Liquid DT Layer Approach To Inertial Confinement Fusion

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DT vapor
for $21<T<26 \, ^oK$
$1.0 < \rho_v < 4.0 \, mg/cm^3$

12 < CR < 25
Liquid DT Layer Approach to ICF Hot Spot Formation

some key points:

• DT ice layer implosions have a high hot spot convergence ratio, CR>30.

• Recent cryogenic liquid DT layer implosions at the NIF demonstrate the ability to control hot spot CR’s in the range of 12<CR<20.

• At low CR, DT layered implosion performance is well predicted by radiation-hydrodynamics simulations, but as CR increases, our understanding of hot spot formation decreases.

• There are potential advantages for a liquid DT layered implosion with reduced hot spot CR (CR<20).
Potential advantages of a liquid DT layer

key advantages:

• A liquid DT layer allows for a higher vapor density compared to a DT ice layer, the ability to create a hot spot from the vapor, and flexibility in hot spot CR.

• With reduced CR, hot spot formation is expected to be more robust to instabilities and asymmetries than high CR ice layer implosions.

• With reduced CR, the hot spot pressure required for self-heating is reduced, and the implosion velocity and fuel adiabat requirements are relaxed. (A trade-off is, that with larger hot spot size, the hot spot energy requirement for self-heating is increased.)
Advantages of a liquid DT layer:

A liquid DT layer allows for selecting a CR by adjusting the cryogenic fielding temperature.

- **CR > 30**
  - DT ice layer
  - DT vapor for T < 19 °K
  - $\rho_v < 0.4$ mg/cm$^3$

- **12 < CR < 25**
  - DT liquid layer (in CH foam)
  - DT vapor for 21 < T < 26 °K
  - $1.0 < \rho_v < 4.0$ mg/cm$^3$

DT layer implosions with reduced CR will have improved robustness to instability growth and distortions related to engineering features.

Brian Haines RAGE simulations*:

Variations on a full scale HDC wetted foam capsule design including detailed and well-resolved models for the capsule fill tube, support tent, surface roughness, and predicted asymmetries in the X ray drive.

Recent experiments on NIF have demonstrated liquid layer implosions

NIF sub-scale liquid layer experiments:

CH foam-lined HDC capsule

Au near-vacuum hohlraum

< 900 kJ 3-shock NIF laser pulse

The NIF cryo team developed thermal designs, along with a process to wick the liquid DT (or D$_2$) into the foam layer.

Very top level procedure:
1. Fill target (liquid wicks into foam)
2. Fix amount of fuel by freezing a plug in the fill tube
3. Hold target and plug temperatures through the shot

The initial experiments successfully demonstrated the ability to select a layered implosion CR in the range of 12<CR<20.

CR = 12
T = 26 °K, ρ_vapor = 4 mg/cm³
(NIF shot N160421)

CR = 17
T = 24 °K, ρ_vapor = 3 mg/cm³
(NIF shot N160626)

CR = 20
T = 21 °K, ρ_vapor = 1 mg/cm³
(NIF shot N161204)

NIF sub-scale liquid layer experiments:

For CR = 12, the hot spot formation is understood – demonstrated by the agreement between experimental data and simulations.

Although the expected CR control was demonstrated, the observed over calculated yield decreased dramatically as CR was increased.

The data trends might be explained by:

• reduced hydrodynamic coupling efficiency due to 3D effects

and/or

• anomalously enhanced thermal conductivity in the DT layer

2D RAGE simulations including drive asymmetry, tent, fill tube, capsule surface roughness, and low-mode foam shape asymmetries.

NIF sub-scale liquid layer experiments:

- B. M. Haines et al., “3D simulations of NIF wetted foam experiments to understand the transition from 2D to 3D flow behavior,” Inertial Fusion Sciences and Application Proceedings (2017)

There are tradeoffs involved in high CR ice layer and reduced CR liquid layer designs

• The hot spot pressure required for self-heating is reduced if the CR is reduced (hot spot radius is increased).

• If the hot spot pressure requirement for self-heating is reduced, the implosion velocity and fuel adiabat requirements are relaxed.

• With larger hot spot size, the hot spot energy requirement for self-heating is increased.

• Although there is a penalty to be paid in energy investment for a larger hot spot, it should be noted that there is a significant benefit in the hot spot alpha particle energy production, which also increases with the square of the hot spot radius.
The hot spot pressure required for self-heating is reduced if the CR is reduced (hot spot radius is increased).

\[ P_{hs} \propto R_{hs}^{-1} \propto CR \]

**Tradeoffs between ice and liquid layer designs:**

NIC point design (ice layer, CR ~ 34)

Reduced CR
If the hot spot pressure requirement for self-heating is reduced, the implosion velocity and fuel adiabat requirements are relaxed.

\[ \text{Pr}_{\text{hs}} \propto v^5 / \beta^{1.5} \] (isobaric stagnation)
tradeoffs between ice and liquid layer designs:

With larger hot spot size, the hot spot energy requirement for self-heating is increased.

\[ E_{hs} \propto R_{hs}^2 \propto CR^{-2} \quad (\text{at fixed } \rho r) \]

Although there is a penalty to be paid in energy investment for a larger hot spot, it should be noted that there is a significant benefit in the hot spot alpha particle energy production, which also increases with the square of the hot spot radius.
Liquid DT layers offer a modest Convergence Ratio (CR) path to an ICF burning plasma. However, reduced CR requires more capsule absorbed energy.

Tradeoffs between ice and liquid layer designs:

- DT liquid layers, CR ~ 20, $E_{\text{cap}}$ ~ 350 kJ
- DT ice layers, CR ~ 35, $E_{\text{cap}}$ ~ 150 kJ

(assumes 1D-like behavior, $\rho R_{\text{tot}} = 2$ g/cm$^2$, 10% hydro-coupling)
Liquid DT layers provide a reduced CR approach to ICF hot spot formation. However, reduced CR requires more capsule absorbed energy.

Summary and Conclusion

• Liquid DT layers provide a reduced CR approach to ICF hot spot formation.
  – flexibility in hot spot CR in the range of 12<CR<25
  – the ability to create a hot spot from the central vapor
  – improved robustness to instability growth, distortions related to engineering features, and drive asymmetries.
  – The hot spot pressure required for self-heating is reduced if the CR is reduced (hot spot radius is increased).
  – DT liquid layer implosions and CR control have been demonstrated in sub-scale NIF experiments.

• Robust reduced CR high adiabat designs require more capsule absorbed energy.
  – > 2x energy investment as compared to a low adiabat CR > 30 DT ice layer design with comparable $\rho R_{\text{tot}}$
back up slides follow
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**summary:**

- DT ice layer implosions have a high hot spot convergence ratio, CR>30.

- Recent cryogenic liquid DT layer implosions at the NIF demonstrate the ability to control hot spot CR’s in the range of 12<CR<20.

- At low CR, DT layered implosion performance is well predicted by radiation-hydrodynamics simulations, but as CR increases, our understanding of hot spot formation decreases.

- There are potential advantages for a liquid DT layered implosion with reduced hot spot CR (CR<20).
As CR increases, our understanding of hot spot formation decreases.

NIF sub-scale liquid layer experiments:

- Ion Temperature vs. CR
- Burn Width vs. CR
- Hot Spot Pr vs. CR

As CR increases, our understanding of hot spot formation decreases.
The hot spot pressure required for self-heating is reduced if the hot spot size is increased ($Pr_{hs} \propto R_{hs}^{-1}$).

for the hot DT plasma:

$$P_{hs} = 7.52 \times 10^2 \rho T \quad (\text{Mbar, keV})$$

multiply and divide by hot spot radius:

$$P_{hs} = 7.52 \times 10^2 \frac{\rho R_{hs} T}{R_{hs}}$$

include the requirement of

$$\rho R_{hs} = 0.3 \text{ g/cm}^2 \text{ and } T > 4.5 \text{ keV}$$

$$P_{hs} > 9.0 \times 10^6 / R_{hs} \quad (\text{Gbar, cm})$$
If the hot spot pressure requirement for self-heating is reduced, the implosion velocity and fuel adiabat requirements are relaxed ($Pr \propto \frac{v^5}{\beta^{1.5}}$).

assuming isobaric stagnation:

cold fuel kinetic energy, $\varepsilon_{KE} \propto v_{imp}^2$

cold fuel specific energy, $\varepsilon_{cf} \propto \beta \rho_{cf}^{2/3}$

peak cold fuel density, $\rho_{cf} \propto v_{imp}^3 / \beta^{3/2}$

stagnation pressure, $P_{cfst} \propto \beta \rho^{5/3}$

hot spot pressure, $P_{hs} \propto v_{imp}^5 / \beta^{3/2}$
With larger hot spot size, the hot spot energy requirement for self-heating is increased \((E_{hs} \propto R_{hs}^2 \propto CR^{-2})\).

The ignition requirement is approximately:
\[ \rho R > 0.30 \text{ g/cm}^2 \text{ and } T > 4.5 \text{ keV.} \]

Hot spot density, \( \rho = 0.3 / R \) (g/cm\(^2\))

Hot spot volume, \( V = 4\pi/3 \ R^3 \) (g/cm\(^3\))

Hot spot mass = \( 4\pi/3 \ R^3 \times 0.3 / R = 1.26 \ R^2 \) (g)

Specific energy of DT in hot spot = \( e_{hs} = 77 \ T \) (J/\(\mu g\), keV)

Thus, hot spot energy = \( E_{hs} = 7.7 \times 10^7 \times 4.5 \times 1.26 \ R^2 = 4.4 \times 10^8 \ R^2 \) (J, cm)

or, in convenient units, \( E_{hs} = 4.4 \times 10^{-3} \ R^2 \) (kJ, \(\mu m\))

In the baseline NIC ignition design, \( CR = 840 / R \) (\(\mu m\)).

Thus, the hot spot energy requirement = \( 3.1 \times 10^3 / CR^2 \) (kJ).

For \( CR = 30 \), \( E_{hs} > 3.4 \) kJ, and for \( CR = 20 \), \( E_{hs} > 7.7 \) kJ.

This analytic hot spot energy scaling \((E_{hs} \propto R_{hs}^2 \propto CR^{-2})\) is in agreement with 1D Hydra simulations*.

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For CR = 12, the hot spot formation is well modeled – demonstrated by the agreement between experimental data and simulations.*

Table I: N160421 implosion metrics

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>2-D HYDRA</th>
<th>1-D RAGE</th>
<th>2-D RAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT neutrons ($10^{14}$)</td>
<td>4.5 ± 0.1</td>
<td>6.4</td>
<td>5.7</td>
<td>4.9</td>
</tr>
<tr>
<td>Nuclear Bang Time (ns)</td>
<td>8.49 ± 0.03</td>
<td>8.6</td>
<td>8.45</td>
<td>8.5</td>
</tr>
<tr>
<td>DT $T_1$ (keV)</td>
<td>3.2 ± 0.1</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>DD $T_1$ (keV)</td>
<td>3.0 ± 0.2</td>
<td>3.1</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Nuclear Burn Width (ps)</td>
<td>313 ± 30</td>
<td>287</td>
<td>243</td>
<td>275</td>
</tr>
<tr>
<td>Hot-Spot Radius ($\mu m$)</td>
<td>64.7 ± 4.7</td>
<td>61.8</td>
<td>65.4</td>
<td>65</td>
</tr>
<tr>
<td>X-ray Image</td>
<td>50.6 ± 2.2</td>
<td>53</td>
<td>52</td>
<td>47</td>
</tr>
<tr>
<td>Neutron Image</td>
<td>16.5 ± 2.6</td>
<td>18.5</td>
<td>17.3</td>
<td>17</td>
</tr>
<tr>
<td>Inferred Pressure (GBar)</td>
<td>23.5 ± 2.6</td>
<td>23.5</td>
<td>21.8</td>
<td>–</td>
</tr>
</tbody>
</table>

The 2D HYDRA YOC is 70%. The 2D RAGE YOC is 92%, in a simulation including the 30 $\mu m$ diameter fill tube, the tent, surface roughness, and low-mode drive asymmetry.