The Development of Indirect Drive ICF and the Countdown to Ignition Experiments on the NIF

Maxwell Prize Address
APS Division of Plasma Physics Meeting
November 15, 2007

John Lindl
NIF and Photon Science Directorate Chief Scientist
Lawrence Livermore National Laboratory

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344
The NIF ignition experiments will be the culmination of five decades of development which started with the invention of the laser in 1960

- Ted Maiman demonstrated the first laser in 1960
- John Nuckolls 1972 Nature paper spelled out the essential requirements for high gain laser driven ICF
- Indirect drive experiments started at Livermore in the mid-1970’s
- Dramatic advances in computations, lasers, diagnostics, and target fabrication over the past 3 decades laid the groundwork for NIF and the National Ignition Campaign (NIC)
- We are designing precision experimental campaigns for hohlraum energetics, shock strengths and times, implosion velocity and ablated mass, and symmetry, which will take 100-200 shots leading up to the first ignition attempts
- Targets near 1 MJ of laser energy have a credible chance for ignition in early NIF operations
- The initial ignition experiments only scratch the surface of NIF’s potential
Inertial Confinement Fusion uses direct or indirect drive to couple driver energy to the fuel capsule.

Indirect Drive:
- Low-z Ablator for Efficient absorption
- 10 mm

Direct Drive:
- Cryogenic Fuel for Efficient compression
- DT gas
- 2.5 mm

Spherical ablation with pulse shaping results in a rocket-like implosion of near Fermi-degenerate fuel.

Cold, dense main fuel (200-1000 g/cm³)
- 0.1 mm

Spherical collapse of the shell produces a central hot spot surrounded by cold, dense main fuel.

There are two principal approaches to compression in Inertial Confinement Fusion:
To illustrate the physics of ICF ignition, we compare a NIF capsule and a possible future high yield capsule.

### NIF capsule
- CH + 0.25% Br + 5%O
- DT solid (0.2 mg)
- DT gas 0.3 mg/cc
- 1.11 mm

### High yield capsule
- Be
- DT solid (7.2 mg)
- DT gas 0.3 mg/cm³
- 3.25 mm

<table>
<thead>
<tr>
<th>Property</th>
<th>NIF Capsule</th>
<th>High Yield Capsule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation temperature</td>
<td>300 eV</td>
<td>210 eV</td>
</tr>
<tr>
<td>Implosion velocity</td>
<td>4 x 10⁷ cm/sec</td>
<td>3 x 10⁷ cm/sec</td>
</tr>
<tr>
<td>Capsule absorbed energy</td>
<td>0.15 MJ</td>
<td>2.0 MJ</td>
</tr>
<tr>
<td>Capsule yield</td>
<td>~ 15 MJ</td>
<td>~ 1000 MJ</td>
</tr>
</tbody>
</table>
Ignition is defined as the point at which $\alpha$-particle deposition sustains the burn with no additional input of energy.

- About 15 kJ of energy is coupled to the fuel for compression and ignition of the 200 kJ NIF sized target.
- At 1 MJ of yield, 200 kJ of $\alpha$-particle energy is coupled to the fuel and it is well into the ignition region - definition of ignition adopted by 1996 NRC review of NIF.
- In ITER with a Q=10, $\alpha$-deposition is twice the external power needed to sustain the plasma.
Why do we believe that ignition will work on NIF?

- Over 3 decades of experiments on Nova, Omega and other facilities have provided an extensive data base to develop confidence in the numerical codes.

- Benchmarked numerical simulations with radiation-hydrodynamics codes provide a first principles description of x-ray target performance (Laser-plasma interactions are treated separately with codes which are now becoming predictive for NIF-relevant plasmas).

- “The Halite/Centurion experiments using nuclear explosives have demonstrated excellent performance, putting to rest fundamental questions about the basic feasibility to achieve high gain” from 1990 NRC review of ICF.
The first laser was demonstrated by Theodore Maiman in Malibu, CA, in May 1960.
John Nuckolls and John Emmett were central to the development of the LLNL ICF Program

John Emmett, who came to LLNL in 1972 was the driving force behind the development of the LLNL laser program.

Disk Amplifier Prototype from the mid 1970’s

John Nuckolls’ vision of small thermonuclear explosions, laid out in his seminal 1972 Nature paper, provided the motivation for an aggressive ICF Program.
Would you hire these people?

- George Zimmerman
- John Lindl
- Mike Campbell

Laser Programs
1978 Manpower Book
Ed Moses did not come to Livermore until the 1980’s but he would have fit right in during the 1970’s.
The first steps leading to indirect drive ignition with lasers took place in the mid 1970’s

- 1970’s: Radiation driven target designs provided a path forward for high gain ICF with relaxed laser beam quality and hydrodynamic instability compared to direct drive


—Cyclops was developed as a prototype beamline for Shiva
The 20 beam 10 kJ 1.06 μm Shiva laser was a major step forward in the scale and complexity of high energy laser systems.
Experiments on the Argus and Shiva lasers provided key results on achievable hohlraum temperatures.

- **1979-1981**: Shiva and Argus experiments show limits to radiation temperature from LPI and a path to $T_R > 200$ eV using frequency converted light ($2\omega$ and $3\omega$)

Hot electron fractions approached 50% in $1\omega$ hohlraums on Shiva.

Shorter laser wavelengths can dramatically reduce hot electrons for a given laser energy into a hohlraum.

$F_{R} = 1.0 - \int_{L}^{t_{c}} \frac{d\rho}{E_{\text{total}}}$

1% at $T_r = 130$ eV

30-50% at $T_r \sim 160-170$ eV
With Nova, the ICF program brought together advances in laser performance, precision diagnostics, and advanced modeling tools needed to establish the requirements for Ignition.
Plasma physics issues constrain the hohlraum temperature and hydrodynamic instabilities establish the minimum required temperature

“Bird’s beak” plot from 1990

Hohlraum physics acceptable below about 300 eV

High \( P_r, T_r, I_L \) \( \Rightarrow \) plasma instabilities

High vol \( \Rightarrow \) large \( \frac{R_o}{R_{\text{final}}} \) \( \Rightarrow \) symmetry

\( \Rightarrow \) large \( R/DR \)

\( \Rightarrow \) hydroinstability

Hydrodynamic instabilities determine the minimum temperature requirement
Experiments on the Nova laser demonstrated key target physics results needed for ignition

- 1985-1990: Nova experiments demonstrated key target physics requirements for laser driven high gain (pulse shaping, symmetry control, Rayleigh-Taylor stabilization by radiation ablation, \( T_R > 200 \text{ eV} \) with \( 3\omega \) light)

- 1990: 300 eV hohlraum temperature demonstrated on Nova led to a reduced scale ignition facility from the 5-10 MJ LMF to the 1-2 MJ NIF as recommended by the 1990 NRC review of ICF

- 1990’s Demonstration of precision control of laser driven hohlraums as required for ignition (Nova Technical Contract from 1990 and 1996 NRC reviews of ICF)
Advanced diagnostics have been central to measuring the phenomena critical to understanding NIF.

MCP gated imagers were operated between 100 eV and 10 keV with 5-50 µm, 30 -300 ps resolution.
The measured growth of ablative hydrodynamic instabilities in ICF agrees with numerical models.
Recently, we have been able to produce well characterized NIF-like plasmas on the Omega laser.

Plasma temperatures measured with Thomson scattering agree well with simulations.

A uniform 6% $n_e/n_{cr}$ plateau is produced between 0.5 and 1.0 ns.

Calculations of these Omega experiments provide evidence of a significant step towards meeting the grand-challenge of predictive modeling of LPI with pf3d.

- PS instantly reduces the contrast, suppressing the amplification from intense speckles
- The pf3D calculations took about 1 million CPU hours
The scale of ignition experiments is determined by the limits to compression.

- Pressure is limited to $P(\text{Max}) \sim 100 \text{ Mbar}$ by Laser Plasma Interaction (LPI) effects.

- Given the pressure limits, hydrodynamic instabilities limit implosion velocities to $V_{\text{imp}} < 4 \times 10^7 \text{ cm/sec}$

- Symmetry and pulse shaping must be accurately controlled to approach the maximum compression.

The graph illustrates the relationship between compression and capsule energy gain, with specific energy limits indicated at different pressure and stability requirements. The NIF marker indicates a specific point of interest in the context of these experiments.
National Ignition Campaign
NIF will provide a qualitative advance in ICF capability with >50X more energy and far greater precision and flexibility than any previous high energy laser facility.
NIF is a 192 beam laser organized into “clusters”, “bundles” and “quads”
The NIF Project is over 94% complete and 15 of the 24 1 µm laser bundles (120 beams) have been performance qualified.
1.8 MJ NIC ignition point design, energy, power, pulse shape & beam smoothing were achieved simultaneously (single beam)
A series of mirrors direct the beams to the target chamber

Mirrors break-up the "2-D" beam geometry into "3-D"
The NIF point design has a graded-doped, beryllium capsule in a hohlraum driven at 285 eV

- **Laser Beams** (24 quads through each LEH arranged to illuminate two rings on the hohlraum wall)
- **Cryo-cooling Ring**
- **Graded-doped Be Capsule** (CH and Diamond are alternates)
- **Solid DT fuel layer**
- **Laser Entrance Hole (LEH) with window**
- **Aluminum assembly sleeve**
- **Capsule fill tube**
- **Hohlraum Wall**: – U or U$_{0.75}$Au$_{0.25}$
- **Hohlraum Fill**: – He$_{0.8}$H$_{0.2}$ at 0.9 mg/cm$^3$
Precision target fabrication and assembly techniques being developed for the NIF meet the ignition target requirements
Gold-Uranium “Cocktail” Hohlraum meets specifications

Key Specifications:
- 7-micron-thick cocktail or depleted uranium layer
- Oxygen content less than 5 atomic percent
- “Shelf-life” greater than 2 weeks
Be Capsule meets specifications

Full Thickness Cu-Doped Be Shell

- 95% Dense
- Gas Impermeable

Power Spectral Density (PSD) of Polished and Unpolished Be Shells

Nikroo YO5-4 Friday
Ignition point design optimization must balance LPI effects, laser performance impacts, and capsule robustness.
Ignition point design optimization must balance LPI effects, laser performance impacts, and capsule robustness.

SSD and Polarization smoothing to be incorporated on NIF raises this threshold.

Design Optimum for initial ignition experiments.

Max allowed hot spot degradation fraction $\varepsilon = 0.2 \ 0.3 \ 0.4$

Initial operations

TR(eV)

Experimental lower limit for 1% scatter

285 eV Point design

225

250

270

300

Tang linear theory 10% scattering

nominal hot spot
Detailed calculations of NIF ignition targets present a number of computational grand challenge problems.
The Advanced Simulation Capability (ASC) computers are essential for a wide variety of 3D effects which impact NIF ignition targets

• Integrated hohlraum and capsule calculations - low spatial frequency perturbations (l=8 or less)
  — Hohlraum radiation flux asymmetry
  — Pointing errors
  — Power Imbalance
  — Capsule misplacement in the hohlraum
  — Hohlraum misalignment in the chamber
  — Missing beams or other off normal operation
  — Holes in the hohlraum or other inherently 3D structure

• Capsule only calculations - intermediate to high spatial frequency perturbations (l=10 to 1000)
  — DT ice roughness
  — Ablator roughness
  — Ablator microstructure

• Single Beam - Very high spatial frequency perturbations
  — laser wavelength and laser frequency scale features in the incident beam and in laser plasma interaction in the hohlraum
Resolving laser wavelength scale phenomena in the propagation of a laser beam in an ignition scale plasma is a grand challenge problem.

- "Letterbox" simulations capture the essential physics for "near 2D" situations, like a NIF hohlraum, “

- A letterbox run for 10’s of picoseconds using the code pF3D requires 8 Terabytes of memory and ~ 2.5M cpu-hours on the 8000 processor Atlas machine or ~ 15M cpu-hours on 32,000 processors of the 128,000 processor BG/L machine
Optimized 2D symmetry calculations meet the point design requirements

- The imploded fuel core shows very little residual angular variation from the NIF multi-cone geometry
Calculations with Hydra of the 300 eV point design show very little intrinsic 3D azimuthal asymmetry.

A 3D hohlraum calculation capable of resolving l=8 radiation asymmetry requires about 0.2M CPU hours.

3D calculations to assess the effects of power imbalance, pointing errors, capsule placement errors, etc are in progress.

Jones YO6-8 Friday
The ignition point design capsule is subject to hydrodynamic instability over a wide range of spatial scales

- Outer surface of the Be ablator - up to about mode 120 during the acceleration process
- Interface between Be and DT - up to about mode 1000 during acceleration
- Inner surface of the DT fuel - up to about mode 30 during deceleration to ignition conditions
Detailed 3D effects of capsule surface roughness are evaluated using HYDRA calculations.

- 3D radiation asymmetry is obtained from integrated hohlraum simulations.
- Nominal “at spec” capsule fabrication perturbations are applied on the DT ice and the ablator.

A full sphere covering modes 1-30 or an octant covering modes 4-120 requires about 170 million zones and ~ 4 million cpu hours on 4000 processors of the 10,000 processor 100 TFLOP purple machine.
Hydrodynamic instabilities at the capsule ablator-fuel interface are a particularly challenging problem.

- Calculations resolve instability growth in 3D, up to mode 1000, at the Be/DT interface.

- Benchmark calculations for a 4.5-9 degree wedge using the HYDRA Code require 44-176 million zones and 1-4 million CPU hours on 1000-4000 processors on the 10,000 processor, 100 TFLOP purple Machine.

Hammel PO6-3 Wednesday
The point design capsule of copper doped Be driven at 285 eV has been specified in detail.

(Cu doped Be shell for 285eV, 1.3 MJ)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Be(285) &quot;current best calc&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbed energy (kJ)</td>
<td>203</td>
</tr>
<tr>
<td>Laser energy (kJ)</td>
<td>1300</td>
</tr>
<tr>
<td>Laser energy (includes ~8% backscatter)</td>
<td></td>
</tr>
<tr>
<td>Coupling efficiency</td>
<td>0.156</td>
</tr>
<tr>
<td>Yield (MJ)</td>
<td>19.9</td>
</tr>
<tr>
<td>Fuel velocity (10^7 cm/sec)</td>
<td>3.68</td>
</tr>
<tr>
<td>Peak rhoR (g/cm^2)</td>
<td>1.85</td>
</tr>
<tr>
<td>Adiabat (P/P_{FD} at 1000g/cc)</td>
<td>1.46</td>
</tr>
<tr>
<td>Fuel mass (mg)</td>
<td>0.238</td>
</tr>
<tr>
<td>Ablator mass (mg)</td>
<td>4.54</td>
</tr>
<tr>
<td>Ablator mass remaining (mg)</td>
<td>0.212</td>
</tr>
<tr>
<td>Fuel kinetic energy (kJ)</td>
<td>16.1</td>
</tr>
</tbody>
</table>

Details in boxes are point-design specifics, not requirements.
A CH capsule at 300eV and 1.3 MJ is the principal alternate to Be at 285 eV

Post-processed hohlraum simulations at 300 eV indicate LPI equivalent to or better than Be at 285eV

Amorphous material with no crystal structure issues

Large data base from Nova and Omega

Less efficient ablator but at 1.3 MJ (&300eV), this target looks attractively robust. More work in progress.

Transparency makes cryo layer easier to characterize but low thermal conductivity makes layer formation in the hohlraum more challenging

<table>
<thead>
<tr>
<th>CH(300)</th>
<th>CH + Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Eabs</td>
<td>17.6 MJ</td>
</tr>
<tr>
<td>Implosion velocity</td>
<td>3.85 x 10^7 cm/s</td>
</tr>
<tr>
<td>Fuel mass</td>
<td>2.3 mg</td>
</tr>
<tr>
<td>Ablator mass</td>
<td>2.3 mg</td>
</tr>
</tbody>
</table>
We are also evaluating a nanocrystalline diamond ablator option at 270 eV and 1.3 MJ

<table>
<thead>
<tr>
<th></th>
<th>Diamond(270)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Eabs</td>
<td>24.7 MJ</td>
</tr>
<tr>
<td></td>
<td>260 kJ</td>
</tr>
<tr>
<td>Implosion velocity</td>
<td>3.58 x 10^7 cm/s</td>
</tr>
<tr>
<td>Fuel mass</td>
<td>0.27 mg</td>
</tr>
<tr>
<td>Ablator mass</td>
<td>5.26 mg</td>
</tr>
</tbody>
</table>

- Higher density: diamond absorbs energy at larger radius. Equivalent to 10 - 20% more laser energy.
- Ablator surface is very smooth. Can tolerate 20x the measured surface roughness.
- LPI analysis indicates 270 eV diamond hohlraum has less risk than Be hohlraum at 285eV
- Complex material properties during pulse shaping: Stays solid after 1st shock, melts with 2nd shock (Be melts with 1st)

1.3 MJ, 270 eV design

- Tube 10 µm SiO₂
- Hole 5 µm
- 1300 µm thick
- DT 61 µm thick
- C (Diamond) 3.51 g/cc
- DT gas 0.3 mg/cc
- DT solid at 18.3 K

Ho TI1-3 Thursday
Assessment of ignition targets utilizes computer calculations, coupled to planned precision target physics campaigns

- We are designing experimental campaigns for hohlraum energetics, shock strengths and times, implosion velocity and ablated mass, and symmetry, which will take 100-200 shots leading up to the first ignition attempts
- Most physics uncertainties will be normalized out with these “optimization” experiments (Residual physics uncertainties for these items are set by how accurately we can do the experiments - the point design specs include estimates for the achievable accuracy)
- Specifications on target fabrication and laser performance are set to achieve the required precision and reproducibility.
- Uncertainty in some physics issues such as DT thermal conduction and alpha particle deposition in Fermi degenerate DT will remain after these experiments

Our key question is not “How well can the codes predict the ignition target a-priori?”, but instead “Will the uncertainties and variability that remain after our tuning programs be acceptable?” This is a key focus of our preparations for ignition experiments
The National Ignition Campaign is focused on preparing for the first ignition experiments in 2010.

### National Ignition Campaign Timeline

<table>
<thead>
<tr>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>96 beams</td>
<td>Drive temperature $T_{\text{rad}}$ (Target scale, energy and focal spot size)</td>
<td>96 beams</td>
</tr>
<tr>
<td>Commission 96 more beams</td>
<td>Demonstrate symmetry, shock timing and ablation rate techniques at NIF scale</td>
<td>Hohlraum coupling with 192 beams for baseline target scale, energy &amp; $T_{\text{rad}}$</td>
</tr>
<tr>
<td>192 beams</td>
<td></td>
<td>Point design symmetry, shock timing, and ablation rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Integrated physics experiments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ignition campaign</td>
</tr>
</tbody>
</table>
The 96 beam campaign will utilize the 30° and 50° beams to emulate the ignition target.
The 96 beam emulators are scaled to preserve hohlraum energy density and per beam intensity.

300 eV
1 MJ, 192 beams)

96-beam Emulator at 70% scale

We use full-size phase plates, so the LEH is not scaled.

We test various $T_{\text{RAD}}$ ignition designs by changing only the laser pulse-shape.

Meezan YP8-38 Friday
The 96-beam scaled experiments closely match the ignition plasma conditions.

\[ \frac{n_e}{n_c} \text{ (max = 0.3) at peak power} \]
“Keyhole” targets to meet the shock timing requirements are one of the optimization targets which precede ignition experiments.
Accurate pulse shaping is a key to “1D” capsule performance

- Jump in fringe shift gives shock arrival
- Fringe position gives shock velocity
We are doing multivariable sensitivity studies to assess the margin and robustness of ignition target designs.

Hohlraum drive symmetry including effects of LPI and laser variability for long wavelength 3D performance.

Pulse shaping and capsule parameters for “1D” performance.

Hydrodynamic instability for shorter wavelength 3D performance.

Salmonson TI1-2 Thursday
We have identified 34 pulse shaping and capsule parameters that impact 1D capsule performance.

**Shock Timing Parameters**
- Shock Levels (4)
- Shock Times (4)
- Steepness of Final Rise (1)

**Capsule Parameters**
- Layer Thickness (7)
- Material Composition (8)
- Impurity Concentration (10)
In order to vary all parameters simultaneously, we incorporate a distribution for each:

- **Normal distribution** for complex physical processes such as shock timing and levels that will likely vary normally.
- **Top-Hat distribution** for fabrication specs such as capsule dimensions that can be measured and rejected.
We use ensembles of simulations to estimate the probability of ignition

Results of 10,000 runs varying all 34 1D parameters randomly within their respective distributions

Be at 1.3 MJ and 285 eV

95% have yield > 2 MJ
Statistical ensembles of 2D simulations include perturbations on all capsule surfaces

- All 1D parameters (dimensions, compositions, densities, drive parameters) sampled statistically
- Roughness for all 2D surfaces set “at spec,” phases varied randomly

**Be layer roughness**

\[
\text{Sqrt(Power)} = \text{rms roughness (nm)}
\]

Modes

![Diagram with Be layer roughness graphs and nominal hot spot image]
2D calculations provide an assessment of the impact of non-spherical effects

Results of 360 2D simulations (A statistical sample of 60 1D capsules with 6 random number seeds in 2D for each 1D point)

- ~85% above 1 MJ
- ~2/3 above 12 MJ
The 285 eV point design has a credible chance for ignition in early NIF operations.

Energy Margin = Target Energy divided by the minimum energy required for ignition

Point design capsule has a margin of 4.8 with all 1D parameters nominal and no 3D effects

Median V, entropy 3D at spec Margin 1.5

Ignition achieved for targets with Margin >1

Haan BP8-34 Monday
Clark TI1-1 Thursday
Ultimately, yields well in excess of 100 MJ may be possible on NIF.

Yields versus laser energy for NIF geometry hohlraums

- Potential NIF performance at $2\omega$ based on stored $1\omega$ energy
- Expected NIF performance at $2\omega$ with optimized conversion crystals and lenses
- Expected NIF performance at $3\omega$

Tr(eV) and Laser energy (MJ) graph:

- 200 eV
- 210 eV
- 225 eV
- 250 eV
- 270 eV
- 300 eV
- 0 eV
- 1 eV
- 2 eV
- 3 eV
- 4 eV

Band is uncertainty in hohlraum performance

2010-2011 experiments
Double shell indirect drive targets are a possible alternate for ignition

- Non-cryogenic
- Low radiation temperature relaxes LPI effects
- Fabrication to control mix is a major challenge
- Inherently limited to relatively low gain because most of the compressed mass is inert
NIF can explore direct drive or fast ignition as alternate approaches to ignition

**Polar Direct Drive**
- Direct Drive in the Indirect Drive Geometry
- Higher coupling efficiency than indirect drive
- Beam smoothing and implosion symmetry are major challenges

**Fast Ignition**
- Separate compression and ignition
- Potentially highest gain
- Short pulse physics is major issue
The NIF ignition experiments will be the culmination of five decades of development which started with the invention of the laser in 1960.

- Dramatic advances in computations, lasers, diagnostics, and target fabrication over the past 3 decades have laid the groundwork for NIF and the National Ignition Campaign (NIC).

- Experiments for hohlraum energetics, shock strengths and times, implosion velocity and ablated mass, and symmetry, will normalize out most remaining physics uncertainties.

- Targets near 1 MJ of laser energy have a credible chance for ignition in early NIF operations …when the required precision of target experiments, laser performance, and target fabrication is achieved.

Ignition is a grand challenge undertaking. It is likely to take a few years to achieve the required level of precision and understanding of the physics and technology needed for success.

- The initial ignition experiments only scratch the surface of NIF’s potential.