Status of Ignition Experiments on the NIF

NIF/JLF Users Group Meeting
Livermore, CA

February 11th, 2015
We are developing a promising path forward with low mix, high velocity implosions and improving symmetry control to reach toward higher yields.
Ignition requires compression to high pressures and temperatures in short time scales to self-heat.

Heating from fusion > Cooling from conduction & x-ray losses

\[
E_{\text{ignition}} \sim \left[ \left( \rho R \right)^3 T^3 \right]_{\text{DT}} \rightarrow \text{const.}
\]

Stagnation pressure depends on how the hot spot was assembled:

\[
P_{\text{stag}} \sim P_{\text{abl}}^{2/5} \frac{V_{\text{imp}}^3}{\alpha^{9/10}} \varepsilon
\]

Cold DT shell

\sim 1000 \text{ g/cc}

Hot spot

Pressure \sim 350 \text{ Gbar}

\rho R \sim 1.5 \text{ g/cm}^2

\sim 0.1 \text{ mm}

\*\rho R = \text{Areal density}
On the NIF, we use a laser driven hohlraum to implode the capsule attempting to create conditions needed for ignition.
Hohlraum dynamics are complicated, and diagnosing plasma conditions is an area of active, ongoing research.

- Backscatter losses ~ 15% (~200kJ)
- Capsule drive is over-predicted ~ 200kJ → drive degradation required for 2D HYDRA simulations to match experiment
- Suprathermal electron generation (0.5 - 2 kJ)
- Poor late-time inner beam propagation requires high inner beam power to achieve implosion symmetry
- Require cross-beam energy transfer (CBET) to control implosion symmetry → leads to time-dependent asymmetries
Cryogenic Ignition target

- Laser entrance hole
- Heaters for mK thermal control
- Windows to observe DT layer prior to shot
- DT fill line
- Si cooling arms covered in light shields
Plastic Ignition Capsule

~2 mm diameter

195 µm
X-ray picture of capsule taken down axis of the hohlraum just before a shot.

2mm diameter capsule

- CH
- Si dopant layers
- Solid DT layer ~ 0.1mm thick
The challenge — near spherical implosion by ~35X

DT shot N120716
Bang Time
(less than diameter of human hair)

~2 mm diameter
The capsule must be designed to withstand hydrodynamic instabilities.
High Foot Campaign increased the power in the start of the laser drive to reduce hydrodynamic instabilities → experimentally confirmed

Rippled target
Hydro-growth radiography (HGR) target
X-ray snapshots

Lo-Foot vs Hi-Foot Growth factor at 650 µm

Mode Number

Optical Depth Growth Factor

Simulation
Low foot
High foot

Raman, Peterson, Smalyuk, Robey
High Foot\textsuperscript{1} experiments represent a seed change in performance – exhibiting significant alpha heating

\textsuperscript{1} O. Hurricane et al, Nature 506, 343–348 (20 February 2014)
Controlling instability with High Foot pulses lets us probe other parameters and obtain a 'derivative' in a complex parameter space.

Coast/No-coast

Increasing Energy

Au→DU hohlraums

Thinner ablators

Repeat?

DU higher drive

Thinner Au→DU

Full Quench

Yield from fuel compression

Yield from self heating

Energy delivered to fuel

Energy delivered to fuel

10
15
20
25
30

0
5
10
15
20
25
30

110608
110615
110620
110826
110904
110908
110914
111103
111112
111215
120126
120131
... Yield (kJ)
Clear progress on the road to ignition → challenges still remain.

DT yield vs ignition parameter $\chi$

- Ignition (G>1)
- Alpha-heating
- $E_{\text{required}}$

High Foot has demonstrated improved control over high-mode instabilities.

Ignition requires:
- Improved implosion symmetry
- Increased implosion velocity
- Increased hot spot compression

$\text{Energy for ignition} \sim \chi^2$
Clear progress on the road to ignition → challenges still remain

**Ignition requires:**

- **Improved implosion symmetry**
- Increased implosion velocity
- Increased hot spot compression

**DT yield vs ignition parameter \( \chi \)**

- Ignition (\( G > 1 \))
- Alpha-heating
- \( E_{\text{required}} \)
- \( \sim 3 \times E_{\text{DT}} \) (today, High Foot)
- \( \sim 10 \times E_{\text{DT}} \) (end of NIC, 2012)
- \( \sim 100 \times E_{\text{DT}} \) (start of experiments)

\[
P_{\text{stag}} \sim \frac{P_{\text{abl}}^{2/5}}{\alpha^{9/10}} \frac{v_{\text{imp}}^3}{\varepsilon}
\]

**Energy for ignition:** \( \sim \chi^2 \)

Low mode asymmetry control still needs to be improved.
Rugby hohlraums are currently under investigation to address implosion symmetry challenges.

Smooth beam coverage along hohlraum wall

50° Outers

44° Outers

He fill with 1.75% Ne Atomic
Clear progress on the road to ignition → challenges still remain

DT yield vs ignition parameter $\chi$

- Ignition (G>1)
- Alpha-heating
- $E_{\text{required}}$
- $3 \times E_{\text{DT}}$ (end of NIC, 2012)
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Ignition requires:
- Improved implosion symmetry
- Increased implosion velocity
- Increased hot spot compression

$P_{stag} \sim p_{abl}^{2/5} \frac{V_{imp}^3}{\alpha^{9/10}} \varepsilon$
Near-vacuum (low He gas-fill) hohlraums have reduced laser-plasma interactions and improved hohlraum efficiency.

- Increased drive temperatures: \( \Delta T_r > 20 \text{ eV} \)
  - Same laser energy leads to a higher temperature to drive the capsule

- Reduced backscatter

Near-vacuum hohlraums have also measured a 100x reduction in suprathermal electron generation.
Clear progress on the road to ignition → challenges still remain

DT yield vs ignition parameter $\chi$

Ignore requires:
- Improved implosion symmetry
- Increased implosion velocity
- Increased hot spot compression (reduced entropy/adiabat)

Ignition (G>1)

Alpha-heating

$E_{\text{required}} \sim 3 \times E_{\text{DT}}$
(todays, High Foot)

$\sim 10 \times E_{\text{DT}}$
(end of NIC, 2012)

$\sim 100 \times E_{\text{DT}}$
(start of experiments)

$P_{\text{stag}} \sim P_{\text{abl}}^{2/5} \frac{v_{\text{imp}}^3}{\alpha^{9/10}}$
Directed pulse shaping (“adiabat shaping”) is predicted to decrease adiabat (increase compression, $\rho R$) while preserving favorable stability.

We have begun exploring this concept through a series of focused experiments and recently, integrated DT layered implosions tests.
We are also exploring alternate ablator materials – Different benefits and different challenges

- **Si-doped CH** (1.1 g/cc)
  - Long pulse
  - Low $\rho$, lower absorbed E
  - Easily doped, fab’ed

- **W-doped HDC** (3.5 g/cc)
  - Short pulse
  - Ablator EOS?
  - Obtaining dopant level?

- **Cu-doped Be** (1.85 g/cc)
  - Intermediate pulse
  - Ablator microstructure?
  - X-ray preheat?
The high density of diamond (HDC) ablators may enable using near-vacuum hohlraums to reach significant alpha heating.

Implosions in near-vacuum hohlraums have been extended from short pulse, low convergence \(\rightarrow\) ignition-relevant, high convergence.

Symmetry control is an ongoing challenge.
Exciting progress on hohlraum and capsule performance depends on NIF’s unique and expanding suite of diagnostics.

**Viewfactors**
(2/3 hohlraum)

*Diagnose wall motion and drive spectrum*

**Dot Spectroscopy**
Time resolved spectrometer (NXS)

*Measure internal plasma temperature*

**Hohlraum plasma conditions**
Exciting progress on hohlraum and capsule performance depends on NIF’s unique and expanding suite of diagnostics

Native surface roughness ("Ultimate" HGR) hydro instability measurements

Divots

Ring

45-nm tent

Capsule implosion

DIXI (Dilation X-ray Imager) fast resolution (~10 ps) of burning core
We are developing a promising path forward with low mix, high velocity implosions and improving symmetry control to reach toward higher yields.

![Graph showing neutron yield and fuel r (g/cm²) with markers for high foot, low foot (NIC), HDC NVH, and adiabat shaped configurations.](image)