Academic Participation and PhD Thesis Research at the NIF: A Case Study with Advanced Diagnostics

Dr. Daniel Casey’s PhD thesis is the first one based on NIF data:

“Diagnosing Inertial Confinement Fusion Implosions on OMEGA and the NIF using Novel Neutron Spectrometry”
Nemo working his magic in Boston this weekend
Collaborators

MIT

LLNL

UR - LLE

GA

LANL

SNL

Indiana University
All MIT Students obtaining NIF data for PhD Theses have LLNL Scientists as Co Advisors

<table>
<thead>
<tr>
<th>LLNL Scientist</th>
<th>MIT Student</th>
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<tr>
<td>Rip Collins</td>
<td>Alex Zylstra</td>
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<td>Joe Kilkenny</td>
<td>Hans Rinderknecht</td>
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<tr>
<td>Nino Landen</td>
<td>Hong Sio</td>
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<td>Andy Mackinnon</td>
<td>Mike Rosenberg</td>
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We thank Ed Moses who has been a strong advocate of this Program.

Dr. Daniel Casey, currently at LLNL, finished his MIT PhD in 2012.
Opportunities for academic participation in programmatic work at the NIF have allowed MIT to

• Work with collaborators on the development of several nuclear diagnostics and platforms for the NIF

• Share in the excitement of scientific discovery and the grand challenge of ignition at the NIF

• Give PhD students extraordinary experience along with data for their theses

The final NIC report states that a primary goal is the enhancement of diagnostic measurements.
Outline of diagnostics and platforms with MIT involvement

• Wedge-Range-Filter (WRF) proton spectrometers
• Particle Time-Of-Flight (PTOF) detector
• Magnetic Recoil Neutron Spectrometer (MRS)
• MIT accelerator facility – diagnostics development
• Developing new platforms and 2nd-generation diagnostics
Outline of diagnostics and platforms with MIT involvement

- **Wedge-Range-Filter (WRF) proton spectrometers**
  - Studies of $\rho_R$ and $\rho_R$ asymmetry at shock burn (student: Alex Zylstra)
  - Studies of shock-driven exploding pushers (student: Mike Rosenberg)
  - Studying fuel $\rho_R$, $T_e$, & mix with secondaries (student: Hans Rinderknecht)
  - Measuring megagauss B fields in hohlraums (student: Alex Zylstra)

- **Particle Time of Flight Detector**

- **Magnetic Recoil Neutron Spectrometer (MRS)**

- **MIT accelerator facility – diagnostics development**

- **Developing new platforms and 2nd-generation diagnostics**
Wedge-Range-Filter (WRF) proton spectrometers are used for all implosions with $D^3He$ or $D_2$ fuel at the NIF.
WRFs are fielded on the pole and equator for diagnosing $\rho R$ at shock-bang time and for probing fields around the LEH.
The WRF spectrometers measure $\text{D}^3\text{He}$-proton spectra, from which yields, $\rho_R$ and $\rho_R$ asymmetries are inferred.
A systematic study of $\rho R$ asymmetry at shock burn (~800ps before stagnation) uncovered interesting trends.

- Changing hohlraum geometry changed implosion symmetry.
- Lower drive power resulted in higher convergence at shock flash and an implosion symmetry change.
High-accuracy $\text{D}^3\text{He}$ proton spectra, used for diagnostic calibration, are also being used to study kinetic plasma effects and mix, and shock driven implosions.

The high-quality of these $\text{D}^3\text{He}$ data bode very well for the fundamental science proton backlighting platform.
Fuel ρR, mix, and kinetic effects in D$_2$ implosions are assessed with combined information on D$^3$He and DT secondary yields.

Primary reactions:

\[
D + D \rightarrow p (3.02 \text{ MeV}) + T (1.01 \text{ MeV}) \\
D + D \rightarrow n (2.45 \text{ MeV}) + ^3\text{He} (0.82 \text{ MeV})
\]

Secondary Reactions:

\[
T (< 1.01 \text{ MeV}) + D \rightarrow \alpha (6.7-1.4 \text{ MeV}) + n (11.9 \text{ – } 17.2 \text{ MeV}) \\
^3\text{He} (< 0.82 \text{ MeV}) + D \rightarrow \alpha (6.6-1.7 \text{ MeV}) + p (12.6 \text{ – } 17.5 \text{ MeV})
\]
A signature of **NO MIX** is similar values of $\rho R_{\text{fuel}}$ inferred from $D^3\text{He}-p$ & DT-n yields

**Thin-glass exploding pushers**

- **4 μm SiO$_2$**
- **~50 kJ**
- **Signature of NO MIX**

Graph showing $\rho R_{\text{fuel}}$ (mg/cm$^2$) vs. DT-n and D$^3$He-p with data points for N110131 and N130129.
A signature of **MIX** is different values of $\rho R_{\text{fuel}}$ inferred from $D^3\text{He-p}$ & DT-n yields

**DIME exploding pushers**

![Diagram showing apparent $\rho R_{\text{fuel}}$ (mg/cm$^2$) vs. DIME exploding pushers.]

- **DT-n**
- **$D^3\text{He-p}$**

See H. Rinderknecht’s poster on Thursday, 11 AM, B481
Images of proton spectra vs. position obtained from NIF shot N101218 indicate ~MGauss B-fields in the direction of LEH.

1. WRF proton spectrometers

See C.K. Li’s poster

Outline of diagnostics and platforms with MIT involvement

• Wedge-Range-Filter (WRF) proton spectrometers

• Particle Time-Of-Flight (PTOF) detector
  – Studies of shock and compression dynamics (student: Hans Rinderknecht)
  – Studies of evolution of $\rho_R$ and $\rho_R$ asymmetries (student: Alex Zylstra)

• Magnetic Recoil Neutron Spectrometer (MRS)

• MIT accelerator facility – diagnostics development

• Developing new platforms and 2\textsuperscript{nd}-generation diagnostics
The Particle-Time-Of-Flight (PTOF) diagnostic is used to measure compression and some shock bang times at the NIF.

- $^3\text{He}$-protons (~10 MeV)
- DD-neutrons (2.45 MeV)
- DT-neutrons (14.1 MeV)
- Hohlraum x-rays
Shock bang time is accurately measured for all directly driven implosions, such as this NIF D3He one.

See H. Rinderknecht’s poster

The 2nd-generation version of pTOF will be Magnetic pTOF: needed to circumvent the huge xray background of the hohlraum.
Outline of diagnostics and platforms with MIT involvement

- Wedge-Range-Filter (WRF) proton spectrometers
- Particle Time-Of-Flight (PTOF) detector

**Magnetic Recoil Neutron Spectrometer (MRS)**
- NIF ignition experiments (former student: Dan Casey**)
- Plasma nuclear science experiments (former student: Dan Casey**)

- MIT accelerator facility – diagnostics development
- Developing new platforms and 2nd-generation diagnostics

** 1st PhD thesis based on NIF data.**
The MRS Neutron Spectrometer is used both for NIF ignition experiments and for plasma nuclear science experiments.
The MRS diagnostic, implemented by MIT, LLNL and LLE, has played an important role in ICF experiments at OMEGA and the NIF.

MRS data and neutron time-of-flight (nTOF) data indicate that the implosions performance has improved ~50x since the 1st layered shot in Sept 2010.

See M. Gatu Johnson’s poster for more details.
The MRS concept was first successfully tested on OMEGA for diagnosing ICF implosions and for conducting basic science. Possible T-T reactions:

\[ T + T \rightarrow {^4}\text{He} + 2n \ (0\text{-}9.5 \text{ MeV}) \]
\[ T + T \rightarrow {^5}\text{He} + n \ (8.7 \text{ MeV}) \]
\[ T + T \rightarrow {^5}\text{He}^* + n \]

These T-T experiments are being conducted at the NIF to very high accuracy.

D.T Casey et al., PRL (2012).
The $^3\text{He}-^3\text{He}$ mirror reaction, important for stellar nucleosynthesis, studied on OMEGA, can be studied with higher accuracy at the NIF.

**Possible $^3\text{He}-^3\text{He}$ reactions:**

- $^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2\text{p} (0-10.8 \text{ MeV})$
- $^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + (\text{pp})$
- $^3\text{He} + ^3\text{He} \rightarrow ^5\text{Li} + \text{p} (9.2 \text{ MeV})$
- $^3\text{He} + ^3\text{He} \rightarrow ^5\text{Li}^* + \text{p}$

**$^3\text{He}-^3\text{He}$ proton spectrum from OMEGA shots 61251-61252**

- 3-body continuum
- $^5\text{Li}$ resonance
- $D^3\text{He}$ peak

**pp1 chain in hydrogen-burning stars**
Outline of diagnostics and platforms with MIT involvement

- Wedge-Range-Filter (WRF) proton spectrometers
- Particle Time-Of-Flight (PTOF) detector
- Magnetic Recoil Neutron Spectrometer (MRS)

- **MIT accelerator facility – diagnostics development**
  - Developing diagnostics and experimental platforms for the NIF
  - Providing students with real hands-on experience

- Developing new platforms and 2\textsuperscript{nd}-generation diagnostics
The MIT accelerator facility for developing and calibrating diagnostic platforms for the NIF

All WRF proton spectrometers used on the NIF have been calibrated on our accelerator.
Outline of diagnostics and platforms with MIT involvement

- Wedge-Range-Filter (WRF) proton spectrometers
- Particle Time-Of-Flight (PTOF) detector
- Magnetic Recoil Spectrometer (MRS)
- MIT accelerator facility – diagnostics development

- Developing new platforms and 2nd-generation diagnostics
  - PTOF → MagPTOF (student: Hans Rinderknecht)
  - Proton Core Imaging System (student: Alex Zylstra)
  - Proton radiography (student: Mike Rosenberg)
  - WRF → Step-WRF / pinhole-scattering WRF (student: Mike Rosenberg)
  - WRF → Neutron-WRF (student: Alex Zylstra)
  - MRS → Time resolved MRS (student: New student)
A 2\textsuperscript{nd}-generation, magnet-based PTOF will be implemented for measuring both shock and compression bang times on the NIF for indirectly driven D3He implosions.

5. Developing new diagnostics and platforms

See H. Rinderknecht’s poster
To enhance mix studies, a method of imaging and measuring D³He burn regions at OMEGA* is being ported to the NIF.

OMEGA experiment
With asymmetric drive

*F.H. Séguin et al., RSI (2004), PoP (2006), and to be submitted
A monoenergetic-proton-radiography technique used on OMEGA is being ported to the NIF: 1st experiments in March

NIF Applications

- Electromagnetic fields and plasma flows in hohlraums
- Fields effects in NIF VIEW-FACTOR experiments
- Backlighting of direct-drive ICF implosions
- Scaled astrophysical jets
- Magnetic reconnection
- Collisionless shock
- Charged-particle stopping power
- Rayleigh-Taylor and other hydrodynamical instabilities

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Monday:

- Chikang Li et al., Observation of strong fields around LEHs of ignition-scale holhraum in ICF experiments at the NIF

Tuesday:

- Mike Rosenberg et al., Studies of Shock-Driven Exploding Pusher Implosions on the NIF and OMEGA
- Johan Frenje et al., Next-generation neutron spectrometry for probing ICF implosions and for conducting basic-science experiments at OMEGA and NIF
- Maria Gatu Johnson et al., Novel nuclear science experiments on the NIF and OMEGA relevant to stellar nucleosynthesis
- Hans Rinderknecht et al., Quantitative assessment of fuel $\rho R$, mix, and kinetic effects using combined $^3\text{He}$ and DT secondary yields from $^2\text{H}$ implosions
- H. Sio, N. Sinenian et al., Upgrade of the MIT Accelerator (LEIA) for development of nuclear diagnostics for Omega, Z and the NIF
- Alex Zylstra et al., Charged-particle measurements of $\rho R$ asymmetry at shock-bang time in NIF implosions

See also H. Rinderknecht’s seminar on Thursday 11 in B481