Inertial Confinement Fusion (ICF) Program Update

Presented to:
NAS Meeting of the Board on
Physics and Astronomy

By:
Michael E. Donovan, Ph.D.
Acting Assistant Deputy Administrator for
Inertial Confinement Fusion and the NIF Project
National Nuclear Security Administration

April 25, 2008
Mission and Strategic Objectives of the ICF Program

Mission:
Provide the experimental capabilities and scientific understanding in high energy density physics to maintain a safe, secure, and reliable nuclear weapons stockpile without underground testing.

Strategic Objectives:
• Achieve thermonuclear ignition in the laboratory and develop it as a scientific tool for stockpile stewardship.
• Support execution of high energy density physics experiments necessary to provide advanced assessment capabilities for stockpile stewardship.
• Develop advanced science and technology capabilities that support the long-term needs of stockpile stewardship.
• Maintain a robust national program infrastructure and attract scientific talent to stockpile stewardship.
Key Points

- The nuclear weapon complex is undergoing major changes (Complex Transformation Office created within NNSA) that result in budgetary pressures within the program.

- Inertial fusion and high energy density physics are key elements of stockpile stewardship — High Energy Density Laboratory Plasma experiments (HEDLP) provide integrated test of advanced simulation codes.

- Highest priority for ICF Program is NIF completion and execution of ignition experiments (National Ignition Campaign) starting in FY2010.

- ICF Program is entering a scientific “golden age” with completion of the refurbished Z (2008), OMEGA EP (2008), and NIF (2009).

- NNSA/SC Joint Program in Laboratory High Energy Density Plasmas created in FY 2008 to steward HEDLP within DOE.

- NNSA is in process of implementing a policy to operate its major facilities as “Shared National Resources”.
NNSA’s Premier High Energy Density (HED) Facilities

• NNSA owns unquestionably the world’s preeminent HED capabilities that can achieve unprecedented progress in a broad range of science and technology in support of NNSA’s Stockpile Stewardship Program and broader national missions
• Access to these facilities is needed for the advancement of basic science and for training the next generation of stockpile stewards
The National Ignition Facility concentrates the energy in a football stadium-sized facility into a cubic millimeter.

<table>
<thead>
<tr>
<th>Conditions</th>
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<tbody>
<tr>
<td>Matter</td>
</tr>
<tr>
<td>Temperature  $\Rightarrow &gt; 10^8$ K</td>
</tr>
<tr>
<td>$\Rightarrow \approx 10$ keV</td>
</tr>
<tr>
<td>Radiation</td>
</tr>
<tr>
<td>Temperature  $\Rightarrow &gt; 3.5 \times 10^6$ K</td>
</tr>
<tr>
<td>$\Rightarrow +300$ eV</td>
</tr>
<tr>
<td>Pressures    $\Rightarrow &gt; 10^{11}$ atm</td>
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NIF Project Status

Total >4900 LRU's Installed

- Laser Bay 1: 100% (2259 LRU's Installed)
- Laser Bay 2: 100% (2289 LRU's Installed)
- Switchyard: 64% (112 LRU's Installed)
- Target Bay: 10% (139 LRU's Installed)

96% Overall Project Completion

Beamlines Activated

- Laser Bay 2: 144/192 Beams
- Laser Bay 1:

3.1 MJ 1ω Energy

99% Overall 1ω Commissioning (infrared laser light)
Achieved the pulse shape, beam uniformity, focal spot and SSD bandwidth required for ignition experiments up to 1.8 MJ
OMEGA EP integration is nearly complete and commissioning is scheduled for Q3 FY 2008

First joint shot in the OMEGA target chamber on 3/31/08, ~1 kJ with short pulse energy to OMEGA on 4/3/08
OMEGA EP will be a flexible HED research platform with short- and long-pulse capabilities.

<table>
<thead>
<tr>
<th>Performance capabilities</th>
<th>Short-pulse Beams</th>
<th>Short-pulse Beams</th>
<th>Long pulse (any beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse width</td>
<td>1 to 100 ps</td>
<td>1 to 100 ps</td>
<td>1 ns</td>
</tr>
<tr>
<td>Energy on target (kJ)</td>
<td>2.6 kJ, 10–100 ps</td>
<td>2.6 kJ, 80–100 ps</td>
<td>2.5 (UV)</td>
</tr>
<tr>
<td></td>
<td>grating limited &lt;10 ps</td>
<td>beam combiner limited &lt;80 ps</td>
<td>6.5 (UV)</td>
</tr>
<tr>
<td>Intensity (W/cm²)</td>
<td>$3 \times 10^{20}$</td>
<td>$\sim 2 \times 10^{18}$</td>
<td>$3 \times 10^{16}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$8 \times 10^{15}$</td>
</tr>
<tr>
<td>Focusing (diam)</td>
<td>&gt;80% in 20 $\mu$m</td>
<td>&gt;80% in 40 $\mu$m</td>
<td>&gt;80% in 100 $\mu$m</td>
</tr>
</tbody>
</table>
The Extended Performance (EP) addition will greatly enhance the capability of the OMEGA laser at LLE.

There are five primary missions.

1. Extend HED research capabilities with high-energy and high-brightness backlighting
2. Perform integrated advanced-ignition experiments
3. Develop advanced backlighter techniques for HED physics
4. Staging facility for the NIF to improve its effectiveness
5. Conduct ultrahigh-intensity laser–matter interactions research
Refurbishment of the **Z** Pulsed Power Generator at Sandia National Laboratories

- New Capacitors – Double Energy Storage
- New Laser Triggering System
- Maximize Utility of Diagnostics Infrastructure
- Update Charging & Triggering Systems
- Incorporate Modern Gas Switch Technology
- Modify Vacuum Stack for Higher Electrical Stress
- Electrically Optimize Pulse Forming Systems
- Incorporate Energy Diverter Systems
- Maximize Utility of Diagnostics Infrastructure
The refurbished Z will provide increased capability

Refurbishment of existing Z facility

- more shot capacity
- improved precision and pulse shape flexibility
- higher current capability
- minimum interruption to ongoing programs
- exercise SNL’s pulsed power research & engineering capabilities

<table>
<thead>
<tr>
<th>Capability</th>
<th>Z today</th>
<th>After Refurbishment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak load current reproducibility</td>
<td>± 5 %</td>
<td>± 2 %</td>
</tr>
<tr>
<td>Pulse shaping flexibility</td>
<td>Minimal</td>
<td>Significant Variability</td>
</tr>
<tr>
<td>Peak Current</td>
<td>18 MA</td>
<td>26 MA</td>
</tr>
<tr>
<td>Power Radiated (Nested Arrays)</td>
<td>230 TW</td>
<td>350 TW</td>
</tr>
<tr>
<td>Energy Radiated (Single Array)</td>
<td>1.6 MJ</td>
<td>2.7 MJ</td>
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</table>
The Z-Petawatt Laser System will provide new capability for diagnosing Z experiments

- Currently, the terawatt-class Z-Beamlet Laser (ZBL) creates a backlighting x-ray source in the 1-10 keV range on Z
- A petawatt-class enhancement, referred to as the Z-Petawatt (ZPW), is being constructed for:
  - New radiography options (X-ray radiography in the 10-40 keV range; Proton radiography)
  - Fast Ignitor fusion research on Z
- System operational in 2007 at 500 J/500 fs with Au gratings, ramping up to 2 kJ/500 fs with MLD gratings in 2009
Ignition is the Highest Priority of the ICF Program

In 2005 the ICF Campaign established an integrated, multi-site effort called the National Ignition Campaign (NIC) to focus programmatic activities on achieving ignition

NIC has two objectives:

1. Perform credible ignition experimental campaigns on the NIF beginning in FY 2010, and;
2. Transition NIF from project completion to routine operations supporting NNSA missions by FY 2013
National Ignition Campaign
NIC is formally managed by NNSA

- NIC is managed as an Enhanced Management Activity and includes a formal execution plan approved by NNSA
  - The execution plan describes the multi-year (beginning-to-end) scope, schedule, and budget baseline
  - NIC baseline is under formal change control and progress is monitored using an earned value management reporting process.
- ~85% of the ICF Budget is planned in the NIC

![Diagram showing laser energy, X-rays, capsule compression, and ignition process.](image)
Major elements of the National Ignition Campaign (FY06–FY12 Q1)

All must be in place for a credible ignition campaign
Major elements of the National Ignition Campaign (FY06–FY12 Q1)

All must be in place for a credible ignition campaign
Highest fuel areal densities achieved with cryogenic deuterium implosions on OMEGA

- Cryogenic deuterium implosion using a complex pulse shape
- By far, the highest areal densities measured in ignition-relevant laboratory implosions - very important for ICF ignition
- Fuel density achieved is more than adequate for ignition on the NIF

Achievement is a key precursor for “Ignition 2010 on NIF”
Z experiments measured the effects of fill tubes on ignition capsule implosions.

Agreement between data and simulations increases our confidence that perturbations from fill tubes will not be a problem for first ignition experiments.

Photo of CH capsule used in Z experiments showing 4 fill tubes (12-45 micron OD).

Radiograph at 6.151 keV at convergence ratio 1.5.

Comparison of experimental radiograph with simulations.

Agreement between data and simulations increases our confidence that perturbations from fill tubes will not be a problem for first ignition experiments.
The NIC is focused on preparing for the first ignition experiments in FY 2010.

**NIF Project CD4**

- Drive temperature $T_{rad}$ & technique validation (Scale 0.7)
- Tritium-free tuning
- Layered THD implosions
- Capsule Physics recovery
- 1st DT Ignition Implosions

**Timeline:**

- 2009: 96 beams
- 2010: 192 beams, Layered targets, Capsule Physics recovery
- 2011: 1st DT Ignition Implosions
- 2012: DT Ignition Implosions
The integrated NIF/NIC schedule is complex and aggressive

<table>
<thead>
<tr>
<th>FY07</th>
<th>FY08</th>
<th>FY09</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
</tr>
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<tbody>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
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**NIF**
- Facility Capability
  - NIF Project
    - Cluster Integrated Controls
  - NIF RA
    - Submit Final Safety Basis Document
- PEPS
  - Tritium MPR
  - Shield Doors
- Diagnostics
  - Optical/X-Ray Diagnostics
  - Implosion Diagnostics
  - Boost Physics Diagnostics
- User Optics
  - Phase Plates 1
  - Phase Plates 2
  - 2 x Optics Complete
- Cryogenics
  - Title II Design
  - ITIC on TARPCS
  - Manual Cryo Ready
  - Automatic Operations
  - Opposed Port Shroud Remover
- Target Fab
  - Start Pilot Production
  - Complete NIC Facilitation
  - Layered Target Demo
  - Omega/2/Trident/Trition/LIL Experiments
  - Start High Energy Drive Ignition Experiments
- Ignition Experiments
  - Start 99 beam experiments
  - Start 192 beam experiments
  - Start Ignition Experiments
- Experimental Campaigns
  - Start Radiation Transport Experiments
  - HED Experiments
  - First Data Available
  - First Hydro Results
  - Start High Z Results
  - Basic Science
The ICF Program is the engine for high energy density science

- Fusion Burn for Stockpile Stewardship
- HED Experiments (Materials, Hydrodynamics)
- Energy and Fundamental Science
Broadening access: the science community is critical to NIF’s success and its role in national security
NIF will support three national research agendas.
NIF’s Unprecedented Scientific Environments

- These are the conditions of Extreme Laboratory Astrophysics
  - $T > 10^8$ K matter temperature
  - $\rho > 10^3$ g/cc density
  - Those are both 7x what the Sun does!
    Helium burning, stage 2 in stellar evolution, occurs at $2 \times 10^8$ K!

- Core-collapse Supernovae, colliding neutron stars, operate at $\sim 10^{20}$ n’s/cc
  - NIF: $\rho_n = 10^{17}$ neutrons/cc

- These apply to Type Ia Supernovae!
  - Electron Degenerate conditions
  - Rayleigh-Taylor instabilities for (continued) laboratory study.

- Only need $\sim$Mbar in shocked hydrogen to study the EOS in Jupiter & Saturn
  - Pressure $> 10^{11}$ bar
An Academic Use of NIF Program has begun with 3 “Participating Research Teams”

- Each team is being provided seed funding
- Close collaboration with LLNL scientists established
- Experiments expected to begin in FY 2010

**Planetary Fluids at High Pressure**

Raymond Jeanloz, PI, UC Berkeley
Thomas Duffy, Princeton U.
Russell Hemley, Carnegie Inst.
Yogendra Gupta, Wash. State U.
Paul Loubeyre, Univ P/M Curie, CEA
POC: Rip Collins

**Astrophysical Hydrodynamics**

David Arnett, U. of Arizona,
Adam Frank, U. of Rochester,
Tomek Plewa, U. of Chicago,
Todd Ditmire, U. Texas-Austin
POC: Bruce Remington

**Laser-Plasma Interactions**

Christoph Niemann, PI UCLA NIF Professor
Chan Joshi & Warren Mori UCLA
Bedros Afeyan, Polymath
David Montgomery, LANL
Andrew Schmitt, NRL
POC: Bob Kirkwood
Importance of fundamental HED Physics has been recognized

National Academy/workshop reports

Plasma Science: Advancing Knowledge in the National Interest

May 2007

Office of Science/NNSA Joint Program in HEDLP

Federal response
LLE’s National Lasers Users’ Facility (NLUF) has been in operation since 1979

- 278 proposals
- 143 approved
- >90 Ph.D. students
Joint Program in High Energy Density Laboratory Plasmas (HEDLP)

- NNSA and Office of Science (OFES) have established a joint program in high energy density laboratory plasmas
- Purpose is to steward effectively this emerging field within DOE while maintaining the interdisciplinary nature of this area of science
- Program includes individual investigators, research centers activities, and user programs (NLUF)
- Other agencies may join in the future (NSF, NASA)

FY08 Funding in Dollars Thousand

<table>
<thead>
<tr>
<th></th>
<th>NNSA</th>
<th>OFFICE of SCIENCE</th>
<th>TOTAL</th>
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<tr>
<td></td>
<td>19,794</td>
<td>18,242</td>
<td>38,036</td>
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The Joint Program funds user facility programs, individual investigators, center research, grant and fellowships and sponsors research in areas such as fast ignition, laser plasma instabilities, magneto-inertial and heavy ion fusion, plasma jets, and warm dense matter
ICF Program is a multidimensional program with far reaching impacts and a promising future.
Summary points

• The nuclear weapon complex is undergoing major changes (Complex Transformation Office created within NNSA) that result in budgetary pressures within the program
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