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,[1] high-yield and high-density laser-fusion experiments can be undertaken. Since the first kilojoule, short-wavelength laser experiments at the beginning of 1985,[2] the highest measured neutron yield has gone up by over a factor of 300, in experiments performed by three laboratories.[3-5] In the most recent experiment,[5] a neutron yield of 1.1×10^{13} was achieved. This corresponds to a yield efficiency (thermonuclear energy divided by the laser energy) of 1.5×10^{-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.I, 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.I
Neutron diagnostics of compressed fusion targets.

Target Parameter	Diagnostic Approach	Sensitivity, Resolution
Neutron fluence (Y_n)	scintillator/photomultipliers	$Y_n > 10^4$, $\Delta\Omega \sim 10^{-3}$ sr
	Ag (n, β^-) Cd	$Y_n > 10^6$, $\Delta\Omega \sim 10^{-2}$ sr
	^{63}Cu(n, 2n) ^{62}Cu	$Y_n > 10^6$, $\Delta\Omega \sim 10^{-2}$ sr
	^{208}Pb(n, 2n) ^{207m}Pb	$Y_n > 10^6$, $\Delta\Omega \sim 10^{-2}$ sr
Neutron energy spectrum [n(E) dE]	neutron TOF spectrometry	$Y_n > 10^8$, $\Delta\Omega \sim 10^{-4}$ sr, $\Delta E \sim 1$ KeV
Neutron emission time [n(t)]	neutron streak camera	$Y_n > 10^{10}$, $\Delta\Omega \sim 10^{-2}$ sr, $\Delta t \gtrsim 10$ ps
Neutron emission region [n(R)]	pinhole imaging	
	zone-plate-coded imaging	$Y_n > 10^{12}$, $\Delta R \sim 5\,\mu m$
	penumbral imaging	$Y_n > 10^{11}$, $\Delta R \sim 10\,\mu m$
	zone-plate-coded imaging (α particles)	$Y_n > 10^8$, $\Delta R \sim 5\,\mu m$
Fuel $<\rho R>$	knock-on DT ion spectrometry	$(Y_n \cdot <\rho R>) > 10^6$ g/cm^2, $\Delta\Omega \sim 10^{-2}$ sr
	^{80}Kr (n, 2n) ^{79m}Kr activation	$(Y_n \cdot <\rho R>) > 10^{10}$ g/cm^2, $\Delta\Omega \sim 10^{-2}$ sr*
Shell $<\rho\Delta R>$	^{28}Si(n, p) ^{28}Al	$(Y_n \cdot <\rho\Delta R>) > 10^7$ g/cm^2, $\Delta\Omega \sim 10^{-2}$ sr

$\Delta\Omega$ = detection solid angle, ΔE = energy resolution, Δt = 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-, Cu-, 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 α 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,[6] comprising a quenched

(t_{rise} ~100 ps) scintillator, close-coupled to a GHz (t_{rise} ~500 ps) Chevron-type microchannel plate (MCP) photomultiplier, located 8.6 m from the target, in conjunction with a GHz oscilloscope.[3] In high-yield experiments without significant shielding, the MCP detector was found to be affected by γ 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, $<T_i>$ (keV), is deduced using Brysk's derivation[7] of the neutron energy spread, $\Delta E \approx 177 <T_i>^{1/2}$, where both ΔE and T_i are in keV. The present device has an energy resolution of ~1 keV. For future high-density experiments in which low ion temperatures ($T_i \lesssim 2$ keV) 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,[8] and x-ray photography[9] 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,[10] 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}Si (n,p) ^{28}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.[12] The number of ^{28}Si transmutations, N_s^*, is obtained by detecting the coincident 1.78-MeV γ ray and 2.86-MeV β particle decays from ^{28}Al. The shell $<\rho \Delta R>$ is then linearly related to the activation yield N_s^* by the formula[13]

$$N_s^* = f(Y_n\, \sigma_f\, A_o / A_w) \cdot <\rho \Delta R> \quad , \tag{1}$$

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

$$N_s^* = N_c / [\eta_c\, \eta_d e^{-\lambda t} (1 - e^{-\lambda \Delta t})] \quad , \tag{2}$$

where η_c and η_d are the collector and detector efficiencies and λ is the ^{28}Al decay constant. The background count level of the system on OMEGA is ~ 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 ~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[14]

$$Q = (\sigma_T < \rho_T R > + \sigma_D < \rho_D R >) Y_n , \quad (3)$$

where ρ_T and ρ_D are the triton and deuteron densities and σ_T and σ_D are their cross sections for neutron elastic scattering (0.92b and 0.62b, respectively). The number of scattered particles detected, N_t^* is given by[14]

$$N_t^* = (0.18 / 4\pi) \Delta\Omega \, \epsilon < \rho R > Y_n , \quad (4)$$

where ϵ 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.[15] This simple technique provides an unambiguous measure of the fuel $<\rho R>$ 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 $\times$ 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 $<\rho R>$ 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[16] is the ^{80}Kr (n,2n) ^{79m}Kr reaction in which the ^{79m}Kr emits γ rays of energy of ~ 130 keV with a half-life of ~ 50 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}Kr concentrations small enough not to impair target performance ($< 10^{-3}$ Kr to DT mass ratio), it will provide a measure of $<\rho R>$ 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 ~ 400 ps,[6] 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.[17-20]

Knowledge of the size of the thermonuclear burn region is important for determining the fraction of the compressed fuel region contributing to neutron generation, for assessing the local fuel conditions, and for determining 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,[21] and penumbral imaging.[22] 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[23] of measuring the burn-region size by zone-plate-coded imaging of the α particles are possible. However, for targets designed to achieve high density, the α 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.

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REFERENCES

1. J. M. Soures, R. J. Hutchison, S. D. Jacobs, L. D. Lund, R. L. McCrory, and M. C. Richardson, *Proceedings of the 10th Symposium on Fusion Engineering*, Philadelphia, PA, 1983 (IEEE, New York, 1984), p. 1392.

2. M. C. Richardson, W. Beich, J. Delettrez, M. Dunn, L. Folnsbee, R. J. Hutchison, S. A. Jacobs, R. Keck, T. Kessler, W. Lampeter, R. Leary, S. Letzring, F. J. Marshall, R. L. McCrory, S. Morse, R. Peck, G. Pien, C. Pruitt, D. Quick, F. Rister, W. Seka, M. Simpson, S. Skupsky, D. Smith, J. M. Soures, C. P. Verdon, W. Watson, and D. Whiteman, *Proc. Conf. on Lasers and Electro-Optics 1985*, Baltimore, MD (Optical Society of America, 1985), p. 234.

3. M. C. Richardson, P. McKenty, R. F. Keck, F. J. Marshall, D. M. Roback, C. P. Verdon, R. L. McCrory, and J. M. Soures (to be published); *Laser Interaction and Related Plasma Phenomena*, Vol. 7 (Plenum Press, NY, to be published)

4. C. Yamanaka *et al., Laser Interaction and Related Plasma Phenomena*, Vol. 7 (Plenum Press, NY, to be published).

5. S. M. Lane, M. D. Cable, S. G. Prussin, S. G. Grendinning, D. H. Munro, S. P. Hatchett, K. G. Estabrook, L. J. Suter, M. C. Richardson, P. W. McKenty, D. Roback, and C. P. Verdon, presented at 6th Topical Conf. High Temp. Plasma Diag., Hilton Head, SC (March 1986).

6. P. B. Lyons *et al.*, *Nucl. Instrum. Methods* **171**, 459 (1980).
7. H. Brysk, *Plasma Phys.* **15**, 611 (1973).
8. B. Yaakobi, D. M. Villeneuve, M. C. Richardson, J. M. Soures, R. Hutchison, and S. Letzring, *Opt. Commun.* **43**, 343 (1982).
9. M. C. Richardson, T. R. Boehly, B. A. Brinker, T. C. Bristow, R. S. Craxton, J. A. Delettrez, G. Enright, A. Entenberg, W. Friedman, L. M. Goldman, J. Hoose, R. J. Hutchison, L. Iwan, S. Kacenjar, K. Lee, S. A. Letzring, L. D. Lund, R. S. Marjoribanks, R. L. McCrory, J. M. Miller, J. Rizzo, W. D. Seka, S. Skupsky, J. M. Soures, C. P. Verdon, D. M. Villeneuve, E. A. Williams, and B. Yaakobi, in *Laser Interaction and Related Plasma Phenomena*, Vol. 6, edited by H. Hora and G. Miley, (Plenum Press, NY, 1984), p. 903.
10. S. Kacenjar, S. Skupsky, A. Entenberg, L. Goldman, and M. Richardson, *Phys. Rev. Lett.* **49**, 463 (1982).
11. E. M. Campbell, W. M. Plaeger, P. H. Lee, and S. M. Lane, *Appl. Phys. Lett.* **36**, 965 (1980).
12. E. M. Campbell, H. G. Hicks, W. C. Mead, L. W. Coleman, C. W. Hatcher, J. H. Dellis, M. J. Boyle, J. T. Larsen, and S. M. Lane, *J. Appl. Phys.* **51**, 6065 (1980).
13. S. M. Lane, E. M. Campbell, and C. Bennett, *Appl. Phys. Lett.* **37**, 600 (1980).
14. S. Skupsky and S. Kacenjar, *J. Appl. Phys.* **52**, 2608 (1981).
15. S. Kacenjar, L. M. Goldman, A. Entenberg, and S. Skupsky, *J. Appl. Phys.* **56**, 2027 (1984).
16. S. Prussin, S. M. Lane, M. C. Richardson, and S. Noyes, presented at the 6th Topical Conf. High Temp. Plasma Diagnostics, Hilton Head, SC (March 1986).
17. C. L. Wang, R. Kalibjian, and M. S. Singh, *International Congress on High-Speed Photography and Photonics* (SPIE, Bellingham, WA, 1983), Vol. 348, p. 276.
18. C. L. Wang, R. A. Lerche, H. Medicki, G. E. Phillips, and M. S. Singh, presented at the 6th Topical Conf. High Temp. Plasma Diagnostics, Hilton Head, SC (March 1986); *Rev. Sci. Instrum.* **57**, 1749 (1986).
19. H. Kislev and G. Miley, *ibid.,* 1746 (1986).
20. H. Niki *et al., ibid.,* 1743 (1986).
21. R. A. Lerche, S. M. Lane, A. M. Hawryluk, and N. M. Ceglio, presented at the 6th Topical Conf. High Temp. Plasma Diagnostics, Hilton Head, SC (March 1986).
22. K. A. Nugent, B. Luther-Davies, and A. Perry, in *Laser Interaction and Related Plasma Phenomena*, Vol. 7, edited by G. Miley and H. Hora (Plenum Press, NY).
23. N. M. Ceglio and L. W. Coleman, *Phys. Rev. Lett.* **39**, 20 (1977).