Present Status and First Experiments on the National Ignition Facility*

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There are two principal approaches to compression in Inertial Confinement Fusion:

**Indirect Drive**
- Low-Z Ablator for Efficient absorption
- Cold, dense main fuel (200-1000 g/cm³)
  - Spherical ablation with pulse shaping results in a rocket-like implosion of near Fermi-degenerate fuel
  - Spherical collapse of the shell produces a central hot spot surrounded by cold, dense main fuel

**Direct Drive**
- Cryogenic Fuel for Efficient compression
- Hot spot (10 keV)
  - Inertial Confinement Fusion uses direct or indirect drive to couple driver energy to the fuel capsule
Optimization in ignition point design have reduced laser energy estimates from 1.8 to 1 MJ

Laser Beams in 2 rings (24 quads)

Cryogenic cooling rings

Capsule Be(Cu)

Solid DT fuel layer

8 mm

Laser Entrance Hole (LEH) with window + LEH shield

Capsule fill tube

Hohlraum Wall: - High-z mixture (cocktail)
- He gas (1 mg/cm³)
- or Low density foam (1 mg/cm³ SiO₂)

Hohlraum Fill

Be Capsule

<table>
<thead>
<tr>
<th>Tube 10 μm SiO₂</th>
<th>Hole 5 μm</th>
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<tbody>
<tr>
<td>Be + Cu</td>
<td>0 %</td>
</tr>
<tr>
<td>0.35 %</td>
<td>0.70 %</td>
</tr>
<tr>
<td>0.35 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>D-T gas</td>
<td>0.3 mg/cc</td>
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<tr>
<td>D-T solid</td>
<td></td>
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Summary

NIF

- NIF facility build is 80% complete, with 20% of optics installed, and eight 20 kJ $1\omega$ beams operational

Diagnostics

- Every type of optical and x-ray facility diagnostic successfully commissioned

Experiments

- A series of direct and indirect experiments using first four $3\omega$ beams exercised all existing facility capabilities and delivered new results

Future

- Activation of rest of NIF beams planned for 2008-2009, followed by activation of nuclear diagnostics and ignition attempt in 2010
NIF concentrates all the energy in a football stadium-sized facility into a mm³

**Laser Specifications**

192 Laser Beams

Energy $\Rightarrow$ 1.8 MJ

Power $\Rightarrow$ 750 TW
NIF is 80% complete
Process, assemble, and install over 5,700 line replaceable units (LRUs)

<table>
<thead>
<tr>
<th>Preamplifier Modules (48)</th>
<th>Laser Amplifiers (672)</th>
<th>Final Optics Assemblies (960)</th>
<th>Laser Mirrors (656)</th>
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<tbody>
<tr>
<td><strong>Spatial Filter Lenses</strong> (960)</td>
<td><strong>Spatial Filter Towers</strong> (72)</td>
<td><strong>Plasma Electrode Pockels Cell</strong> (192)</td>
<td><strong>Flashlamps</strong> (1008)</td>
</tr>
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</table>

1200 LRUs installed to date
Completed One Bundle of Eight Beams that Produced 152 kJ at 1ω

NIF is now the most energetic pulsed laser
2(ω) and 3(ω) beamline energies are highest ever achieved

11.4 kJ 2(ω), 5 ns

10.4 kJ 3(ω), 3.5 ns

NIF Completion Criteria as well as Functional Requirements and Primary Criteria have been demonstrated on a single beamline at 3(ω)
A wide range of pulse shapes have been produced: Haan Ignition Pulse

**Haan Ignition Pulse Shape (3ω)**

- **CR = 50:1**
- **Expanded**
NIF pointing requirement (<50 \mu m RMS) was demonstrated in June '04 Hydro Campaign

- 17 shot pointing deviation is 30 \mu m RMS
  — Better than NIF FR & PC pointing requirement of 50 \mu m RMS
NIF energy repeatability (<2% rms) supports power balance primary criteria

Hydro campaign shot energy histogram

8% RMS Functional Requirements and Primary Criteria

1.95% measured RMS

Beam Energy (J)

Measured RMS deviation of 1.95% is a small fraction of 8% power balance requirement
NIF can be used for both indirect and direct-drive ICF and High Energy Density (HED) Physics

Indirect drive ICF

Direct drive ICF

Indirect drive HEDS

Direct drive HEDS

E.g. EOS

E.g. Hydrodynamics

E.g. Material Strength
The success of first experimental campaigns was due to efforts of multiple integrated experimental teams encompassing multiple laboratories.
NIF commissioned a broad suite of optical and x-ray diagnostics for early experiments.

- **10 m Diameter NIF Target Chamber**
- **Diagnostic Insertion Module (DIM) Flexable x-ray imager**
- **Near Backscatter Imager**
- **FFLEX Hard x-ray spectrometer**
- **DANTE Soft x-ray temperature**
- **Static x-ray imager**
- **VISAR Shock Velocity**
- **Full Aperture Backscatter**

1st Quad up to 16 kJ, 8 TW 1-9 ns $10^{15}$-$10^{16}$ W/cm$^2$

Two Diagnostic Insertion Manipulators (DIM) installed for use on all NIF 1\textsuperscript{st} Quad campaigns

Using opposing port telescope, we aligned DIM-based instruments to 50 µm, 2x better than required
DIM-insertable hard or soft x-ray streak and framing cameras were essential to first campaigns.
NIF planar direct-drive experiment activated VISAR interferometer and demonstrated steady shock.

- Shock speed steady to 3%
- 15 Mbar
- 660 nm VISAR streaked data

Normal incidence drive

Target mounted mirror

NIF drive (1 quad)
1 mm CPP
We have demonstrated beneficial effects of beam smoothing on beam propagation in long scale low Z plasmas.

1 atm. CO$_2$ filled gas tube (7% $n_c$)

3.5 keV X-ray images of beam propagation
Filamentation / beam spray expected and observed
Filamentation and beam spray reduced

LASNEX ray tracing simulations including backscatter losses agree with data with PS and SSD

We expect similar benefits for ignition hohlraum plasmas


16 kJ in 3.5 ns; 2.5x10$^{15}$ W/cm$^2$
500 $\mu$m Phase-Plate (CPP) with and without 90 GHz SSD + Polarization Smoothing

CPP only
Data
CPP, PS, and SSD
An international team successfully activated hohlraum capability using NIF 1\textsuperscript{st} quad

**Plasma filling** (9 keV gated x-ray imaging), 84.4°

**Thin wall Au Hohlraum**

**Hot electron production** (FFLEX) 113°

**Hohlraum Temperature** (Dante) 21.6°

NIF Q31B
4 beams, 0.5 mm spot, 4-17 kJ, 2 - 9 ns, 1-3\times10^{15} \text{ W/cm}^2
w beam smoothing

8 channel, 20-120 keV, Absolute, time integrated

18 channel, 0.1-10 keV, Absolute, time resolved

Laser Backscatter (SBS and SRS) in lenses (FABS) and outside the lenses (NBI)
18 channel absolutely calibrated “Dante” power diagnostic measured 50 eV - 10 keV hohlraum spectrum

Measured and simulated Dante spectra at the end of the drive

Total flux divided by source size yielded a radiation temperature to 2-3% accuracy

Dante diode array – time resolved radiation drive

Filtered x-ray diodes

1.2 mm hohlraum
275 eV

Data + fit

2.4 mm, 151 eV

Post-processed LASNEX
A variety of vacuum hohlraums driven with 1 - 9 ns pulses demonstrated expected radiation temperature

Peak $T_{\text{RAD}}$ matches simulations within 2-3% Dante uncertainty. Negligible backscatter and hot electron fraction (< 1%) for all vacuum hohlraums < 300 eV.
For larger hohlraums, no evidence of volume emission due to plasma filling

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<tr>
<th>2.4 mm Hohlraum</th>
<th>16 kJ, 6 ns Flattop drive</th>
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<tr>
<td>T_R (eV)</td>
<td>GW/sr</td>
</tr>
<tr>
<td>250</td>
<td>40</td>
</tr>
<tr>
<td>200</td>
<td>30</td>
</tr>
<tr>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
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</table>

Filling minimal; Dante T_r ≈ internal T_r at all t

Data

9 keV X-ray images

1 mm

16 kJ, 6 ns Flattop drive

For larger hohlraums, no evidence of volume emission due to plasma filling.
However, signatures of plasma filling observed as predicted when hohlraum size decreased.

**2.4 mm Hohlraum**

- $T_R$ (eV) vs. GW/sr
- Dante
- LASNEX Dante
- LASNEX internal $T_R$
- $> 2$ keV
- 9 keV X-ray images
- Data
- Simulations
- Filling minimal; Dante $T_R \approx$ internal $T_R$ at all $t$

**16 kJ, 6 ns Flattop drive**

**1.6 mm Hohlraum**

- $T_R$ (eV) vs. GW/sr
- Dante view
- Signatures of plasma filling
- Data
- Simulations
- Filling important; Hard x-rays $\uparrow$, Dante $T_R \uparrow$, internal $T_R \downarrow$
When I.B. absorption length comparable to LEH radius $r$, *hydrodynamic* and *coronal radiative* losses out of LEH $\uparrow$ and internal $T_r \downarrow$

Plasma parameters from (J. Lindl 1995):
X-ray ablated plasma pressure = Laser channel pressure
Heat conduction loss = I.B. heating Hohlraum power balance

$T_r = 1.0 \frac{P_L^{0.2}}{r^{0.2}} t^{0.07}$

$\frac{E_L^{0.2}}{r^{0.2}} t^{0.27}$
The first quad of NIF was used to both drive and backlight hydrodynamic jets of astrophysical interest.

NIF met or exceeded experimental precision required:

- Relative drive beam / target alignment to 60 µm rms, exceeding 100 µm required
- Shot-to-shot beam energy to 4% rms, exceeding 7% required
- Smooth, flat spatial profile over 500 µm as required
To record the complicated flow, the 3D targets were imaged from orthogonal views.

Data used to validate new generation of 3D codes

A dual jet experiment explored the physics of interacting jets.

Equal Size Jets

Different Size Jets

Simulations predict no mixing between the jets, however the data suggests that they may...
NIF Project and NIF Ignition Campaign (NIC) culminate in ignition attempt in 2010 at 1 MJ laser energy

We have developed a self-consistent 150 shot ignition campaign shot plan for 2010 and a further 100 shot campaign for 2011.
A ignition experiment will use diagnostics with sensitive components located behind the 2-m thick concrete shield wall.

- Magnetic Recoil Spectroscopy (MRS), $T_{\text{ion}}$ and $\rho_r$, 6m (no vulnerable components)
- 10-20 keV core imaging, 20m
- $\gamma$-ray bangtime, 20m
- PROTEX, yield 20m
- Neutron Time of Flight $T_{\text{ion}}$ and $\rho_r$, 20m
- Neutron Imaging Hot spot and fuel asymmetry, 40m
- Activation, yield and $\rho_r$, ~30m
Advanced Radiographic Capability (ARC) using kJ-class short pulse NIF beams is also being developed.

- Stable, correctly phased and timed seed pulse generation
- Compression and diagnosis of amplified split beam pulses
- Precision split-aperture pulse generation and injection
- 20-1000 keV ps x-ray sources
- 10-100 MeV ps proton/ion sources

NIF could eventually support fast ignition capability.

Future
Vision: ARC 50 keV source for probing super-solid implosion plasmas by x-ray scattering

Compton Scattered spectrum = \( f(T_e, T_{\text{fermi}}) \), hence of fuel adiabat

- Multi-kJ, PW beam
- 57 keV Ta K\( \alpha \)
- CsI/CCD

Accessible supersolid plasma regime

\[ n_e \sigma_T \tau \approx 10^{26} \times 10^{-24} \times 0.01 \approx 1! \]


In addition, forward scattering would allow study of:
- Structure factors
- Collective plasmon modes

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