Overview and Status of the National Ignition Campaign on the NIF

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The National Ignition Facility

The capabilities of the laser, targets, diagnostics, and experimental platforms are now in place for the push to ignition.
The NIF project was completed in March 2009 and initial subscale experiments with 500 kJ to 1 MJ carried out with minimal diagnostics in Aug-Nov 2009 demonstrated LPI and radiation drive consistent with ignition in near ignition scale hohlraums.

NIF can now deliver 1.45 – 1.65 MJ, 420 TW of $3\omega$ light to the target chamber in an ignition pulse meeting ignition power balance requirements.

We will be able to deliver its full design energy and power of 1.8 MJ and 500 TW beginning in June.
December 2009 to September 2010 was devoted to installing major infrastructure and nuclear diagnostics: The CryoTarpos supports formation of cryogenic fuel layers outside the chamber prior to insertion into target chamber center at shot time.
THD fuel layers are formed with the target mounted in a dedicated cryogenic target positioner thermally isolated by a removable shroud.
A multi-laboratory effort in fabrication has given NIF the production capability for targets with unprecedented precision.

“Storm windows” were developed to cover the LEH in order to prevent condensation of residual chamber gas – one of the challenges in early cryo-layered targets.
Thirty types of diagnostic systems are planned for the National Ignition Campaign. Developing, installing, calibrating, and performance testing NIF’s 50+ diagnostic systems has been a major focus of the National Ignition Campaign (NIC).

One of two Dante soft X-ray Spectrometers
There are multiple time scales for the use and evolution of numerical models within the NIC.

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**Longer Term – Improvements to models**
- DCA for hohlraum and non-local thermal conduction now part of standard model
- Improvements to EOS, and NLTE for ablator now under development

**Updates to point design based on new data**
- Revisions to CH point design
- Updated ignition designs using alternate ablators (Be, HDC, B$_4$C, Al) and modified hohlraum geometry

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**Preshot using ab initio model prior to initial data**
- Specifications
- Playbooks
- Scenario Development
- Campaign Strategy – Sudoku

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**Data Modified Models**
- Data informed playbooks,
- Preshot – Expected performance informed by data
- Scenario development with models modified to match existing data
- Specifications modified by data

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**Near Term – Shot-to-shot during the Campaign**
- Postshot using as-shot conditions

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**Models**
- Equations
- Algorithms
- Databases
- Computers
Summary of Ignition Campaign Status

- We are one year into the campaign to carry out precision optimization of ignition scale implosions

- We have achieved hohlraum temperatures in excess of the 300 eV ignition goal with hot spot symmetry and shock timing near ignition specs

- Slower rise to peak power and longer “no-coast” pulses result in lower hot spot adiabat and main fuel $\rho r$ at about 85% of the ignition goal

- Nuclear data indicates that long wavelength variation in the main fuel density may be contributing to performance degradation

- Mix performance boundary with more mass remaining than the point design will require thicker shells (+20-30%) to reach ignition velocity without mix
Ignition Target designs have a number of general features

- Pure Au or U hohlraum with Au surface layer
- Laser Beams: 24 quads through each LEH arranged to control symmetry
- Capsule fill tube ~10 μm
- He fill to control symmetry and minimize LPI
- Capsule with low-z ablator (CH, Be, or HDC*) and cryo fuel layer
- Laser Entrance Hole sized to balance LPI and radiative losses – 56–60% of LEH diameter

*High Density Carbon
The initial ignition campaign is using a CH capsule

- Silicon doped layers reduce X-ray preheat at ablator-DT interface to make favorable Atwood number during acceleration to control mix
- Ablator thickness is adjusted to vary sensitivity to mix of fuel and ablator resulting from ablation front instability growth

- Amorphous material with no crystal structure issues
- Large data base from the Nova and Omega (LLE) lasers
- Reduced Facility impact relative to Be
- All of the diagnostics and infrastructure needed for optimizing ignition implosions are essentially independent of capsule ablator

Si-doped layers (2-4% peak)

~1110 µm

~195 µm

~70 µm THD
To achieve ignition, the NIC must generate the data needed to optimize the principal characteristics of an ICF implosion.

The NIC aggregates the impact of hundreds of actionable input variables into their impact on four key implosion input variables and assess performance by measuring improvements to the key compression variables.

1D quantities, e.g.:
- Peak Laser Power
- Foot Laser Power
- Shock timing

3D quantities, e.g.:
- Ice Perturbations
- Capsule Roughness
- Intrinsic Asymmetry
- Laser Power Balance ...

- Velocity (V)
- Hot spot Shape (S)
- Adiabat
- Mix (M)
- Total \( \rho R \)
- Hot spot \( \rho R \)
- \( T_{HS} \)

With the goal of alpha heating and burn to ignition.

- The key variables for ICF have been known for decades
- Since NIF was first proposed, we have worked to better quantify the specifications for ignition at the megajoule scale.
From September 2010 to April 2011, the NIC focused on validating a series of experimental platforms to optimize the capsule shape, adiabat, velocity, and mix.

**Adiabat**
- VISAR interferometry

**Velocity**
- X-ray Backlit Shell Trajectory

**Mix**
- Ge Spectra
- Soft X-ray Reemission

**Shape**
- X-ray or neutron core image
The National Ignition Campaign (NIC) is designed to generate the data needed for an optimal implosion in the most efficient sequence of experiments.

<table>
<thead>
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<tr>
<td>Growth factor</td>
<td>Mixcap</td>
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<td>Ge/Cu emission, YoC</td>
<td>THD</td>
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<td><strong>Control Parameters</strong></td>
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- Picket cone fraction
- Foot power, CF
- Pulse timing, 4th slope
- Peak cone fraction, α1,2
- Hohlraum length, LEH, Pointing
- Capsule ID, Au vs. U, Peak power
- Ablator thickness
- Capsule dopant %
- Ice thickness
We began precision optimization experiments in May 2011 and completed the first pass through all key variables in April 2012 with the first mix campaign.

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- The optimal sequencing was studied extensively prior to the start of experiments in the Red Team / Blue Team study.
- That sequencing has been largely validated in experiments although a few new experimental platforms have been added to those originally envisioned and others may be needed to achieve ignition.
We have achieved the ignition goal of $\text{Tr} > 300$ eV with coupling of 83–2% nearly independent of laser energy up to 1.6 MJ.

- 17% LPI losses are about twice what was anticipated prior to first experiments.
- Increased loss is consistent with improved understanding of the plasma conditions resulting from the implementation of the DCA NLTE atomic physics model and non-local electron transport which results in increased importance of multi-quad overlap effects on LPI.

9.43 mm by 5.75 mm Hohlraum, 3.1 mm LEH

**Peak Tr vs Absorbed Laser Energy**

- DU
- Au

**Absorbed Fraction vs Incident Laser Energy**

- Absorbed Fraction
- Incident Laser Energy (MJ)

- 0.75
- 0.80
- 0.85
- 0.90

- 1.1
- 1.2
- 1.3
- 1.4
- 1.5
- 1.6
- 1.7
Standard calculations overestimate laser entrance hole closure by about 20%.

Recent zoning studies indicate that much of this discrepancy could be numerical.

- Heating of the blowoff plasma by various plasma processes not included currently could help keep LEH open.

N120126, DT, Slow rise (3 ns) Au hohlraum, Large (3.375 mm) LEH Laser Energy_{LEH} = 1393 kJ

\[ D_{\text{data}} = 2.86 \text{ mm} \]
\[ D_{\text{sim}} = 2.59 \text{ mm} \]

Area Ratio = 1.22
When corrected for laser entrance hole size, calculations with the flux versus time needed to match implosion trajectories, match the Dante peak flux to about 4%.

- Standard calculations overestimate the measured Dante flux by about 8% on average — much of this difference may be explained by numerical zoning effects in calculations.
- Observed shell trajectories are consistent with about 4% less flux than observed on average — NLTE effects in the ablator are predicted but currently estimated to be small.
Measured fluxes corrected for the observed LEH closure provide the best estimate when comparing data to calculations of the hohlraum drive and capsule response.

- Measured Dante fluxes are ~8% lower on average than standard Hydra calculations — much of this difference may be explained by numerical zoning effects in calculations.
- Observed shell trajectories are responding as if the flux were about 4% less than Dante on average — NLTE effects in the ablator are predicted but currently estimated to be small.

Shot 120205

Dante/Calculated Peak Flux

- Standard Hydra Calculation
- Hydra Calculation modified to match measured implosion trajectory

Calculation which matches measured implosion trajectory (LEH corrected)

Shot 120205
Crossed laser beams in the hohlraum plasmas produce intensity modulations that drive density modulations.

• Density modulation (grating) produced in the plasma allows energy to be transferred between beams.

• Adjusting the wavelength shift between beams allows us to control energy transfer between cones.

• This process can work in both directions (into and out of the hohlraum).
Reemit Target sets the cone power ratio for the first 2 ns to ensure symmetric foot drive

**Experimental Geometry**

Bi sphere “Reemit” replaces layered capsule

Nov. 2010
0.7 keV X-ray images

Observable:
Limb brightness vs angle

2 mm
May 2011: Re-emit brightness set picket cone fraction to 1% in the Scale 544 hohlraums used before August 2011

- Experiments showed larger cross-beam transfer than estimated using saturation parameter from peak power
- Experiments are better matched with no saturation
Aug 2011: Re-emit confirmed expected lower inner cone fraction for Scale 575 hohlraum

P² Foot Picket Flux Asymmetry vs. Foot Inner Cone Fraction

Optimum CF decreased from 0.18 to 0.10 because outers closer to equator
Implosion symmetry at the peak of the laser pulse is achieved by tuning the wavelength of the outer cone.

First demonstrated in experiments at 500 kJ in 2009, tuning the $\Delta \lambda$ between inner and outer beams allows us to optimize implosion symmetry without changing the laser cone fraction.

$P_2/P_0 = -0.5$,
$P_4/P_0 = 0.3$

$P_2/P_0 = -0.07$,
$P_4/P_0 = -0.03$

P2/P0 = -0.5, P4/P0 = 0.3

P2/P0 = -0.07, P4/P0 = -0.03
Hot spot symmetry demonstrated in recent implosions is very close to the ignition specs

There is often a feature in the polar x-ray images which may be associated with fill tube

Symmetry at the peak of the pulse for shot 120205: 1.45 MJ pulse, 420 TW, 3 ns rise
Hot spot symmetry demonstrated in recent implosions is very close to the ignition specs

Time history of symmetry for shot 120205: 1.45 MJ pulse, 420 TW, 3 ns rise
Nuclear measurements indicate that the main fuel can have large $\rho R$ variations even when the hot spot appears quite symmetric.

FNADS (Flange Nuclear Activation Detectors) are Zirconium threshold detectors which measure the primary neutron yield.

- Some shots show significant signal variations (high $\rho R$ on poles) – on a typical shot with $\rho R \sim 1 \text{ g/cm}^2$ in DT, about 20% of the neutrons are downscattered, so a 10% variation in the measured primary yield corresponds to a 50% $\rho R$ variation (needs better calibration for required accuracy).

- $\rho R$ variations also indicated by Neutron Time of Flight (NTOF) and Magnetic Recoil Spectrometer (MRS) data.
We are developing imaging diagnostics which will give us improved shell-in-flight and compressed fuel measurements.

**Compton radiography – DT fuel at stagnation**

- 1e16 W/cm², 3ω
- 8 TW, 0.5 ns
- 30 μm tilted Au wire
- Imploded THD fuel scattering
- 60-200 keV
- 2 frames 40-80 ps Gated MCP

Demonstrated at OMEGA

**2D absorption radiography – shell in-flight**

- 10-15 keV
- 400 μm
- Time
- Simulated radiographs

Density during implosion

Simulated images Upgrade has 2 strips

Fuel density at stagnation

Contours of the shell show high level of ungated background.
The mirrored keyhole targets are used to optimize shock timing and velocity as well as the pole to waist asymmetry for all 4 shocks in the pulse.

Calculations show that asymmetric 2nd and 3rd shocks give rise to symmetry swings in the imploded core.
Shock asymmetries can lead to $P_2$ swings in core shape and fuel $\rho r$ nonuniformities

Example of measured THD core X-ray $P_2/P_0$ evolution near bangtime

Future: Check if reduced $P_2$ swings in final core compression phase
Mirrored keyhole experiments were used to improve the shock symmetry

**Before 2\textsuperscript{nd} and 3\textsuperscript{rd} cone fraction tuning**

- N110823 VISAR data

<table>
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<tr>
<th>Velocity (\textmu m/ns)</th>
<th>Time (ns)</th>
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<tr>
<td>100</td>
<td>13 14 15 16 17 18 19 20</td>
</tr>
<tr>
<td>10</td>
<td>13 14 15 16 17 18 19 20</td>
</tr>
</tbody>
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**2\textsuperscript{nd} and 3\textsuperscript{rd} shocks out of spec**

**After 2\textsuperscript{nd} and 3\textsuperscript{rd} cone fraction tuning**

- N111027 VISAR data

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**2\textsuperscript{nd} and 3\textsuperscript{rd} shocks in spec**
Swings in symmetry are reduced after 2\textsuperscript{nd} and 3\textsuperscript{rd} cone fraction optimization

\textbf{Before 2\textsuperscript{nd} and 3\textsuperscript{rd} cone fraction tuning}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{before.png}
\caption{N110904 DT}
\end{figure}

Large swing in P2 vs time

\textbf{After 2\textsuperscript{nd} and 3\textsuperscript{rd} cone fraction tuning}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{after.png}
\caption{N111029 THD}
\end{figure}

Modest swing in P2 vs time
The first tests of the impact of variations in the temporal shape of the peak power pulse changed the rate of rise to peak power.

4th pulse rise variation

Laser pulses

Keyhole target

VISAR streak

4th shock velocity

VISAR velocity data

1ns (fast)
2ns (nominal)
3ns (slow)

1ns (fast)
2ns (nominal)
3ns (slow)

Slower rise pulses are predicted to be less sensitive to fluctuations in drive in 4th rise.
As a result of these tests, we adopted the slower “3ns rate of rise” as the primary pulse shape through April 2012.
Backlit Capsule sets peak power and capsule ablator thickness (trading off velocity vs mix susceptibility)

Capsule backlit by x-rays from separate laser plasma

Until March 2012, implosion kinematics were measured using gated backlit radiography

9 keV gated radiograph

Technique measures shell radius, velocity, \( \rho R \) profile, and remaining ablator mass
In March, we activated streaked backlit radiography (3/24/12)

Capsule backlit by x-rays from separate laser plasma

Provides continuous record of ablator kinematics

9 keV streaked radiograph

- Self-emission
- Fiducial wire
- Ablator limb
- Explosion shock
- Time
- Radius

Zn foil
In March, experiments moved to longer “no-coast” pulse to avoid capsule decompression prior to stagnation.

Simulated capsule center of mass radius vs time

Radius and laser power for DU at 320 TW, 1.53 MJ

Previous laser pulse turns off before capsule fully committed

New longer, lower power prevents decompression, and maintains velocity
“No Coast” behavior: Ablator stays compressed by extending pulse out to $r = 300 \, \mu m$

Maintaining the drive prevents shell from decompressing -> higher stagnation pressure

No Coast core size is 13% smaller ~50% higher pressure
Feb-March 2012 Campaigns increased down scattered neutron ratio (dsr) \( \sim \frac{\rho R}{20} \)

Recent improvement attributed to reduction in coasting (longer laser pulse) and reduction in interface mix (2XSi dopant in ablator reducing preheat)
Fuel $\rho r$ is now at about 85% of the ignition point design but we need to increase yields a factor of 5-10 to get into the strongly self-heated regime.
We have developed a standardized approach for generating 1D capsule drives used in calculating cryo-layered capsule performance. This approach allows us to explore the incremental differences between the models and the data as we move through the implosion process and to correct for those differences as we move forward.

The radiation drive is modified so that the calculation matches the visar and Convergent Ablator Data.
When the drive is adjusted to match the keyhole data and the shell radius versus time, the remaining mass and shell thickness are also matched within the error bars.
Calculations of layered implosions with these modified drives match much of the observed data but typically over estimate yields by a factor of several.

- Calculations do not include the known 3D long wavelength asymmetry in the capsule, hohlraum, and laser power.
- 3D calculations to mode 100 are under development.

<table>
<thead>
<tr>
<th></th>
<th>DSR (%)</th>
<th>$P_0$ (µm)</th>
<th>$P_2/P_0$</th>
<th>HS pres. (Gbar)</th>
<th>HS den. (g/cm$^3$)</th>
<th>HS mass (µg)</th>
<th>$T_\text{ion}$ (keV)</th>
<th>neutrons ($10^{14}$)</th>
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<tbody>
<tr>
<td>1-D*</td>
<td>4.41</td>
<td>—</td>
<td>—</td>
<td>176.6</td>
<td>80.9</td>
<td>6.70</td>
<td>2.90</td>
<td>22.9</td>
</tr>
<tr>
<td>asym. only*</td>
<td>4.95</td>
<td>25.15</td>
<td>- 0.05</td>
<td>212.6</td>
<td>92.8</td>
<td>7.49</td>
<td>2.95</td>
<td>24.7</td>
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<tr>
<td>with tent &amp; roughness*</td>
<td>4.60</td>
<td>25.36</td>
<td>- 0.05</td>
<td>161.2</td>
<td>71.6</td>
<td>3.59</td>
<td>2.91</td>
<td>17.8</td>
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<tr>
<td>N120205</td>
<td>4.54</td>
<td>22.89</td>
<td>- 0.15</td>
<td>105.1</td>
<td>44.3</td>
<td>4.80</td>
<td>3.39</td>
<td>5.64</td>
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* with α particle momentum and energy deposition switched off
We have just completed the first iteration on a mix campaign.

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CH Ablation driven implosions follow a rocket curve which allows us to explore mix versus velocity

- Capsule drive in the simulations are adjusted to match the keyhole shock timing data and the convergent ablator radius versus time
- Data is estimated to have 1% less mass remaining at a given velocity than the 1D simulations
- We are exploring whether hydro instability in the imploding shell contributes to this difference
Calculations of the convergent ablator experiments are used to assess the velocity and remaining mass in cryo layered implosions.

- We find a mix performance boundary at 20-40% more mass remaining than that calculated for the point design.
We find a fairly sharp performance boundary with ~20-40% more ablator mass remaining than that for the point design.

DT Yield vs. ablator velocity or ablator mass left
195µm ablator (no-coast slow rise pulse)

Point Design
Mass Remaining
Implosions with coasting decompress and appear to have a mix performance threshold at lower mass remaining, but get much lower $\rho R$ and a lower fraction of 1D yield.

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![Graph showing DT Yield vs. ablator velocity or ablator mass remaining with NIF-0000-00000.ppt](attachment:NIF-0000-00000.ppt)
Increasing the yield a factor of 3-5 yield at the current velocity is a key element of upcoming experiments.

DT Yield vs. ablator velocity or ablator mass left
195µm ablator

- Yield deficit ~ 3-5X
- Low mode asymmetry? 1D hydro – adiabat?
- Residual Mix?
To get to the point design velocity, we need to increase velocity while keeping mass remaining “mix safe”

\[
V_{\text{imp}} \sim \sqrt{\left(\frac{Z\cdot T_r}{A}\right) \ln \left(\frac{M_0}{M_r}\right)}
\]

**Per Rocket Model:**
- +20% \(V_{\text{imp}}\), same \(M_r\):
  - +20-30% \(M_0\) (+40 to 60 µm)
  - +10% \(T_r\) (290 to 320 eV)

**Same DU hohlraum:**
- +40-50% Peak Power
  - (320 to 450-500 TW)
- +0.4-0.5 MJ (1.9 to 2 MJ)

- Improve capsules to reduce seeds
- Measure RT and RM growth to identify ways to reduce growth
- Reduce low mode asymmetry to minimize “thin spots” in fuel
Summary of Ignition Campaign Status

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- Nuclear data indicates that long wavelength variation in the main fuel density may be contributing to performance degradation

- Mix performance boundary with more mass remaining than the point design will require thicker shells (+20-30%) to reach ignition velocity without mix

These areas plus the temporal history of the main pulse will be the focus of ignition experiments moving forward
Inside of the NIF chamber: NIF is taking advantage of decades of ICF research to field a sophisticated array of diagnostics - 50+ systems currently collecting more than 300 channels of Optical, X-ray, and Nuclear data.