The National Diagnostic Plan

Joe Kilkenny, Greg Rochau, Craig Sangster, Steve Batha, Ray Leeper, Perry Bell, Mike Campbell, Johan Frenje, Warren Hsing, Bob Kauffman, Jim Knauer, Jeff Koch, Doug Larson, John Moody, Rich Petrasso
NIF has about 65 Diagnostic Systems

- LLNL
- LANL
- LLE
- NSTec
- U of M
- LBNL
- AWE
- MIT
- CEA
- Duke
- SNL
- GSI
Where are we with NIF Diagnostics?

- Excellent set of NIF Diagnostics – developed over many years. But the ideas and technology are mainly old.
- A new generation of diagnostics is needed to measure more parameters.
We have three marvelous facilities- but diagnostics are largely based on old technology

A standard HED imaging system

Bradley, Bell, Kilkenny et al., NOVA & OMEGA, c. 1990
We have three marvelous facilities- but diagnostics are largely based on old technology

A standard HED imaging system

Pinhole 11th century.

Gated MCP 1980s.

Film 19th century

Bradley, Bell, Kilkenny et al., NOVA & OMEGA, c. 1990

Innovation is needed to keep NIF, Z, OMEGA exciting, attractive and mission relevant for the next generation of scientists and engineers

Read “The Innovators”- Walt Isaacson
A future HED imaging system

- Nested Mult-layer Wolter Optic
- Pulse-Dilation Tube
- Multi-frame Fast-gated Hybrid cMOS

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Res</td>
<td>10s of microns</td>
<td>&lt; 5 micron</td>
</tr>
<tr>
<td>Time Res</td>
<td>~100 ps</td>
<td>&lt; 10 ps</td>
</tr>
<tr>
<td>Frames</td>
<td>Few</td>
<td>10s</td>
</tr>
<tr>
<td>Solid Angle</td>
<td>~10^{-7}</td>
<td>~10^{-5}</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Broad (filters)</td>
<td>Narrow (Multi-layers)</td>
</tr>
</tbody>
</table>
Implosion systems are rich in interesting physics
Implosion systems are rich in interesting physics

Warning- simulations. Any resemblance to experiments—living or dead is err .....
Implosion systems are rich in interesting physics

Warning - simulations. Any resemblance to experiments –living or dead is err .....

We measure hardly any of this rich set of phenomena
The National Diagnostic Plan - created by 100 scientists and engineers
The National Diagnostic Plan builds on exciting recent developments in transformative technologies

- The hybrid CMOS
  >4, ~1 ns x-ray gates on each 512 x 512 array of 25 micron pixels.

- Manipulate in time or space X-ray images.

- 10 psec Photo-multipliers

- X-ray imaging up to 50 keV

- Stand alone 10 J laser in deep u.v.

DIXI: magnifies time, demagnifies space
MIT develops diagnostics for OMEGA and the NIF and uses them to study ICF, HEDP, and plasma nuclear physics.

The MIT Accelerator Facility for Diagnostic Development is used for testing and calibrating ICF diagnostics ...

... for studying:
- Shock and compression yields
- Areal densities at shock- and compression-bang times
- Asymmetries in areal density

... producing $D^3He-p$ spectra like this ...

... such as compact proton spectrometers ...
The research needs span a wide range of platforms, plasma conditions, and measurement requirements.

**High Pressure Materials**
- Phase and structure
- Strength
- Conductivity
- Temperature

**Complex Hydrodynamics**
- High convergence radiography
- 3-D plasma conditions
- Meso-scale / Multi-shock hydro instabilities
- Mix fraction

**Ignition Applications and Burn**
- Electron, ion temperature equilibration
- Ionization state
- Stopping power of alphas
- Radiochemistry
- Radiography/Imaging
- Burn history

**Radiation Transport, Opacity, & Effects**
- Radiation T, ne in 3D spatial, time
- Hohlraum conditions
- Non-thermal electrons
- X-ray source characterization
18 major diagnostic efforts were discussed at the National Diagnostic Working Group meeting Sept. 9-11, 2014

- 9th in a series dating back to 2009
- 117 participants from 13 institutions
- 69 presentations in 3 parallel sessions
- 10 plenary talks summarizing present efforts and needs at NIF, Z, and OMEGA

X-ray Imaging
- Single LOS gating
- ‘small dv’ imaging
- High energy imaging

X-ray Spectroscopy
- High resolution
- High energy (20-80 keV)
- Diffraction

Calibration
- Neutron sources
- Pulsed x-ray sources
- High energy x-ray cals

Neutron & Gamma
- Gamma spectroscopy
- 3-D neutron imaging
- Alpha heating diag.
- Furlong
- Radchem

Optical
- Thomson Scattering
- PDV

Other
- Radiation Hardening
- Magnetic Fields on NIF

Drop me an email to get invitation- kilkenny1@llnl.gov
The diagnostic management group binned activities into three categories: Transformational, Broad, and Local

**Transformational:** Major national efforts with the potential to transform experimental capability for the most critical science needs across the complex

**Broad:** Significant national efforts that will enable new or more precise measurements across the complex

**Local:** Important efforts involving implementation of known technology for a local need

<table>
<thead>
<tr>
<th>Transformational</th>
<th>Broad</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-frame high time-res gating</td>
<td>Particle Temporal Diagnostic</td>
<td>KB microscope</td>
</tr>
<tr>
<td>UV Thomson Scattering</td>
<td>Precision nToF</td>
<td>High energy spectroscopy</td>
</tr>
<tr>
<td>Fusion Gamma((t,h\nu))</td>
<td>B-fields on NIF</td>
<td>Various NIF/Omega snouts</td>
</tr>
<tr>
<td>3-D fusion burn imaging</td>
<td>Pulsed x-ray cal source</td>
<td>Crystal imaging &amp; backlighting</td>
</tr>
<tr>
<td>Fusion Neutron((t,h\nu))</td>
<td>Pulsed neutron cal source</td>
<td>Radchem</td>
</tr>
<tr>
<td>X-ray((t,h\nu)) (\lambda/\delta\lambda \sim 10000)</td>
<td>High-res x-ray streak cameras</td>
<td>Photonic Doppler Velocimetry</td>
</tr>
<tr>
<td>30-50keV image, 10 ps, &lt;10(\mu)m</td>
<td>High energy detectors</td>
<td>…many more…</td>
</tr>
<tr>
<td>Diffraction((t))</td>
<td>Radiation hardening</td>
<td></td>
</tr>
<tr>
<td>High resolution n/(\gamma) spectra</td>
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Some of the local (LLNL) diagnostic work this year

<table>
<thead>
<tr>
<th>Rad Hard CMOS detector</th>
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<tbody>
<tr>
<td>ARC X-ray Imaging System- (AXIS)</td>
</tr>
<tr>
<td>X-ray Microscopes (KB)</td>
</tr>
<tr>
<td>X-ray survey Spectrometer (NSS)</td>
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<tr>
<td>North Pole nTOF</td>
</tr>
<tr>
<td>Hohlraum x-ray spectrometer (VIRGIL)</td>
</tr>
<tr>
<td>Soft x-ray snout</td>
</tr>
<tr>
<td>Upgrade to VISAR</td>
</tr>
<tr>
<td>Large sample collector (VASER)</td>
</tr>
<tr>
<td>X-ray diffraction Spectrometer (TARDIS)</td>
</tr>
<tr>
<td>Magnetic pTOF</td>
</tr>
<tr>
<td>Rapid Access Collection (RACER)</td>
</tr>
<tr>
<td>Gamma spectrometer (GCD)</td>
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<tr>
<td>Optical Thomson Scattering (OTS)</td>
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Rest of the talk will on transformative diagnostics
Hybrid CMOS Camera System Motivation

Currently On NIF, Z, OMEGA → Image Plate & Film

Image Plate Disadvantages
- Multiple Shots Required To Do A Time Scan
- Measurement @ Single Time
- Expensive To Process
- Issue of Non-Reproducibility

Image Plate Replacement

Future On All Facilities → Hybrid CMOS (hCMOS) Imager

Picket Fence Pulse
- 22 to 40 keV X-rays
- μ-flag backlighter

Hybrid CMOS Capabilities
- >256x256, Buttable
- 4-8, 1ns Frames
- Several Pixel Sizes/DILATION Tube
- 3D X-ray Diode

A hCMOS image sensor can, with X-ray source development, eliminate the need for multiple shots making multiple measurements at user defined times within one shot.
Fast-gated multi-frame CMOS sensors will transform capability across all HED programs

**High Pressure Materials**
- Diffraction
- Strength

**Complex Hydrodynamics**
- Radiography

**Ignition Applications**
- Laser Preheat
- Stagnation
- Spectroscopic Mix

**Opacity, Outputs & Effects**
- Absolute Gated Spectra
- High-Z K-α Imaging
Research Thrust: Broad enabling capability of multi-frame single line-of-sight (SLOS) time-gating

Science Drivers
• Multi-frame gating at 10 ps - 1 ns for high res, large solid angle imaging and backlighting
• Time-resolved x-ray diffraction
• Time-resolved absolute x-ray spectroscopy
• MCP and image plate replacement

Transformational Diagnostic Approach
• Up to 16-frame Hybrid CMOS (hCMOS) sensors for direct optical or x-ray detection at gates > 1 ns
• hCMOS coupled to pulse-dilation for gates 0.01 – 1 ns
Coupling hCMOS sensors to pulse-dilation provides ultra-fast gating and flexible detection area.

<table>
<thead>
<tr>
<th>High Pressure Materials</th>
<th>Complex Hydrodynamics</th>
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<tbody>
<tr>
<td><strong>Diffraction</strong></td>
<td><strong>High Speed Radiography</strong></td>
</tr>
<tr>
<td>Large angular coverage</td>
<td></td>
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<tr>
<td>High strain rates</td>
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<table>
<thead>
<tr>
<th>Ignition Applications</th>
<th>Opacity, Outputs &amp; Effects</th>
</tr>
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<tbody>
<tr>
<td><strong>Z-Pinch Stagnation</strong></td>
<td><strong>MCP replacement</strong></td>
</tr>
<tr>
<td>Hot-Spot Imaging</td>
<td>Faster gating $&lt;10$ ps up to 1 ns</td>
</tr>
<tr>
<td></td>
<td>Smaller Pixels $25 , \mu m$</td>
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<td></td>
<td>Higher DR $\sim 1000$</td>
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<tr>
<td></td>
<td>Single LOS Better optics</td>
</tr>
<tr>
<td></td>
<td>Calibrated no $V^{12}$ dependence</td>
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$T_e (r, \theta, \phi, t)$

3-D
Research Thrust: Local determination of the plasma conditions in low-density plasmas.

Science Drivers
- Hohlraum plasma formation and energetics
- Radiation channel evolution
- MagLIF LEH window interaction and gas heating
- Coronal conditions of direct-drive capsules
- Electron transport
- Independent of spectroscopy

Transformational Diagnostic Approach
- Time-resolved Optical Thomson Scattering at deep UV for localized probing of electron temperature and density

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>Facility Implementation</th>
<th>Collaborating Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTS</td>
<td>Omega, NIF</td>
<td>LLE, LLNL, LANL, NRL</td>
</tr>
</tbody>
</table>
A robust and precise deep UV OTS platform will transform our understanding across multiple missions

**Hohlraum Underdense channel plasma**
- Laser propagation
- Electron transport
- Laser-plasma interaction physics
- Wall-channel interactions

**Direct Drive Underdense Plasma**
- Laser propagation
- Electron transport
- Laser-plasma interaction physics

**Radiation Physics**
- Independent plasma parameters
- Cross-check of line broadening models

**MagLIF Preheat**
- Laser heating
- LEH, gas interactions
- Electron transport
- Magnetic flux loss
- Laser-plasma interactions
Research Thrust: High energy, high resolution many-frame imaging.

Science Drivers
- Non-thermal x-ray production
- Material strength with high-energy radiography
- Complex hydro
- Three-dimensional ICF implosion dynamics
  - Characterize final stages of implosions and propagating burn
  - 3-D through multiple views

Transformational Diagnostic Approach
- Multi-layer Wolter microscopes for flexible field-of-view and high solid angle with high spatial res
- Coupled to SLOS for time-res

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<th>Collaborating Institutions</th>
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<tbody>
<tr>
<td>KB + SLOS</td>
<td>NIF</td>
<td>LLNL, GA, LLE</td>
</tr>
<tr>
<td>Wolter + SLOS</td>
<td>Z, NIF, Omega</td>
<td>LLNL, SNL, LLE</td>
</tr>
<tr>
<td>Spherical Crystal + SLOS</td>
<td>Z, Omega</td>
<td>SNL, GA, LLE</td>
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</table>
Nested multilayer Wolter optics coupled to a pulse-dilation SLOS will enable space-resolved $T_e$ of capsule

**Nested Wolter with 3-different multilayers**

![Graph showing capsule emission spectrum with energy vs. intensity](image)

- **20 keV Image**
- **25 keV Image**
- **30 keV Image**

$I \propto e^{-\frac{h\nu}{kT_e}}$

**≥ 8 cm**

**Wolter optic**

**3 narrow E band images**

**Benefit:** enables multi-monochromatic imaging (MMI) in the optically-thin regime
Research Thrust: Detailed determination of fusing plasma evolution and burn propagation.

Science Drivers
• Hot spot formation
• Ablator – hot spot mixing
• rho-r evolution
• Fusion propagation
• Ion – electron equilibration
• Nuclear Astrophysics

Transformational Diagnostic Approach
• High sensitivity Gas Chenkov Detectors (GCD) for high resolution fusion gamma spectroscopy
• Magnetic Recoil Spectrometer (MRS) coupled to time-resolved detectors (>1E16 yields)
• Neutron/gamma imaging from multiple orthogonal directions
• High resolution x-ray spectrometer for Ti, Te, ne
Research Thrust: Detailed determination of fusing plasma evolution and burn propagation.

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<td>Super GCD</td>
<td>NIF, Omega</td>
<td>LANL, LLNL, AWE, Photek, LLE</td>
</tr>
<tr>
<td>3-D n/γ-imaging</td>
<td>NIF</td>
<td>LANL, LLNL</td>
</tr>
<tr>
<td>HiRes</td>
<td>Omega, NIF, Z</td>
<td>NSTec, LLNL,LLE,PPL, Aartep, SNL</td>
</tr>
<tr>
<td>MRS-t</td>
<td>NIF, Omega</td>
<td>MIT, LLE, LLNL, GA</td>
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</table>

Multiple orthogonal lines of sight

Analysis by N. Izumi

Reconstructed 3-D Contour

X: +23.6um
Y: -23.6um
Z: -19.7um
Z: -18.7um
The temperature of cold, compressed matter can be measured with EXAFS

Current NIF Experiment: Ramp-compress sample
  • Measure velocity with Visar to deduce STRESS
  • Measure DENSITY with Diffraction

NEED to measure Temperature

OMEGA experiments used EXAFS to measure Temperature

EXAFS data (ramp compressed Fe)

Temperature vs Stress

Extending these studies of cold, compressed matter to mid and high Z materials needs NIF

Research Thrust: Time-dependent phase change in materials at high pressure.

Science Drivers
• Phase determination at high pressure
• Lattice deformation at high stress

Transformational Diagnostic Approach
• Time-gated x-ray diffraction

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</tr>
</thead>
<tbody>
<tr>
<td>Fast Phosphors</td>
<td>Z</td>
<td>SNL, NSTec</td>
</tr>
<tr>
<td>TARDIS + SLOS</td>
<td>NIF</td>
<td>LLNL, GA, SNL</td>
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## Summary

1. **Why a new diagnostics for HED science**
2. **Lots of people involved**
3. **Transformative technology- selection of eight diagnostics will allow new attributes to measured**

<table>
<thead>
<tr>
<th>Mission</th>
<th>New Observable</th>
<th>Technique</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Strength vs time of compressed matter</td>
<td>&gt; 4 images/costly target</td>
<td>SLOS</td>
</tr>
<tr>
<td></td>
<td>Phase change compressed matter - rates</td>
<td>Time dependent diffraction</td>
<td>TARDIS-time</td>
</tr>
<tr>
<td></td>
<td>T of compressed Pu</td>
<td>Extended x-ray fine structure</td>
<td>Hi Res</td>
</tr>
<tr>
<td>Complex Hydro.</td>
<td>3D structure at ~ 50 keV</td>
<td>X-ray bands imager +SLOS</td>
<td>Wolter</td>
</tr>
<tr>
<td>Rad. Flow</td>
<td>$T_e$ of Marshak wave</td>
<td>Deep u. v. Thomson scattering</td>
<td>OTS</td>
</tr>
<tr>
<td>Burn</td>
<td>Time history of burn</td>
<td>Ultra-fast Cerenkov detector</td>
<td>GCD</td>
</tr>
<tr>
<td></td>
<td>3D $T_e$ and density vs time</td>
<td>Dilation tube + SLOS+Wolter</td>
<td>DIXI-SLOS</td>
</tr>
<tr>
<td></td>
<td>3D burn, 3D mix vs time</td>
<td>3D neutron/γ imaging</td>
<td>NIS</td>
</tr>
<tr>
<td></td>
<td>$T_{ion}$ and areal density vs time</td>
<td>Neutron spectrum vs time</td>
<td>MRS-time</td>
</tr>
<tr>
<td>All</td>
<td>Hohlraum- density &amp; $T$ vs space &amp; time</td>
<td>Deep u. v. Thomson scattering</td>
<td>OTS</td>
</tr>
</tbody>
</table>
END