High-Energy-Density Science at the National Ignition Facility (NIF)

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Presentation to: MIT UROP
Jan 13, 2016

LLNL-PRES-718178
Outline

- National Ignition Facility
- Inertial Confinement Fusion experiments on NIF
- Discovery science experiments on NIF
- Diagnostic capabilities
- Summary
The National Ignition Facility is the world’s most energetic laser
NIF concentrates 192 laser beams (~10 kJ each at 351 nm) into a few mm$^3$ in a few nanoseconds

Matter
temperature $>10^8$ K
Radiation
temperature $>3.5 \times 10^6$ K
Densities $>10^2$ g/cm$^3$
Pressures $>10^{11}$ atm
We performed 416 shots in FY16 – shot rate has been increasing

- **Four major groups of users**
  - ICF
  - HED Stewardship Science
  - Discovery Science
  - National Security Applications

- **Developing the capability for enhanced data rate experiments**
  - 5 shots in 25 hours used to characterize x-ray and proton sources
  - 8 shots in 28 hours used to develop backlighter sources
  - More experiments enable a faster rate of learning, more exploration, and more users on the facility
Over 50 active target diagnostics enable cutting edge science on the NIF

- LLNL
- LANL
- LLE
- NSTec
- U of M
- LBNL
- MIT
- CEA
- Duke
- SNL
- GSI
- AWE

Number of active target diagnostics

Cumulative Diagnostic Count

- Nuclear
- Xray
- Optical

Year

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Active Target Diagnostics</th>
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<tbody>
<tr>
<td>2009</td>
<td>10</td>
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<tr>
<td>2010</td>
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<td>2012</td>
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<td>50</td>
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<td>2014</td>
<td>60</td>
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New diagnostics are needed to develop new insights and applications.

- Neutron and $\gamma$ Diagnostics
- Optical Diagnostics
- Diagnostic Support Systems
- X-Ray Diagnostics

- Yield, Tion, mix, rho-$r$, bang time, ...
- Hard x-rays >20 keV
  EHXI, FFLEX
- Soft x-rays .05 to 12 keV
  (Hohraum temperature)
- X-ray Imaging 5 to 100 keV
  1D, 2D, spectroscopy, bang time
NIF can reach a broad range of regimes for High Energy Density (HED) Science spanning ultra-dense-matter to high temperature plasmas. We now have the ability to study relevant physics in those regimes.
Indirect Drive Inertial Confinement Fusion (ICF) uses a hohlraum to convert laser energy to X-rays

- Hohlraum should provide
  - Spatial smoothing of the laser
  - Symmetric x-ray illumination of the capsule which results in uniform ablation of capsule
  - Temporal shaping of the X-ray drive resulting in an implosion with the required velocity and adiabat

![Diagram of hohlraum](image)

- Laser entrance hole (LEH)
- Plastic, Diamond or Be Ablator
- Gold hohlraum wall
- Helium gas
- Inner cone beams
- Outer cone beams
- Laser Pulse Shape

![Graph of laser pulse shape](image)
The capsule compresses DT fuel and creates a hot core

\[ \text{DT Shell} \]

\[ V \sim 2\pi R^3 P \]

\[ \frac{1}{2} M V^2 \varepsilon \sim 2\pi R^3 P \]

The hotspot is inertially confined by the assembled shell $\rho R$

Newton’s Law: $M \ddot{R} = 4\pi R^2 P$

For a thin shell: $M \approx \rho r 4\pi R^2$

For a massive shell: $\rho r \sim \rho R$

$$\tau \sim \sqrt{R/\ddot{R}} \sim \sqrt{\frac{\rho R}{P}} R$$

From earlier: $\frac{1}{2} M V^2 \epsilon \sim 2\pi R^3 P$

Combining together gives $P\tau \sim \epsilon^{1/2} \times \rho R \times V$

Ignition requires: high $V$, high compression $\rho R$, and high HS coupling $\epsilon$

Lawson criteria measures progress toward ignition
Current status $\chi_{\text{no-}\alpha} = P_t/P_{\tau_{\text{IGN}}} \sim 0.65$

- Quantities have alpha-heating off as a measure of implosion quality
Lawson criteria measures progress toward ignition
Current status $\chi_{\text{no-}\alpha} = P_{\tau}/P_{\tau_{\text{IGN}}} \sim 0.65$

- Quantities have alpha-heating off as a measure of implosion quality
- Implosions are grouped into high convergence $\sim 45$ and lower convergence $< 35$
- Lower convergence implosions have performed better – better hydrodynamic stability
- Experiments have since confirmed that these lower convergence implosions are more stable at the ablation front
We can plot an equivalent Lawson criteria in terms of measurable quantities for ICF: Yield X ρr

- Highest yield shots to date have significant alpha heating contribution ~ no-alpha yield
- Diamond (HDC) ablators are .85x scale
The first published measurements of high-\(\rho r\) came from the Magnetic Recoil Spectrometer, an MIT led diagnostic

**Assembly of High-Areal-Density Deuterium-Tritium Fuel from Indirectly Driven Cryogenic Implosions**

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(Received 15 December 2011; published 24 May 2012)

The National Ignition Facility has been used to compress deuterium-tritium to an average areal density of \(1.0 \pm 0.1 \text{ g cm}^{-2}\), which is 67% of the ignition requirement. These conditions were obtained using 192 laser beams with total energy of 1–1.6 MJ and peak power up to 420 TW to create a hohlraum drive with a shaped power profile, peaking at a soft x-ray radiation temperature of 275–300 eV. This pulse delivered a series of shocks that compressed a capsule containing cryogenic deuterium-tritium to a radius of 25–35 \(\mu\text{m}\). Neutron images of the implosion were used to estimate a fuel density of \(500–800 \text{ g cm}^{-2}\).

DOI 10.1103/PhysRevLett.108.215005
PACS numbers: 52.57.-z, 52.38.-r, 52.50.-b
Ignition on NIF requires convergence ~ 35 to reach ~350 Gbars and 1000 gm/cc

If nature were 1 D

\[ E_{\text{ignition}} \sim \rho R^3 T \sim \frac{(\rho R)^3 T^3}{P_{\text{stag}}^2} \]

But experiments are like this

Dense DT shell
~1000 gm/cc

Hot spot
100 gm/cc
5 keV

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

\[ P \sim 350 \text{ GB} \]

\~ .1 mm

Polar emission

NIS
Currently the conditions are ~ 2x from what is needed

Best performance on a single shot

Cold DT shell
~1000 gm/cc

Hot spot
100 gm/cc
5 keV
α redeposits energy

ρR ~ 1.5 g/cc
P ~ 350 GB

~ .1 mm

~500 gm/cc

~40 gm/cc
~ 5 keV

~.75 gm/cc
~ 200 GB
Two major factors currently believed to be limiting performance are hydro instabilities and drive symmetry.

Hydrodynamic instabilities seeded by capsule features: support & fill tube

Poor time-dependent control of x-ray flux symmetry from the hohlraum

Once these issues are addressed, there may be others that may have to be solved.
Hydrodynamic instabilities can cause mix and prevent efficient stagnation

Focused experiments needed to guide mitigations and improve models
Techniques and diagnostics are being developed to measure in all phases of the implosion

This will allow us to validate our understanding and modeling and guide mitigations

- Ablation front
  - acceleration phase HGR

- Ablator-ice interface
  - acceleration phase layered HGR

- Deceleration growth by self backlighting

- Measure mix at peak compression
  - Meteor imaging, spectroscopy
  - CD layers
In-flight x-ray radiography measurements of rippled spherical capsules allows experimental Rayleigh-Taylor growth factors to be compared with simulations.
Imaging a single limb of the capsule in the Hydro-Growth Radiography (HGR) target quantifies the $\rho R$ perturbation.

Removing the tent is still a work in progress. Several options being pursued and tested:

- Minimal wire support
- Supported fill tube

H. Robey, V. Smalyuk
Implosions using diamond ablators showed a prominent jet of material at the location of fill tube greater than predicted.
Radiographic measurements of the fill tube perturbation revealed an issue not captured in 2D simulations.

Radiographic image showing Rho-r variations in magnitude to fill tube.
Imaging the fill tube perturbation revealed an issue not captured in 2D simulations.

We are developing mitigations – smaller 5μ fill tubes, prepulse expansion.
Two major factors currently believed to be limiting performance are hydro instabilities and drive symmetry.

Hydrodynamic instabilities seeded by capsule features: support & fill tube

Poor time-dependent control of x-ray flux symmetry from the hohlraum

Once these issues are addressed, there may be others that may have to be solved.
Gas-filled hohlraums are complex environments

Inverse Bremsstrahlung Absorption (collisional absorption)
Thermal Conduction to walls

Walls expand inward and radiate X-rays
Capsules ablate and plasma expands outwards

Parametric instabilities cause
- Scattered light (200kJ backscattered)
- Hot electrons (preheat fuel)

Cross beam energy transfer is needed to transfer energy to inner beams in high gas fill hohlraums

Lower gas fills where laser plasma instabilities are low is the approach now being taken – challenge is plasma filling
Adding a little gas helps: looks promising for longer pulses needed for CH and Be, and appear to further reduce symmetry swings.

Gas-fill study

Best operating range?

In flight

Expt.
P0 = 158 μm
P2 = -10 μm
P2/P0 = -19%

Sim.
P0 = 156 μm
P2 = -7.5 μm

Stagnation

P0 = 67 μm
P2/P0 = -35%

Shape

LLNL-PRES-718178
Focused experiments are underway to measure the temperature and wall motion in gas fill hohlraums

- Ne,Te, flow in beam path & energy deposition
- Ne,Te, Z* gold bubble highly resolved spectra
- Gold bubble expansion and spot motion
- Bubble-capsule interaction

Allows us to compare in greater detail where models deviate
Ways to mitigate wall motion are being developed

Allows us to improve symmetry or use larger capsules and couple more energy

20 mg/cc Ta$_2$O$_5$ delays filling by ~1 ns
On approach to reduce to the impact of asymmetrical drive is to reduce the convergence of the implosion.
Recent experiments have demonstrated the ability to get symmetrical implosions with convergence ~ 25

Implosion of 80µm undoped diamond shell

- **P2 = 4 µm**
- **P2 = 5 µm**
- **P2 ~ 2 µm**

**Key results**
- Coupling remains high, very low LPI / hot electrons with intermediate gas fill (.6mg/cc He)
- Symmetric implosion, predicted by code (a~3, CR~20, v ~ 230 km/s)
- Predicted drive spectrum slightly too hard

We are also exploring lower convergence, higher adiabat implosions
Goals for IDI over the next 5 years

- Develop a near 1D implosion close to ignition space that is understood and predictable
  - Identify through measurements, issues and develop mitigations

- Slopes around that space that is understood and predictable

- Understand the key physics necessary for ID ignition
NIF can reach a broad range of regimes for High Energy Density (HED) Science spanning ultra-dense-matter to high temperature plasmas.

We now have the ability to study relevant physics in those regimes.
We are able to reach ~ Gbar shock pressures where ionization effects the equation of state.

<table>
<thead>
<tr>
<th>Density (g/cm³)</th>
<th>Pressure (Gbar)</th>
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<tbody>
<tr>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>0.001</td>
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</table>

**Quantum model**

- **Nova data**
- **Omega data**
- **Osaka data**

**Convergent single shock radiography**

- Neutron time of flight
- Thomson scattering
- X-ray Radiography
- Backlighter

**Gigabar Equation of State experiment**

Kraus, Swift, Doeppner, Kritcher, Falcone, et al.
NIF can reach a broad range of regimes for High Energy Density (HED) Science spanning ultra-dense-matter to high temperature plasmas.

We now have the ability to study relevant physics in those regimes.
The EOS of diamond (carbon) was measured by ramp compression up to 50 Mbar at NIF

Data show a significantly stiffer response compared to the isentrope

Previous solid state data

Velocity of several thicknesses + Lagrangian analysis -> $\sigma_x - V$

[Ray F. Smith et al., Nature 511, 330 (2014)]
The crystal structure of ramp-compressed carbon up to peak pressures of ~15 Mbar on NIF has been measured.
NIF can reach a broad range of regimes for High Energy Density (HED) Science spanning ultra-dense-matter to high temperature plasmas.

We now have the ability to study relevant physics in those regimes.
The NIF astrophysical collisionless shock experiment is seeing the beginning stages of shock formation.

Laser hitting the target
X-ray brightening from self-emission of hot plasmas

8 lasers ~4 kJ, 1 ns
Protons
D³He capsule
18 beams (~9 kJ, 1 ns, not shown)

8 lasers ~4 kJ, 1 ns

Self-generated proton imaging
(Self generated) X-ray imaging

PIC simul. of Weibel interactions
Omega exprmnt

Self-generated protons imaged with a pinhole onto CR39

[Courtesy of Hye-Sook Park, Youichi Sakawa and Steve Ross]

Astrophysical Collisionless Shock effort is a world wide collaboration

LLNL (USA)
H.-S. Park, D. Casey, F. Fiuza, C. Huntington, C. Plechaty, B. Remington, S. Ross D. Ryutov

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E. Liang, M. Levy

LULI (France)
M. Koenig, A. Ravasio

Yale University (USA)
D. Froula, G. Fiskel, P.-Y. Chang

University of Michigan (USA)
R. P. Drake, C. Kuranz, W. Wan

MIT (USA)
R. Petrasso, C. Li, A. Zylstra
Nine new NIF Discovery Science experiments have started in FY16

- Metastability of dynamically compressed C
  - Wark (Oxford)

- Iron melt curve, magnetospheres, and habitable Super Earths
  - Hemley (Carnegie)

- Pressure ionization at extreme densities
  - Neumayer (GSI)

- Direct-drive hydrodynamics
  - Casner (CEA)

- Self-similar instabilities
  - Shvarts (Israel)

- Charged particle stopping powers
  - Zylstra (MIT)

- Stellar and Big Bang nucleosynthesis
  - Gatu-Johnson (MIT)

- Magnetogenesis and B field amplification
  - Gregori (Oxford)

- Collisionless astrophysical shocks
  - Sakawa (Osaka)
New class of petawatt lasers have potential for accessing and probing high energy density conditions

- High intensity electric and magnetic fields are generated

\[ \frac{\varepsilon E^2}{2} = 1 \text{ Mbar} \]

\[ E \sim 10^{11} \text{ W/cm}^2 \sim \frac{e}{r^2} \]

Electric field in Bohr atom

\[ I \sim 3 \times 10^{15} \text{ W/cm}^2 \]

\[ \rightarrow \quad \text{Hot electrons} \quad \longrightarrow \quad \text{Ka X-rays} \]

\[ I \sim 10^{18} \text{ W/cm}^2 \]

\[ \text{quiver momentum} \quad \frac{m_e c}{1} \]

\[ I \sim 10^{19} \text{ W/cm}^2 \]

\[ \rightarrow \quad \text{Mev Bremstrahlung} \]

\[ I \sim 10^{20} \text{ W/cm}^2 \]

\[ \rightarrow \quad \text{Mev protons, 400 MG, pair production} \]
The Advanced Radiographic Capability (ARC) has been commissioned and the first experiments are being performed.

Currently 750 J per beamlet routine
Working towards 1.5kJ per beamlet
The first use of ARC will be to provide X-ray sources for radiography

X-ray radiography with ARC allows imaging of dense, high-z targets

- Material strength data
  - Sm
  - Ta ripples
  - Gated X-ray Detector

- Complex Hydro data
  - Ag

Compton scattering

- Imploded core scattering
  - ARC
  - 22 keV
  - 20µm Au wire

- AXIS
  - 75-200 keV

Data from a double shocked HDC sphere
We are investing in “Transformational” diagnostics that are at the resonance between the most compelling needs and the most promising technologies

<table>
<thead>
<tr>
<th>High Pressure Materials</th>
<th>Complex Hydrodynamics</th>
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<tr>
<td>Phase and structure</td>
<td>Meso-scale Hydro Instabilities</td>
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<tr>
<td>Time-dependent X-ray diffraction</td>
<td>Multi-layer Wolter</td>
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<tr>
<td>Strength</td>
<td>Mix Fraction</td>
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<td>Multi-layer Wolter</td>
<td>Time-Resolved $\gamma$ Spect</td>
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<tr>
<th>Ignition Applications and Burn</th>
<th>Radiation Transport, Opacity, &amp; Effects</th>
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<tr>
<td>DT gas Exploding Pusher</td>
<td>X-ray Source Formation</td>
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<td>Ice DT gas Ignition Capsule</td>
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<td>Time-resolved Burn</td>
<td>Localized Te/ne</td>
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<td>-vs. Energy</td>
<td>Optical TS</td>
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<td>Time-Resolved $n/\gamma$ Spect. – MRS (t)</td>
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<td>-vs. Space</td>
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<td>3-D $n/\gamma$ Imaging</td>
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<td>-Equilibration</td>
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<tr>
<td>High-Res X-ray Spect.</td>
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</table>
There is a multi-national effort in developing the next generation diagnostics on HED facilities

A new generation of diagnostics is needed to fully exploit our three marvelous HED facilities
This is a great time for HED science: experimental facilities, diagnostics, computational capabilities and challenging scientific questions to answer.

We VERY MUCH value the partnership we have with MIT on HED science.
High Energy Density Summer Scholar Program
2017

Seeking students with interest in plasma, hydrodynamic, nuclear, and spectroscopic physics associated with the study of matter under extreme conditions.

More information can be found: http://students.llnl.gov
Undergraduate and Graduate students can apply to Job ID 101685: http://careers-ext.llnl.gov
Contact Art Pak (pak5@llnl.gov) for more information

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344