<td>1.85</td>
</tr>
<tr>
<td>$P_{peak}$ [TW]</td>
<td>379</td>
<td>345</td>
<td>358</td>
<td>367</td>
<td>412</td>
<td>523</td>
</tr>
<tr>
<td>$(\lambda_{23}, \lambda_{36})-\lambda_{out}$ [Å]</td>
<td>3.5, 3.5</td>
<td>8.1, 6.6</td>
<td>8.1, 6.6</td>
<td>3.5, 3.5</td>
<td>9.7, 8.5</td>
<td>8.5, 7.3</td>
</tr>
<tr>
<td>In-flight shape</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>n/a to symcaps</td>
<td></td>
</tr>
<tr>
<td>$P2/P0$ % @ 200 um</td>
<td>-14</td>
<td>+2.7</td>
<td>+12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P4/P0$ % @ 200 um</td>
<td>+11</td>
<td>+8.5</td>
<td>+2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hotspot shape</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P2/P0$ [%]</td>
<td>-14</td>
<td>-11</td>
<td>+7.5</td>
<td>-6</td>
<td>+16</td>
<td>-20</td>
</tr>
<tr>
<td>$P4/P0$ [%]</td>
<td>-10</td>
<td>+3</td>
<td>+15</td>
<td>-20</td>
<td>+3</td>
<td>0</td>
</tr>
</tbody>
</table>
Warm shot hotspots “round” (P$_2$ small) for less $\Delta \lambda$ than similar to low-foot cryos

<table>
<thead>
<tr>
<th>Shot</th>
<th>N130509 2DConA</th>
<th>N121219 2DConA</th>
<th>N130211 2DconA</th>
<th>N130405 symcap</th>
<th>N120726** symcap</th>
<th>N120705 symcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{las}}$ [MJ]</td>
<td>1.34</td>
<td>1.34</td>
<td>1.33</td>
<td>1.27</td>
<td>1.37</td>
<td>1.85</td>
</tr>
<tr>
<td>$P_{\text{peak}}$ [TW]</td>
<td>379</td>
<td>345</td>
<td>358</td>
<td>367</td>
<td>412</td>
<td>523</td>
</tr>
<tr>
<td>($\lambda_{23}, \lambda_{30}$)-$\lambda_{\text{out}}$ [Å]</td>
<td>3.5, 3.5</td>
<td>8.1, 6.6</td>
<td>8.1, 6.6</td>
<td>3.5, 3.5</td>
<td>9.7, 8.5</td>
<td>8.5, 7.3</td>
</tr>
<tr>
<td>Hohlraum, LEH</td>
<td>Au -300, small</td>
<td>Au -300, small</td>
<td>Au +700, large</td>
<td>Au nom, large</td>
<td>Au nom, large</td>
<td>U nom, small</td>
</tr>
<tr>
<td><strong>Hotspot</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xray BT [ns]</td>
<td>22.32</td>
<td>22.91</td>
<td>22.90</td>
<td>22.44</td>
<td>24.31</td>
<td>23.83</td>
</tr>
<tr>
<td>P0 GXD [um]</td>
<td>57.8</td>
<td>52.1</td>
<td>54.9</td>
<td>64.4</td>
<td>43.78</td>
<td>46.56</td>
</tr>
<tr>
<td>P2/P0 [%]</td>
<td>-14</td>
<td>-11</td>
<td>+7.5</td>
<td>-6</td>
<td>+16</td>
<td>-20</td>
</tr>
<tr>
<td>P4/P0 [%]</td>
<td>-10</td>
<td>+3</td>
<td>+15</td>
<td>-20</td>
<td>+3</td>
<td>0</td>
</tr>
</tbody>
</table>

Warm cryo
Polar shape in Hydra: large $M_0$, broad profile but no donut

**N130405_ps03 post-shot**

- From $Y=0$, time $= 22.38$ (ns)

**Peak x-ray time = 22.38 (ns)**

**M4/M0 = 0.000424 (%) M0 = 75.1 (µm)**

**Phase = 39.2 (deg) M4 = 0.000318 (µm)**

**N130405: warm symcap**

**Measurement at bang time**

- Color map with x and y coordinates, showing intensity distribution.