Section 2
PROGRESS IN LASER FUSION

2.A Neutron Diagnosis of Compressed ICF Targets

With the development of large, short-wavelength laser systems, such as the 24-beam OMEGA laser, high-yield and high-density laser-fusion experiments can be undertaken. Since the first kilojoule, short-wavelength laser experiments at the beginning of 1985, the highest measured neutron yield has gone up by over a factor of 300, in experiments performed by three laboratories. In the most recent experiment, a neutron yield of \(1.1 \times 10^{13}\) was achieved. This corresponds to a yield efficiency (thermonuclear energy divided by the laser energy) of \(1.5 \times 10^{-3}\). The generation of high fluences of neutrons in ICF experiments permits the development of neutron-dependent diagnostic approaches to the determination of compressed core parameters. We review here a number of these diagnostics, some of which have been deployed on OMEGA for assessing the implosion uniformity. In particular, we stress that simultaneous measurements of several parameters of the compressed core at the time of neutron generation are necessary for unambiguous evaluation of the symmetry and integrity of the thermonuclear burn region.

The compressed core parameters accessible through neutron-dependent diagnostics, at present activated on the OMEGA facility or under development, are listed in Table 27.1, together with estimates of their current sensitivity and resolution. In the following we review the characteristics and limitations of these diagnostics.

Neutron fluence from a transient point source can be measured by a variety of techniques with high accuracy (<1%) for neutron yields...
Table 27.1
Neutron diagnostics of compressed fusion targets.

<table>
<thead>
<tr>
<th>Target Parameter</th>
<th>Diagnostic Approach</th>
<th>Sensitivity, Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron fluence (Y_n)</td>
<td>scintillator/photomultipliers</td>
<td>(Y_n &gt; 10^4, \Delta \Omega \sim 10^{-3} \text{ sr})</td>
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<tr>
<td></td>
<td>Ag ((n, \beta^-) \text{Cd})</td>
<td>(Y_n &gt; 10^6, \Delta \Omega \sim 10^{-2} \text{ sr})</td>
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<tr>
<td></td>
<td>(^{63}\text{Cu}(n, 2n) \text{Cu})</td>
<td>(Y_n &gt; 10^6, \Delta \Omega \sim 10^{-2} \text{ sr})</td>
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<tr>
<td></td>
<td>(^{208}\text{Pb}(n, 2n) \text{Pb})</td>
<td>(Y_n &gt; 10^6, \Delta \Omega \sim 10^{-2} \text{ sr})</td>
</tr>
<tr>
<td>Neutron energy spectrum ([n(E) , dE])</td>
<td>neutron TOF spectrometry</td>
<td>(Y_n &gt; 10^8, \Delta \Omega \sim 10^{-4} \text{ sr}, \Delta E \sim 1 \text{ KeV})</td>
</tr>
<tr>
<td>Neutron emission time ([n(t)])</td>
<td>neutron streak camera</td>
<td>(Y_n &gt; 10^{10}, \Delta \Omega \sim 10^{-2} \text{ sr}, \Delta t \geq 10 \text{ ps})</td>
</tr>
<tr>
<td>Neutron emission region ([n(R)])</td>
<td>p/hole imaging</td>
<td>(Y_n &gt; 10^{12}, \Delta R \sim 5 \mu \text{m})</td>
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<tr>
<td></td>
<td>zone-plate-coded imaging</td>
<td>(Y_n &gt; 10^{11}, \Delta R \sim 10 \mu \text{m})</td>
</tr>
<tr>
<td></td>
<td>((\alpha) particles)</td>
<td>(Y_n &gt; 10^8, \Delta R \sim 5 \mu \text{m})</td>
</tr>
<tr>
<td>Fuel (&lt;\rho R&gt;)</td>
<td>knock-on DT ion spectrometry</td>
<td>((Y_n \cdot &lt;\rho R&gt;) &gt; 10^6 \text{ g/cm}^2, \Delta \Omega \sim 10^{-2} \text{ sr})</td>
</tr>
<tr>
<td></td>
<td>(^{85}\text{Kr} (n, 2n) \text{Kr}) activation</td>
<td>((Y_n \cdot &lt;\rho R&gt;) &gt; 10^{10} \text{ g/cm}^2, \Delta \Omega \sim 10^{-2} \text{ sr})</td>
</tr>
<tr>
<td>Shell (&lt;\rho \Delta R&gt;)</td>
<td>(^{28}\text{Si}(n, p) \text{Si})</td>
<td>((Y_n \cdot &lt;\rho \Delta R&gt;) &gt; 10^7 \text{ g/cm}^2, \Delta \Omega \sim 10^{-2} \text{ sr})</td>
</tr>
</tbody>
</table>

\(\Delta \Omega = \) detection solid angle, \(\Delta E = \) energy resolution, \(\Delta t = \) time resolution

*Assumes a 10\(^{-3}\) mass ratio between Kr tracer gas and DT fuel

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Exceeding 10\(^6\). Most common in ICF experiments is the use of Ag\(^{111}\), Cu\(^{64}\), and Pb-activation techniques, which have high sensitivity even with counting times of less than five minutes and relatively small collection-solid-angles \(\Delta \Omega\).

The ion temperature \((T_i)\) of the fusion fuel can be measured by a variety of techniques, including neutron time-of-flight (TOF) spectrometry. For some target configurations, a simultaneous measurement of \(T_i\) through TOF spectrometry of the various fusion products is desirable. These include the deuterium-tritium (DT), 14.1-MeV neutrons and the 3.5-MeV \(\alpha\) particles, as well as the deuterium-deuterium (DD) fusion, 3.02-MeV protons. The neutron time-of-flight spectrometer on OMEGA consists of a single ultrafast neutron detector,\(^5\) comprising a quenched
(t_{\text{rise}} \sim 100 \text{ ps}) \text{ scintillator, close-coupled to a } GHz\ (t_{\text{rise}} \sim 500 \text{ ps})\ \text{Chevron-type microchannel plate (MCP) photomultiplier, located 8.6 m from the target, in conjunction with a } GHz\ \text{oscilloscope.}\ \text{In high-yield experiments without significant shielding, the MCP detector was found to be affected by } \gamma\ \text{rays produced by neutron reactions occurring in the 75-mm-thick stainless-steel target-chamber wall. This signal could be so intense as to degrade the linearity of the MCP for the neutron-burst detection. Other recording devices utilizing MCP's, such as image intensifiers in streak cameras, were similarly affected. The mean ion temperature, } <T_i>\ (\text{keV}),\ \text{is deduced using Brysk's derivation}\ \text{of the neutron energy spread, } \Delta E = 177 <T_i>^{1/2},\ \text{where both } \Delta E\ \text{and } T_i\ \text{are in keV.}\ \text{The present device has an energy resolution of } \sim 1 \text{ keV. For future high-density experiments in which low ion temperatures } (T_i \lesssim 2 \text{ keV})\ \text{are expected, greater spectral resolution will be required.}

A primary parameter of target performance is the fuel areal density \( <\rho R> \) at the time of peak compression. This parameter can be determined by both x-ray and nuclear diagnostics. Although x-ray spectroscopy of tracer gases in the fuel, and x-ray photography of the compressed shell can provide a measure of the density of the fuel and its spatial extent, nuclear diagnostics have the advantage of diagnosing the fuel conditions at the time of neutron generation. Up to now these nuclear diagnostics have been (a) knock-on ion spectrometry,\ providing a direct estimate of the fuel \( <\rho R> \), and (b) neutron activation of Si in the shell, giving a measure of the shell areal density \( <\rho\Delta R> \) and, through hydrodynamic code simulations, an estimate of the final fuel conditions. The latter technique detects the total number of \( ^{28}\text{Si} \quad (n,p)\quad ^{28}\text{Al} \) reactions induced in the imploding glass shell. A small known fraction of the target debris is collected in a thin Ti cone and rapidly transferred to a radiochemical counting system.\ The number of \( ^{28}\text{Si} \) transmutations, \( N_e^* \), is obtained by detecting the coincident 1.78-MeV \( \gamma \) ray and 2.86-MeV \( \beta \) particle decays from \( ^{28}\text{Al} \). The shell \( <\rho\Delta R> \) is then linearly related to the activation yield \( N_e^* \) by the formula\text{\footnote{This is a footnote.}}

\begin{equation}
N_e^* = \frac{f}{\eta_c} \frac{\alpha}{\Lambda_f} \cdot <\rho\Delta R>,
\end{equation}

where \( \alpha \) is the cross section for the \( ^{28}\text{Si} \quad (n,p)\quad ^{28}\text{Al} \) reaction (0.250 b), \( f \) is the fraction of Si ions in the shell, \( \alpha \) is Avogadro's number, and \( \Lambda_f \) is the average atomic weight of the shell. The value of \( N_e^* \) is determined, from the number of coincidence decays \( N_c \) detected over a time \( \Delta t \) starting at a time \( \tau \) after the laser shot, by the equation

\begin{equation}
N_e^* = \frac{N_c}{\eta_c \eta_d e^{-\lambda \Delta t} (1 - e^{-\lambda \Delta t})},
\end{equation}

where \( \eta_c \) and \( \eta_d \) are the collector and detector efficiencies and \( \lambda \) is the \( ^{28}\text{Al} \) decay constant. The background count level of the system on OMEGA is \( \sim 0.54 \) counts/min, and thus for a signal of ten counts recorded over a five-minute interval a minimum value of the \( Y_n \cdot <\rho\Delta R> \) product of \( \sim 10^7 \) neutron-g/cm\(^2\) is detectable.

In the measurement of the fuel \( <\rho R> \), a fraction of the deuterons and tritons scattered by 14.1-MeV neutrons in the compressed fuel is
collected by thin (140-μm) CR-39 nuclear-track detectors inserted in Ta-filtered cells, subtending a total solid angle of \( \Delta \Omega \sim 1\% \). The total number of scattered fuel ions (Q) is related to the fuel conditions by

\[
Q = (\sigma_T \langle \rho_T R \rangle + \sigma_D \langle \rho_D R \rangle) Y_n ,
\]

where \( \rho_T \) and \( \rho_D \) are the triton and deuteron densities and \( \sigma_T \) and \( \sigma_D \) are their cross sections for neutron elastic scattering (0.92b and 0.62b, respectively). The number of scattered particles detected, \( N_i \), is given by

\[
N_i = (0.18 / 4\pi) \Delta \Omega \varepsilon \langle \rho R \rangle Y_n ,
\]

where \( \varepsilon \) is the fraction of particles that can produce a signal in the CR-39, and is determined from its response characteristics, filter transmission functions, and other factors. This simple technique provides an unambiguous measure of the fuel \( \langle \rho R \rangle \) for targets in which the deuteron and triton energy spectra are not moderated by passage through the compressed shell. It is ideal for the diagnosis of high-yield implosions of high-aspect-ratio targets, but is expected to be of limited value for thick-glass shell targets designed for moderately high-density (e.g., 50 x liquid density) implosions. With the fabrication of cryogenic polymer shell targets, which should provide optimal high-density performance, knock-on ion spectrometry will again become a valid diagnostic.

An alternative approach that does not suffer from compressed-shell moderation effects depends on the activation of tracer gas elements in the fuel. The specific reaction being investigated is the \( ^{80}\text{Kr} (n,2n) ^{79}\text{mKr} \) reaction in which the \( ^{79}\text{mKr} \) emits \( \gamma \) rays of energy of \( \sim 130 \text{ keV} \) with a half-life of \( \sim 50 \text{ s} \). The use of krypton has the advantage that the gas is inert, does not permeate into glass, and is compatible with cryogenic targets. This technique does not have the sensitivity of knock-on ion spectrometry, but for \( ^{80}\text{Kr} \) concentrations small enough not to impair target performance (\( < 10^{-3} \text{ Kr to DT mass ratio} \)), it will provide a measure of \( \langle \rho R \rangle \) for targets having complex shell structures and high final fuel densities.

Other parameters of value in determining target performance and in comparing the latter to hydrodynamic code simulations are the time, duration, and region size of the neutron emission. Considerable effort is now being made to satisfy these demands.

Available detectors for single bursts of 14.1-MeV neutrons have temporal resolutions of \( \sim 400 \text{ ps} \), insufficient to resolve the thermonuclear burn time for most fusion targets. Several approaches have been proposed or are currently under investigation to provide better than 100-ps resolution.
terminating the symmetry of the implosion. Several approaches to imaging the neutron emission directly have been proposed, including the use of pinhole imaging, zone-plate-coded imaging, and penumbral imaging. All these techniques are limited in sensitivity. Nonetheless, we can expect exploratory studies in the near future with high-yield targets producing neutron yields in excess of $10^{11}$. Additionally, for these targets, demonstrated techniques of measuring the burn-region size by zone-plate-coded imaging of the $\alpha$ particles are possible. However, for targets designed to achieve high density, the $\alpha$ particles will be stopped in the compressed shell.

In summary, it can be seen that current fusion experiments are providing conditions that enable the development of a number of diagnostics of the compressed fuel region. It is evident that an unambiguous assessment of the physical state of the compressed fuel and of its symmetry cannot be obtained, or compared with the predictions of hydrodynamic code simulations, without the simultaneous use of several of these diagnostics.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy Office of Inertial Fusion under agreement Nos. DE-FC08-85DP40200 and W-7405-ENG-48, and by the Laser Fusion Feasibility Project at the Laboratory for Laser Energetics, which has the following sponsors: Empire State Electric Energy Research Corporation, General Electric Company, New York State Energy Research and Development Authority, Ontario Hydro, Southern California Edison Company, and the University of Rochester. Such support does not imply endorsement of the content by any of the above parties.

REFERENCES


