The Nuclear Diagnostic Suite for the NIF

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First NIF neutrons

NIF nTOF4.5-D2

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The installation of the nuclear diagnostics suite is underway at the National Ignition Facility

- The capabilities of the nuclear diagnostics were established by the requirement to tune target performance using the Ignition Threshold Factor – Edwards (O2.6.2)
  - Accurate fuel areal density is particularly important
- The primary instruments include:
  1. Neutron Time-of-Flight (nTOF) - this talk!
  2. Magnetic Recoil Spectrometer (MRS) – Frenje (O3.6.3)
  3. Gamma Reaction History (GRH) – Herrmann (O3.6.2)
  4. Neutron Imaging System (NIS) – Wilke (O3.6.1)
  5. RadioChemistry (RadChem) – Nelson (P10.061) and Grim (P10.065)
  6. Activation (NAD)
- The nTOF system will provide a comprehensive picture of target performance—primary yield, ion temperature, neutron bang time, and fuel areal density

The development of this instrumentation has been ongoing on OMEGA for nearly a decade.
The NIC ignition diagnostic effort has benefitted from international collaboration.

Major collaborations exist for most diagnostics.
There are only a few options available to measure the fuel areal density in DT implosions

1. **Externally** backlight (point-projection) the core and compressed shell using a high-energy petawatt-class laser

   - **“Petawatt” laser**
   - 5 kJ, 10 ps
   - High-energy x rays (~100 keV)
   - High-Z wire target
   - High-energy x-ray imager (HEXRI; LLNL)

2. **Internally** backlight the compressed shell using the fusion neutrons and additional fusion reactions

   - Dense fuel shell
   - Hot spot
   - n scattering in the fuel is proportional to $\rho R$
   - Multistep reactions in the fuel lead to the emission of a high-energy n whose yield is proportional to $(\rho R)^2$
   - (1) nTOF spectroscopy (LLE/LLNL)
   - (2) Magnetic recoil spectroscopy (MIT/LLE)
   - (1) $^{12}$C activation (LLE)
   - (2) nTOF spectroscopy (LLE/LLNL)
Much of the target performance can be inferred from the emitted neutron spectrum.

**Issues:**
- T+T fusion neutrons restrict the down-scatter “window” to 10 to 13 MeV.
- Tertiary neutron measurements require higher yields.
- Dynamic-range requirements (D$_2$ → THD → DT → IGN) means that different techniques are required to measure $Y_n$, $t_{bang}$, $T_{ion}$ and $\rho R_{fuel}$.
- Cross section uncertainties – (n,D), (n,T), (T+T).
- Energy-dependent detector sensitivities.
The neutron time-of-flight (nTOF) technique has been used to infer yield and ion temperature for decades. The bang time, yield, $T_{\text{ion}}$, and $\rho R$ can be inferred from the nTOF spectrum.

$T_{\text{ion}}$ to 3% accuracy at 4.8 keV implies $\Delta t$ accuracy to 360 ps at 4.5-m-high bandwidth, well characterized response and minimal background.

$\Delta t = 122 \times d \times \sqrt{T_{\text{ion}}}$
The requirements on the NIF nTOF diagnostic exceed what has been done in the past (NOVA/OMEGA)

- Yield: 7%–10% for $\text{D}_2/\text{DT}$ from $10^9$ ($\text{D}_2$) to $10^{19}$ (DT)
- Ion temperature: 3%–5% for THD/DT from $10^{11}$ to $10^{19}$
- $n$ bang time: $\leq 30$ ps for THD/DT from $10^{12}$ to $10^{16}$ (GRH up to ignition)
- $\rho R$ fuel: $\leq 10\%$ for THD/DT from $10^{12}$ to $10^{16}$ (MRS up to ignition)

First principles response models are being used to ensure the required measurement accuracy can be achieved.
The first of the NIF nTOF detectors has been installed in a 4.5-m diagnostic well.

The instruments in the diagnostic wells will be operationally qualified by end of 2009.
The high-yield and down-scatter fraction (DSF) nTOF detectors will be located outside the target bay.

Three lines-of-sight for neutron DSF measurements were shown to be adequate for the average $\rho R$. 
Independently calibrated yield diagnostics are being used to reduce the primary yield error at the NIF.

An independent Zr activation measurement is being developed to verify the calibration transfer from OMEGA to the NIF.

rms = 3.6%, average difference is 1.8%

Compare:
1. CEA Cu activation
2. LLE nTOFh
3. MRS (data added soon)
4. LLNL Protex
The calibration of the NIF nTOF 4.5-x detectors will be complete in a matter of weeks.

Signal integral (pC) vs. NIF-equivalent neutron yield

Calibration includes response characterization for \( T_{\text{ion}} \) as well as \( n \) sensitivity for primary yield.

These detectors will be used for primary yield, \( T_{\text{ion}} \), and \( n \) bang time for the THD campaign next spring/summer.
The nTOF4.5-BT consists of 3 CVD diamond detectors with a range of sensitivity.

Even though the impulse response is hundreds of picoseconds, the bang time can be determined to within a few tens of picoseconds.
Tests of nTOF 4.5-BT detectors at 4.5-m on OMEGA demonstrated sub-10-ps precision

Four CVD detectors: 2× CVD16 × 1 mm and 2× CVD10 × 1 mm were tested 4.5-m from TCC with DT yields from $9.3 \times 10^{12}$ to $3.0 \times 10^{13}$

The bang time precision is given by $\frac{\Delta t}{\sqrt{\# \text{n's}}} \Rightarrow \sim 30 \text{ ps}$ for THD yields

Additional experiments have shown that the temporal calibration technique used on OMEGA (100-ps x-ray pulses from a gold-coated sphere) will work at the NIF.
The design and fabrication of NIF nTOF20-IgnLo and IgnHi detectors is completed; calibration is underway.

4× PMT’s mounted around the scintillator comprises nTOF20-IgnLo

BC422 scintillator

4× CVD detectors mounted on the back of the IgnLo housing comprises IgnHi

Filter glass

Calibration setup for nTOF20-IgnLo
The four CVD diamond detectors for nTOF20-IgnHi are being calibrated now

The OMEGA yields are scaled to the equivalent yield at 20 m in the NIF

Signal integral $V$ (ns)

NIF-equivalent neutron yield

Shot 49600, DT, $Y_n = 2.9 \times 10^{13}$

Least sensitive detector

2 mm × 2 mm Black diamond*

E6, $\varnothing$ 10 mm × 1 mm
E6, $\varnothing$ 1 mm × 0.3 mm
E6, $\varnothing$ 5 mm × 0.25 mm
Black diamond

*Applied Diamond, Inc.
E6 = Element Six
A new liquid scintillator without a long decay component is being tested for nTOF20-Spec ($\rho R$ from the DSF)

$O_2$ saturation quenches the long decay component by a factor of $\sim 100 \times$ for the relevant $n$ time-of-flights

A comparison of the x-ray response from 10 ps, 1 kJ in gold cone-in-shell targets

This is the first measurement of neutron yield from OMEGA fast ignition targets!
The design of the liquid-scintillator–based nTOF20-Spec is complete

- 2× units will be manufactured for the NIF; 1× unit for OMEGA

Metal bellows expansion for pressure relief

Fused silica windows

Photek PMT 140 Gain E3

Photek PMT 240 Gain E6

Filter glass

4-in.-diam × 1-in.-thick stainless steel cavity filled with Xylene

The calibration of this detector will begin in early October.
The installation of the nuclear diagnostics suite is underway at the National Ignition Facility

Summary/Conclusions

The capabilities of the nuclear diagnostics were established by the requirement to tune target performance using the Ignition Threshold Factor – Edwards (O2.6.2)

– Accurate fuel areal density is particularly important

The primary instruments include:

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6. Activation (NAD)

The nTOF system will provide a comprehensive picture of target performance—primary yield, ion temperature, neutron bang time, and fuel areal density

The development of this instrumentation has been ongoing on OMEGA for nearly a decade.
The NIF nTOF suite consists of 18 detectors and multiple technologies.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Standoff</th>
<th>Technology</th>
<th>No.</th>
<th>Campaign</th>
<th>Yield range</th>
<th>Meas.</th>
<th>Abs accuracy</th>
<th>Rel accuracy</th>
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</thead>
<tbody>
<tr>
<td>nTOF-BT</td>
<td>4.5 m</td>
<td>CVD diamond</td>
<td>3</td>
<td>THD/DT</td>
<td>$10^{12}$ to $10^{16}$</td>
<td>$Y_n, T_{ion}$</td>
<td>$\pm8%, \pm5%$</td>
<td>$\pm8%$–$10%$, $\pm3%$–$5%$</td>
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<tr>
<td>nTOF-D2</td>
<td>4.5 m</td>
<td>BC-422 + GPMT 40 × 20 mm</td>
<td>1</td>
<td>D2</td>
<td>$10^9$ to $5 \times 10^{11}$</td>
<td>$Y_n, T_{ion}$</td>
<td>$\pm15%$, $\pm5%$–$10%$</td>
<td>$\pm5%$–$10%$, $\pm5%$–$10%$</td>
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<tr>
<td>nTOF-DTLo</td>
<td>4.5 m</td>
<td>BC422Q + GPMT 40 × 10 mm</td>
<td>1</td>
<td>D2</td>
<td>$10^{10}$ to $5 \times 10^{12}$</td>
<td>$Y_n, T_{ion}$</td>
<td>$\pm10%$–$15%$, $\pm5%$</td>
<td>$\pm5%$, $\pm5%$</td>
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<tr>
<td>nTOF-DT</td>
<td>4.5 m</td>
<td>CVD diamond 10 × 1 mm</td>
<td>1</td>
<td>DT, THD</td>
<td>$10^{13}$ to $5 \times 10^{14}$</td>
<td>$Y_n, T_{ion}$</td>
<td>$\pm8%$, $\pm3%$</td>
<td>$\pm3%$, $\pm3%$</td>
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<tr>
<td>nTOF-IgnLo</td>
<td>~20 m</td>
<td>Scint + GPMT/PD 40 × 20 mm</td>
<td>4</td>
<td>Ignition</td>
<td>$10^{12}$ to $2 \times 10^{19}$</td>
<td>$Y_n, T_{ion}$</td>
<td>$\pm8%$–$10%$, $\pm3%$–$5%$</td>
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<tr>
<td>nTOF-IgnHi</td>
<td>~20 m</td>
<td>CVD diamond</td>
<td>4</td>
<td>Ignition</td>
<td>$1 \times 10^{15}$ to $2 \times 10^{19}$</td>
<td>$Y_n, T_{ion}$</td>
<td>$\pm7%$–$8%$, $\pm3%$</td>
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<td>nTOF-Spec Equatorial</td>
<td>~20 m</td>
<td>Liq scint + GPMT</td>
<td>2</td>
<td>THD</td>
<td>$10^{12}$ to $10^{15}$</td>
<td>$Y_n, T_{ion}$</td>
<td>$\pm7%$–$8%$, $\pm3%$–$5%$</td>
<td>$\pm3%$, $\pm3%$</td>
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<td>nTOF-Spec Alcove</td>
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<td>Liq scint + GPMT</td>
<td>2</td>
<td>THD</td>
<td>$10^{12}$ to $10^{15}$</td>
<td>$Y_n, T_{ion}$</td>
<td>$\pm7%$–$8%$, $\pm3%$–$5%$</td>
<td>$\pm3%$, $\pm3%$</td>
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</table>

First principles response models are being used to ensure the required measurement accuracy can be achieved.
The diagnostic suite for THD/DT was defined in December 2008

### Phase I

<table>
<thead>
<tr>
<th>Performance</th>
<th>Yield</th>
<th>( T_{HS} )</th>
<th>( \rho R_{HS} )</th>
<th>( \rho R_{total} )</th>
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<tbody>
<tr>
<td>nTOF-BT</td>
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<td>nTOF-D(_2)</td>
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<td>MRS</td>
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<td>R&amp;D</td>
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<td>hSXD</td>
<td>R&amp;D</td>
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<td>GRH</td>
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### Phase II—to be added in FY11 or FY12

<table>
<thead>
<tr>
<th>What went wrong?!</th>
<th>( t_{bang} )</th>
<th>( \text{Shape}_{HS} )</th>
<th>( R_{HS} )</th>
<th>( \text{Shape}_{fuel} )</th>
<th>( R_{fuel} )</th>
<th>( t_{burn} )</th>
<th>( \text{HS mix} )</th>
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What went wrong?!