Diagnosing Implosion Performance at the NIF by Means of Neutron-Spectrometry and Neutron-Imaging Techniques

Presentation to
24th IAEA Fusion Energy Conference
San Diego, CA, USA
October 8-13, 2012

Johan Frenje on behalf of the NIF team
Massachusetts Institute of Technology
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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
The neutron data have been essential to the progress of the experiments on the NIF

- The neutron-spectrometry data indicate that the tuning campaigns have improved the implosion performance by $\sim 50\times$ since the 1st shot in Sept 2010.

- We have achieved a radial convergence of $\sim 35$, fuel $\rho R$ values up to $\sim 1.3$ g/cm$^2$, and inferred hot-spot pressures up to $\sim 150$ Gbar.

- The maximum pressure is $\sim 2\times$ lower than point design, and the observed neutron yields are $3-10\times$ lower than expected.

- The pressure and yield deficits are most likely explained by higher than predicted fuel-ablator mix and $\rho R$ asymmetries often observed in the implosions.

- A path forward to address these issues has been defined.
The neutron spectrum is used to diagnose neutron yield \( Y_n \), ion temperature \( T_i \) and areal density \( \rho R \).

**Primary neutrons (n):**
- \( Y_n \)
- \( T_i \) \( T_i \propto \Delta E_D^2 \)
- Residual kinetic effects

**Scattered neutrons (n’):**
- \( \rho R \) \( \rho R \propto \frac{Y_n'}{Y_n} = dsr \)

\[ \rho R (g/cm^2) \approx 21 \times dsr_{10-12\ MeV} \]

Measurement of the detailed shape of the low-energy part of neutron spectrum provides 3D information about implosion.

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1) J.A. Frenje et al., these proceedings; to be submitted to Nucl. Fusion.
Primary and scattered neutrons are imaged to diagnose neutron-source size ($R$) and thickness of high-density shell ($\Delta R$), resp.

**Images of neutron source and high-density shell**

High-density Shell ($\Delta R$)

Neutron source ($R$)

**Primary neutrons ($n$):**
- $R$ of neutron source

**Scattered neutrons ($n'$):**
- $\Delta R$ of high-density shell
Several neutron spectrometers and an imaging system have been fielded at various locations on the NIF.

This provides good implosion coverage for reliable measurements of $Y_n$, $T_i$, $\rho R$, and $\rho R$ asymmetries.

M. Gatu Johnson et al., RSI (2012).
F.E Merrill et al., RSI (2012).
Spectra and images are now measured routinely on the NIF (Example: DT shot N120205)

**Shot N120205**
- Neutron yield: \( Y_n = (5.6 \pm 0.2) \times 10^{14} \)
- \( \rho R = 900 \pm 40 \) mg/cm\(^2\)
- Target ion energy: \( T_i = (3.4 \pm 0.1) \) keV

**Neutron images**
- Single-scattering
  - Primary peak (unscattered)

**Neutron spectrum**
- Single-scattering
  - Primary peak

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The spectrometry data indicate that the tuning campaigns have improved the implosion performance by $\sim 50 \times$ since Sept 2010.

### Implosion performance$^1$:

$$ITFx \approx \left( \frac{Y_n}{3.2e15} \right) \left( \frac{\rho R}{1.47} \right)^{2.3}$$

### Lawson-type parameter$^2$:

$$\frac{E_\alpha}{E_{\text{losses}}} \approx \sqrt{ITFx}$$

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$^2$ R. Betti et al., OV/5-3
Spectrometry and imaging data self-consistently indicate that the tuning campaigns have improved the convergence by $\sim 2\times$.

\[ \frac{\Delta R}{R} = 0.49 \pm 0.16 \]

(fit to all neutron-imaging data)

Sept 2010 $R^2$ data inferred from x-ray images.
Inferred hot-spot pressure is $\sim 2\times$ lower than point design, and yields are $\sim 3-10\times$ lower than predicted.

Untuned 09/10 – 02/11
Symmetry 11/11 – 12/11
Shock timing 06/11
Mix/No Coast 03/12 – 07/12
Velocity 08/11 – 09/11

What’s causing this pressure and yield deficit?

1) P. Springer et al., IFSA (2011).
The pressure and $Y_n$ deficits can be explained partly by larger than predicted CH-ablator mixed into the hot spot.

Untuned 09/10 – 02/11
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The higher-convergence implosions display more mix, which reduces $T_i$ and $Y_n$. Other data indicate that the “mix-performance cliff” occurs at a remaining shell mass that is ~30-40% larger than the point design.
The $Y_n$ and pressure deficits can also be explained partly by the systematic low-mode $\rho R$ asymmetries often observed.

Neutron measurements of un-scattered neutrons also indicate similar low-mode $\rho R$ asymmetries.
When using the 6-10 MeV range, Spec-E and Spec-A nTOFs probe similar portion of the implosion, and provide similar $\rho R$ values.

Neutron measurements of un-scattered neutrons also indicate similar low-mode $\rho R$ asymmetries.

Johan Frenje – IAEA 2012
Need to address the observed higher-than-predicted levels of mix and low-mode $\rho R$ asymmetries

- Understand the origin and structure of mix and low-mode $\rho R$ asymmetries.

- Lower CR implosions (more 1D) should be examined and understood to improve the modeling capabilities before conducting the high CR implosions necessary for ignition.

- Engineering solutions and new diagnostic capabilities need to be implemented:
  - Implement in-flight 2D x-ray radiography of the ablator.
  - Implement in-flight Compton radiography of the fuel.
  - Implement a new nTOF-neutron spectrometer for probing $\rho R$ on the south pole.
  - Reduce size and/or patch up diagnostic holes and star burst, and reduce diameter of the fill tube to improve drive symmetry.
The neutron data have been essential to the progress of the experiments on the NIF

- The neutron-spectrometry data indicate that the tuning campaigns have improved the implosion performance by ~50× since the 1st shot in Sept 2010.

- We have achieved a radial convergence of ~35, fuel $\rho R$ values up to ~1.3 g/cm², and inferred hot-spot pressures up to ~150 Gbar.

- The maximum pressure is ~2× lower than point design, and the observed neutron yields are 3-10× lower than expected.

- The pressure and yield deficits are most likely explained by higher than predicted fuel-ablator mix and $\rho R$ asymmetries often observed in the implosions.

- A path forward to address these issues has been defined.
In contrast to the 10-12 MeV dsr data, the 6-10 MeV dsr data show no \( \rho R \) asymmetries
A single scattering model cannot explain the low-energy neutron spectrum in high-$\rho R$ implosions

MRS data for Cryo DT, Nov. 12, 2011

$\rho R$ asymmetries and multiple scattering may be important at energies below $\sim9$ MeV, and will be considered
Neutron spectrum simulations indicate that multiple scatter is important in high $\rho R$ implosions.

More sophisticated analysis of the neutron spectrum is currently being developed.
The MRS measures the neutron spectrum, using the recoil technique combined with a magnetic spectrometer.

\[ E_d \approx \frac{8}{9} E_n \cos^2 \theta_{nd} - \frac{1}{\cos \varphi_r} \int_{x_0}^{t_f} \frac{dE(E_d)}{dx} \, dx \]

The background in the $dsr$ region is determined from DT exploding pushers, then subtracted to get $dsr$ for DT cryo shots

Cryo DT, Nov. 12, 2011

DT Exp Push, Nov. 21, 2011

$dsr = 4.8\pm0.4\%$
$T_i = 3.49\pm0.40$ keV
$T_i = 5.68\pm0.64$ keV

$dsr = 3.9\pm0.2\%$
$T_i = 3.53\pm0.38$ keV
$T_i = 5.35\pm0.59$ keV
To gain insight about the implosions, a simple model can be used to infer hot-spot properties from emitted neutrons, X-rays and \( \gamma \)-rays.

**Measured hot spot quantities**

- Hotspot
- Cold shell
- Neutrons, \( \gamma \)-rays, X-rays

\[
Y \sim Vol \times t_{\text{burn}} \times <\sigma v> \times n^2
\]

- **Derived hot spot quantities**
  - Density, \( \rho \sim nA \)
  - Mass, \( M_{\text{HS}} \sim \rho V \)
  - Pressure, \( P \sim nT \)
  - Energy, \( E \sim PV \)

- More sophisticated model uses isobaric assumption (\( n \sim 1/T \))
- Allows 3D spatial profiles to be fit to match all observables
- Time dependence not yet included

From P. Springer et al., IFSA (2011).