Diagnostics for High-Energy-Density Physics

• High throughput
• Proven diagnostics
• Proven cryogenics

CryoNTD

Neutronics

Petawatt beam - OMEGA EP

X-ray imaging

Direct-drive DT cryo capsules and cone-in-shell targets

CR-39 track data

Charged-particle spectroscopy

\[ \Delta E_p > (\text{MeV}) \]

\[ \rho_R \text{ asymmetry} \]

\[ \rho_{\text{Total}} (\text{mg/cm}^2) \]

\[ \rho_{\text{R asymmetry}} \]

\[ \rho_{\text{Total}} (\text{mg/cm}^2) \]

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University of Rochester
Laboratory for Laser Energetics

HEDP Summer School
University of California, Berkeley
12 August 2005
HEDP systems are diagnosed by optical, x-ray, and nuclear means.

- HEDP systems emit some or all of
  - visible light
  - VUV and x-ray photons
  - charged particles
  - neutrons.
- These systems can also be probed with similar particles.
- A comprehensive diagnostic suite can allow a great deal to be learned about the systems.
- Diagnosing HED systems requires subnanosecond temporal resolution and ~10-μm spatial resolution.

Over the past 30 years a large suite of diagnostics has been developed for HEDP systems.
Outline

- Diagnostic issues and concepts
- Basic diagnostic building blocks
  - simple detectors
  - pinhole imaging
  - time resolution
    - framing cameras
    - streak cameras
  - spectroscopy
  - radiography
  - equation of state
  - nuclear diagnostics
    - neutrons
    - charged particles
Diagnostic performance is determined by the resolution and signal-to-noise levels

- Spatial, temporal, or energy (or wavelength) resolution determines the diagnostic properties.
- The resolution depends on the design and on the signal-to-noise (background) ratio.
- The signal level depends on
  - source brightness
  - solid angle of the detector
    \[ \Delta \Omega = \frac{A_{\text{det}}}{4\pi D^2}, \]
    where
    - \( A \) is the effective diagnostic area
    - \( D \) is the distance from the source to the diagnostic
- The noise (background) level is determined by design and intrinsic noise levels (e.g., photon statistics).
- For example, when low numbers of particles \( (N) \) are detected, the uncertainty scales as \( \sqrt{N/N} \).
Photons can be detected on film or electronically.

- When film is exposed to photons or other particles a chemical reaction occurs.

Film typically has high resolution and low noise but limited sensitivity and requires processing time.
Electronic detectors provide rapid readout

- Electronic detectors are typically semiconductors or ionization-based stacks (e.g., photomultipliers).

Semiconductor detectors

Ionization detectors

\[
\hbar \omega
\]
The simplest imaging device is a pinhole camera.

- Magnification = \( \frac{d_2}{d_1} \)
- Infinite depth of field (variable magnification)
- Pinhole diameter determines
  - resolution \( \sim a \)
  - light collection: \( \Delta \Omega = \frac{\pi}{4} \frac{a^2}{d_1^2} \)

Imaging optics (e.g., lenses) can be used for higher resolutions with larger solid angles.
2-D images can be recorded on film or electronic detectors

- A 2-D detector is required for a pinhole camera
  - film—requires processing
  - electronic
    - semiconductor arrays—signal proportional to incident flux per pixel (CCD or CID)
    - array of ionization detectors
    - single photo counters—limited dynamic range
A streak camera provides temporal resolution of 1-D data

Basic principle

\[ \hbar \omega \rightarrow e^- \]

Photocathode

\[ V(t) \propto V_{ot} - \delta V \]

Detector

A streak camera can provide 2-D information

\[ \hbar \omega \rightarrow x \]

2-D detector
LLE has built a streak camera around the Phillips 510 streak tube.
The LLE streak camera design consists of a streak tube module and an autocalibration/optical input module.
A framing camera provides a series of time-gated 2-D images, similar to a movie camera.

- The building block of a framing camera is a gated microchannel-plate detector (MCP).

- An MCP is a plate covered with small holes.

- A voltage pulse is sent down the plate, gating the detector.

Multiple electrons are produced each time an electron hits the wall.

The detector is only on when the voltage pulse is there.
Temporal response can also be simulated using a time-resolved Monte Carlo code.

- All electrons in cascade are tracked in three dimensions as the voltage pulse is applied.
Two-dimensional time-resolved images will be recorded using x-ray framing cameras.

- Temporal resolution = 35–40 ps
- Imaging array: pinholes: 10- to 12-μm resolution, 1–4 keV  
  RAM: ≪5-μm resolution, 1–10 keV
- Space-resolved spectrum can be obtained by using Bragg crystals and imaging slits.
A typical detector consists of a microchannel plate (MCP) in front of a phosphor screen.

- Electrons are multiplied through MCP by voltage $V_c$.
- Images are recorded on film behind phosphor.
- Insulating $\text{Al}_2\text{O}_3$ layer allows $V_{\text{ph}}$ to be increased, thus improving spatial resolution of phosphor.
Second-generation x-ray framing camera jointly developed by LLNL and LLE has 40-ps framing time
Ideally, one would like to collect energy (spectral), spatial, and temporal information simultaneously.

- An HEDP source has five characteristic degrees of freedom:
  - 3-D spatial dimensions
  - energy spectra
  - temporal evolution

- Typical detectors can provide 2-D information:
  - 2-D integrated in time
  - 2-D gated in time (some temporal resolution)
  - 1-D in space and 1-D in time
  - 1-D in time and 1-D in energy

- Holography could add a third dimension but is extremely difficult to implement.

A collection of HEDP diagnostics allows all five degrees of freedom to be measured.
The second dimension of a streak camera image could be either spatial or spectral (energy)
The trajectory of an imploding shell can be measured with streak and framing cameras.
The implosion trajectory is measured with an imaging x-ray streak camera and a framing camera.

**Framing camera image**
- 6× magnification, foot-ramp pulse

**Streak camera image**
- 2-ns foot-ramp, 21 kJ, 20-μm CH

Example:
Shot 13377

**Time**

Position (μm)

Time (ps)

IXRSC image 13377
The imaging x-ray streak and the x-ray framing cameras show similar shell profiles.

Radial profile of x-ray emission, shot 13377 at 2.05 ns, foot-ramp pulse, 20-\(\mu\)m CH target.
The imaging x-ray streak and the x-ray framing cameras show similar shell trajectories and agree with 1-D simulations.

**Example**

Comparison of radius determined from 13377, 13378, and 13380 with a foot-ramp pulse of ~21 kJ.

Comparison of LILAC and measured trajectory, shot 13377.

Foot-ramp pulse, 20-μm CH shell, 21 kJ.
The photon energy spectrum provides valuable information

- Plasma conditions can be determined for the photon spectrum
  – visible light: absorption and laser–plasma interactions
  – x-rays: electron temperature, density, plasma flow, material mixing

- There are three basic tools for determining the spectrum detected.
  – filtering
  – grating spectrometer
  – Bragg spectrometer

- The latter rely on interface of outgoing rays.

- The electrons in a typical atom are arranged in a series of shells.

Example: Al $Z = 13$
- Electrons
  - 2 K shell
  - 8 L shell
  - 3 M shell
The atomic structure determines the transmission of a filter

- Above the K-edge, photons are strongly absorbed by ionizing K-shell electrons

Stacks of filters of different materials provide relatively narrow bandpass
Step targets were used to determine sensitivity, x-ray spectrum, and spatial resolution.

- Targets: 3 mm × 3 mm
- A 500-μm-wide, 10-μm-thick Pt strip down the center of the target is used to measure the edge resolution.

<table>
<thead>
<tr>
<th>Material</th>
<th>K abs. edge</th>
<th>Step thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>(0.28 keV)</td>
<td>50 μm</td>
</tr>
<tr>
<td>Si</td>
<td>(1.84 keV)</td>
<td>20 μm</td>
</tr>
<tr>
<td>Ti</td>
<td>(4.97 keV)</td>
<td>10 μm</td>
</tr>
<tr>
<td>Ni</td>
<td>(8.33 keV)</td>
<td>12.5 μm</td>
</tr>
</tbody>
</table>

Multiple materials isolate regions of the spectrum.
Spectral of Ti backlighter peaks near 6.5 keV

- 6.5-keV peak observed
- Expected: 4.7-keV He-α peak (seen in crystal spectrograph) high-energy continuum contributes to the x-ray spectrum.
- Fe BL spectrum in progress

Filter packs have limited resolution.
Spectral information can be obtained by taking advantage of the wave nature of light.

Light passing through an array of slits is diffracted.

In the limit of a large number of slits, the diffraction pattern has maxima when

\[ d \sin \theta_m = m \lambda_1. \]
A diffraction grating is equivalent to an array of slits

The grating equation is:
\[ d(\sin \theta_i + \sin \theta_o) = n \lambda \]

If \( \theta_i \) is the same for all wavelengths, \( \theta_o \) depends on wavelength:
\[ \sin \theta_o = \frac{n \lambda}{d} - \sin \theta_i \]

\( d \) is the groove spacing and \( 1/d \) is the number of lines in a given distance.
A basic spectrometer images a source onto a detector through a grating

- A spectrometer can be coupled to a streak or framing camera for temporal or spatial information.
X rays undergo interference when scattering from crystals—Bragg scattering

- X rays incident on a crystal are partially reflected at each lattice site.

\[ \lambda = 2d \sin \theta \]

- At particular angles, the outgoing waves constructively interfere, giving reflection.

- Different wavelengths will be scattered into different angles.
X-ray absorption spectroscopy is used to study shock heating produced by square and ramp pulses.

Example

Six drive beams, $I \sim 4 \times 10^{14}$ W/cm$^2$

Drive Pulse Shapes

Intensity ($10^{14}$ W/cm$^2$) vs. Time (ns)
Simulated\textsuperscript{1} Al absorption spectra show progressive ionization states as temperature increases.
Al absorption spectroscopy shows progressive heating by shocks and the heat front.
In targets with gold-coated foam layers, both radiation and shock heating are observed.
Spherical plastic-shell targets were imploded with a 23-kJ, 1-ns square laser pulse

- Predicted convergence ratios ranged from 13 to 40.
- Laser irradiation with 1-THz SSD, PS, and on-target beam-to-beam power imbalance < 5% rms.

Example

Cl dopant level 0.25 to 1% atomic
Streaked x-ray spectroscopy is used to measure time-dependent Cl K-shell spectral line shapes.

Example

Shot #29798: D₂ (15 atm), CH Cl [5.9 \( \mu \text{m}, 1\% \)], CH [18 \( \mu \text{m} \)]

- Spectral line shapes of Cl He\( \beta \), Cl He\( \gamma \), and Cl Ly\( \beta \) are analyzed to infer the time history of emissivity-averaged \( n_e \) and \( T_e \).
Significant changes in the Ar K-shell emission spectrum occur during the course of implosion.

SN 22507
DD (15), Ar (0.054), CH [20]

- **t = 1.77 ns**
  - Onset of Ar K-shell emissions

- **t = 1.93 ns**
  - Peak neutron production

- **t = 2.15 ns**
  - Compressed core disassembles

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Intensity (arbitrary units)

Photon energy (keV)

- Modeled spectrum
- Measured spectrum
- X-ray continuum
Example

At peak neutron production, $n_e = 2.5 \times 10^{24} \text{ cm}^{-3}$ and $T_e = 2.0 \text{ keV}$

- Electron pressure $\sim 8 \text{ Gbars}$
Core conditions close to 1-D predictions are observed on OMEGA direct-drive implosions with convergence ratios of $\sim 15$.

Higher measured electron density is attributed to fuel–pusher mix.
Linear Rayleigh–Taylor growth rates associated with ICF capsule implosions are below incompressible fluid results due to a number of physical processes.

\[
\gamma = \alpha \sqrt{k g} - \beta k V_a
\]
X-ray framing cameras are used to radiograph instability growth

- The backlighter transmission depends on wavelength and target optical depth. Mass perturbations lead to optical depth perturbations.

**Framing cameras**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>8–10 μm (two dimensions)</td>
</tr>
<tr>
<td>Spatial field of view</td>
<td>500 μm (magnification = 12)</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>30–80 ps</td>
</tr>
<tr>
<td>Temporal field</td>
<td>(4) 300-ps strips</td>
</tr>
</tbody>
</table>
2-D images of imposed mass perturbations were measured from 1.0 ns to 2.5 ns after the start of the pulse.
We use a framing camera (with pinhole array and microchannel plate) for through-foil radiography.

![Diagram of the framing camera system](image)

- **X rays** from the U backlighter pass through the target and are directed to the MCP.
- An 8-μm pinhole is used to select the desired region of interest.
- The signal passes through the MCP and is recorded on film.
- A 20×20-μm aperture is used to further refine the image.
- The signal is digitized and fed into the measurement system.
The x-ray framing camera spatial resolution is measured with grid target.
Measurement of a $\lambda = 50\,\mu m$ perturbation with a Gaussian pulse agrees with hydrodynamic simulation.
VISAR provides the baseline EOS data

- Conservation relations \( P = \rho_0 U_s U_p \)
  \[ \rho/\rho_0 = 1/(1 - U_p/U_s) \]

- Temperature is measured separately
Shock velocities were measured using time-resolved VISAR*.

*Velocity Interferometry System for Any Reflector (designed and implemented by LLNL); Barker and Hollenbach, J. Appl. Phys. 43, 4669 (1972).
The velocity interferometer system for any reflector (VISAR) detects doppler shifts to measure velocity

Etalon delay $\tau = \left(\frac{2h}{c}\right)(n - \frac{1}{n})$

$\phi = \omega(t)$; $\phi' = \omega'(t + \tau)$

$\omega' = \omega\left(1 + \frac{2v}{c}\right)$

$\Delta\phi = \phi' - \phi = \omega\tau\left(\frac{2v}{c}\right) \propto \left(\frac{\tau}{t}\right)\nu$

$\phi = \omega[t + \delta(x)]$

Reference fringe pattern
To understand the experimental difference, we have performed impedance-match experiments similar to Z

Experimental setup
Aluminum
Laser drive
Window
D₂
Quartz “witness plate”

Single shock data record
Distance (μm)
0 2 4 6 8 10
300
0
-300

OMEGA 1-shock data is consistent with “intermediate” \( \rho/\rho_0 \) on the Hugoniot between 1 and 2.5 Mbar

D. G. Hicks (submitted)
Fusion reaction products provide a wealth of information about implosions.

<table>
<thead>
<tr>
<th>Process</th>
<th>Reaction</th>
<th>Information encoded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary fusion</td>
<td>D + D → T (1.01 MeV) + p (3.02 MeV) 50%</td>
<td>D₂ primary yield</td>
</tr>
<tr>
<td></td>
<td>→ ³He (0.8 MeV) + n (2.45 MeV) 50%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D + T → α (3.5 MeV) + n (14.1 MeV) 100%</td>
<td>DT primary yield/reaction history</td>
</tr>
<tr>
<td></td>
<td>→ ⁵He + γ (&lt;16.7 MeV) 10⁻⁵</td>
<td>DT burnwidth/reaction history</td>
</tr>
<tr>
<td>Secondary fusion</td>
<td>³He (0.8 MeV) + D T (1.01 MeV) + D → α (1.7–6.6 MeV) + p (12.5–17.4 MeV)</td>
<td>Low &lt;ρR&gt;ᵣₑᵤₐₜ with D₂</td>
</tr>
<tr>
<td>(n,n') scattering</td>
<td>n (14.1 MeV) + p → n' + p (&lt;14.1 MeV)</td>
<td>DT primary yield (e.g., ProtEx)</td>
</tr>
<tr>
<td></td>
<td>n (14.1 MeV) + D → n' + D (&lt;12.5 MeV)</td>
<td>&lt;ρR&gt;ᵣₑᵤₐₜ+shell</td>
</tr>
<tr>
<td></td>
<td>n (14.1 MeV) + T → n' + T (&lt;10.6 MeV)</td>
<td>&lt;ρR&gt;ᵣₑᵤₐₜ+shell with D₂ fuel</td>
</tr>
<tr>
<td></td>
<td>n (11.9–17.2 MeV) + D/T → n' + D/T</td>
<td>&lt;ρR&gt;ᵣₑᵤₐₜ+shell with D₂ fuel</td>
</tr>
<tr>
<td></td>
<td>n (2.45) + D → n' + D (&lt;2.2 MeV)</td>
<td></td>
</tr>
<tr>
<td>Tertiary fusion</td>
<td>(1) D + T → α (3.5 MeV) + n (14.1 MeV)</td>
<td>&lt;ρR&gt;ᵣₑᵤₐₜ &lt; 1 to 2 gm/cm²</td>
</tr>
<tr>
<td></td>
<td>(2) n (14.1 MeV) + D → n' + D (&lt;12.5 MeV) or n' + T (&lt;10.6 MeV)</td>
<td>&lt;ρR&gt;ᵣₑᵤₐₜ &lt; 1 to 2 gm/cm²</td>
</tr>
<tr>
<td></td>
<td>(3) D (&lt;12.5 MeV) + T → α + n (&lt;30.1 MeV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>or (4) T (&lt;10.6 MeV) + D → α + n (&lt;28.6 MeV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(n, 2n) reactions n (14.1 MeV) + D → n' + n + p</td>
<td>background n</td>
</tr>
<tr>
<td></td>
<td>n (14.1 MeV) + T → n' + n₁ + n₂ + p</td>
<td></td>
</tr>
</tbody>
</table>
Copper activation is a standard diagnostic to measure primary neutron yield in DT implosions

- Copper nuclei are activated by the reaction
  \[ n + ^{63}\text{Cu} \rightarrow ^{62}\text{Cu} + 2n \]
- Reaction threshold = 10.9 MeV, cross section = 0.5 b at 14.1 MeV
- \(^{62}\text{Cu}\) emits a positron that produces two gamma rays:
  \[ ^{62}\text{Cu} \rightarrow ^{62}\text{Ni} + e^+ \left( \tau_{1/2} = 9.8 \text{ min.} \right) \]
  \[ e^+ + e^- \rightarrow 2\gamma \left( 0.511 \text{ MeV} \right) \]
- The coincidence of two gamma rays is detected by two NaI detectors.
The OMEGA copper activation system was designed for primary DT yield measurements.

**Target bay**

- **Cu retractor**

**La Cave**

- **Disk transport**

**Nal (T\(\ell\)) crystals** detect coincident annihilation \(\gamma\) rays.

**Automatic pneumatic retractor**

- **Cu disk**: 76-mm diam \(\times\) 9.5 mm
- **Disk-to-target distance**: 40 cm
- **Detector threshold**: \(~10^7\) neutrons
Fast-scintillator-based NTOF detectors are used to measure primary yield, secondary yield, and ion temperature.
Fast current-mode nTOF detectors are being developed for scattered neutron spectroscopy

- Polycrystalline CVD diamond wafers could be implemented inside the NIF target chamber*:
  - Large band gap (insensitive to γ’s)
  - High bandwidth (< 100 ps)

- Ideally suited as nTOF for $T_{\text{ion}}$ on the NIF:
  - Validated on OMEGA
  - Soon to be incorporated into OMEGA neutronics

- Issues to resolve:
  - Radiation/flux-dependent response
  - Cable/readout circuitry
  - Energy response function
  - Unfolding to spectrum

PTD/CryoNTD* is a TIM-based example of how a neutron-based reaction history can be measured at the NIF.

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*C Stoeckl et al., RSI 74, 1713 (2003).
Magnet-based charged-particle spectrometers (CPS’s)

\[ D + ^3\text{He} \rightarrow P(14.7 \text{ MeV}) + \alpha(3.6 \text{ MeV}) \]

Precision \( \sim 0.05 \text{ MeV} \)

Absolute accuracy \( \sim 0.10 \text{ MeV} \)
The OMEGA charged-particle spectrometers (CPS) measure the total $\rho R$

20-μm-thick, 3-atm DHe$^3$-filled CH targets, 1-ns square pulse

D-He$^3$ reaction proton spectrum

Observed downshift $\Delta E$

Birth energy

Energy loss $\Delta E = 1.63 \pm 0.04$ MeV

Implied areal density $\rho R_{\text{total}} = 70 \pm 5$ mg/cm$^2$

Averaged over three shots
Recent work indicates that a wealth of information is encoded in the scattered neutron spectrum.

Calculations courtesy of S. Hatchett, LLNL
The scattered fraction of the primary DT neutrons between 4 and 10 MeV is proportional to the total $\rho R$.

A similar relationship is valid for scattered DT secondaries in D$_2$ fuel.

Calculations courtesy of S. Hatchett, LLNL.
The tertiary-to-primary ratio correlation with $<\rho R>$ is least sensitive to $T_{ion}$ for $E_n \geq 20$ MeV

Options:
- $^{12}$C(n, 2n)$^{11}$C activation
- Multi-hit neutron array

Calculations courtesy of S. Hatchett, LLNL.
$^{12}\text{C}(n,2n)^{11}\text{C}$ is an ideal reaction to measure tertiary neutrons via activation* 

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Based on the design specifications modeled above, at a yield of $10^{14}$ and a $\rho R$ of 0.15 g/cm$^2$, approximately 400 neutrons will be detected.

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A magnetic recoil spectrometer (MRS) is ideally suited to measure the scattered neutron spectrum.

\[ n + CH \rightarrow c + p + n \]

Forward scattering: \( E_{\text{out}} (p) = E_{\text{in}} (p) \)

- Dynamic range
- Background
- EMP

Target chamber

Protons or deuterons

CH foil or CD foil

Target

Neutrons

Magnet

6- to 24-MeV protons or 3- to 12-MeV deuterons

Vacuum chamber

Lead

Coincidence CR-39

CVD-strip detectors

Current-mode scintillators
The schematic of a neutron imaging system is deceptively straightforward.

Aperture and alignment
- Penumbral (coded)
- Pinhole (array)

Detector and readout system
- Scintillator array (1 mm)
- Capillary array (100 μm)
- Bubble chamber (10 μm)

Source

$\ell_1 \Rightarrow \ell_2$

$M = \frac{\ell_2}{\ell_1}$

$\sim 5 \mu m$ at source $X M (\sim 200 \times) = 1 \text{ mm at detector}$

Neutron imaging developmental platform on OMEGA

Penumbral aperture

CCDD + MCP

Lens

Mirror

85-μm capillaries

Neutron detector
Fusion reaction history should provide information on shock timing and implosion dynamics near bang time.

The Gas Cherenkov Detector (GCD) is being developed by LANL* in collaboration with LLNL for burn history measurements using DT $\gamma$ rays.

- Threshold ($\gamma$ energy) detector to maximize S/B ($\text{CO}_2$ gas)
- Simulations indicate a gas cell temporal response under 10 ps.
- Demonstrated 30-ps streaked resolution at a LINAC

*S. E. Caldwell et al., RSI 74, 1837 (2003); R. R. Berggren et al., RSI 72, 873 (2001).
A streaked record of the DT fusion $\gamma$-ray signal observed on OMEGA in May 2003

- Cherenkov signal consistent with expected timing
- Signal vanishes without CO$_2$
- Signal proportional to neutron yield

This result is a definitive proof-of-principle for an important ignition diagnostic technique for the NIF.
Summary/Conclusions

HEDP systems are diagnosed by optical, x-ray, and nuclear means

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  - VUV and x-ray photons
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  - neutrons.
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