Neutron diagnosis of compressed ICF targets

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The final stages in the compression of microencapsulated DT fueled ICF targets require detailed characterization for meaningful comparison with predictions of hydrodynamic codes. The determination of such parameters as the fuel and shell areal densities, the average ion temperature, and the impact of implosion nonuniformities in high-density target implosions present a strong challenge. We describe several approaches utilizing the self-generated neutrons to diagnose these conditions, including neutron spectrometry, neutron activation of tracer gas and shell materials, and neutron scattering techniques. The importance of making simultaneous measurements of several core parameters to limit ambiguity in interpretation is discussed.

With the development of large, high-intensity, multibeam, short-wavelength laser systems, such as the 24-beam 351-nm, 2.5-kJ, nanosecond OMEGA symmetric irradiation facility,[1] high-yield, and high-density laser fusion experiments can be made. Since the commencement of the first kilojoule short-wavelength (351 nm) irradiation experiments at the beginning of 1985,[2] the highest measured neutron yield has risen by over a factor of 300, arising from experiments performed in three separate laboratories.[3–5] In the latest experiments, a neutron yield efficiency, defined as the ratio of neutron to incident laser energy of 1.5×10^{-3} was achieved with a neutron yield of 1.1×10^{13}. 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. In this paper we review a number of these diagnostics, some deployed on OMEGA for assessing the uniformity of direct-drive fusion experiments. In particular, we stress that simultaneous measurements of several parameters of the compressed core at the time of neutron generation are necessary for an unambiguous interpretation of the symmetry and integrity of the thermonuclear burn region.

The compressed core parameters accessible through neutron-dependent diagnostics presently on line at the OMEGA facility or under development are listed in Table 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 transient point source targets can be measured by a variety of techniques with high precision

TABLE I. Neutron diagnostics for compressed fusion target analysis. ($\Delta\Omega$ = detection solid angle, ΔE = energy resolution, and Δt = time resolution.)

Target parameter	Diagnostic approach	Sensitivity, resolution
Neutron flux (Y_n)	Scintillator/photomultipliers	$Y_n > 10^4$, $\Delta\Omega \gtrsim 10^{-3}$ s.r.
	$Ag(n,\beta^-)Cd$	$Y_n > 10^6$, $\Delta\Omega \sim 10^{-2}$ s.r.
	$^{63}Cu(n,2n)^{62}Cu$	$Y_n > 10^6$, $\Delta\Omega \sim 10^{-2}$ s.r.
	$^{208}Pb(n,2n)^{207m}Pb$	$Y_n > 10^6$, $\Delta\Omega \sim 10^{-2}$ s.r.
Neutron energy spectrum $[E(n)dE]$	Neutron TOF spectrometry	$Y_n > 10^8$, $\Delta\Omega \sim 10^{-4}$ s.r., $\Delta E \sim 1$ keV
Neutron emission time $[n(t)]$	Neutron streak camera	$Y_n \sim 10^{10}$, $\Delta\Omega \sim 10^{-2}$ s.r., $\Delta t \gtrsim 10$ ps
Neutron emission region $[n(R)]$	Pinhole imaging	
	Zone plate coded imaging	$Y_n \gtrsim 10^{12}$ $\Delta R \sim 5\ \mu m$
	Penumbral imaging	$Y_n \gtrsim 10^{11}$ $\Delta R \sim 10\ \mu m$
	Zone plate coded imaging (α particles)	$Y_n \gtrsim 10^{8}$ $\Delta R \sim 5\ \mu m$
Fuel $\langle \rho R \rangle$	Knock-on DT ion spectrometry	$(Y_n \langle \rho R \rangle) > 10^6$ g cm^{-2}, $\Delta\Omega \sim 10^{-2}$ s.r.
	$^{80}Kr(n,2n)^{79m}Kr$ activation	$(Y_n \langle \rho R \rangle) > 10^{10}$ g cm^{-2}, $\Delta\Omega \sim 10^{-2}$ s.r.[a]
Shell $\langle \rho \Delta R \rangle$	$^{28}Si(n,p)^{28}Al$	$(Y_n \langle \rho \Delta R \rangle) > 10^7$ g cm^{-2}, $\Delta\Omega \sim 10^{-2}$ s.r.

[a] Assumes a 10^{-3} mass ratio between Kr tracer gas and DT fuel.

($<1\%$) for neutron yields $>10^6$. Most common in ICF experiments is the use of Ag, Cu, and Pb activation techniques which, for a low-collection solid angle ($\Delta\Omega$), have high sensitivity for manageable counting times (<5 min).

The fusion fuel ion temperature (T_i) 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 DT fusion 14.1-MeV neutrons, the 3.5-MeV α particles, and the DD fusion 3.02-MeV protons would be desirable.

The neutron time-of-flight spectrometer on OMEGA consists of a single ultrafast neutron detector,[6] comprising a quenched ($t_{\rm rise} \sim 100$ ps) scintillator, close coupled to a GHz ($t_{\rm rise} \sim 500$ ps) chevron-type microchannel plate (MCP) photomultiplier, spaced 8.6 m from 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. With suitable protection from γ-ray deexcitation, the mean ion temperature, $\langle T_i \rangle$ (keV) is deduced from Brysk's derivation[7] of the neutron energy spread $\Delta E \simeq 177 \langle T_i \rangle^{1/2}$. 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 anticipated, greater spectral resolution will be required.

A primary determination of target performance is an estimation of the average fuel $\langle \rho R \rangle$. This parameter can be assessed 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 diagnostics have been knock-on ion spectrometry[10] directly providing an estimate of $\langle \rho R \rangle$ and neutron activation of Si in the shell, which give a measure of the shell areal density $\langle \rho \Delta R \rangle$ and through hydrodynamic code simulations an estimate of the final fuel conditions. The latter technique detects the number of ${}^{28}\mathrm{Si}(n,p){}^{28}\mathrm{Al}$ reactions induced in the imploding glass shell. A small known fraction of the target debris is collected in a thin Ti cone and rapidly diagnosed in 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 $\langle \rho \Delta R \rangle$ is then linearly related to the neutron yield Y_n by the formula[13]

$$N_s^* = (Y_n \sigma f A_0 / A_w) \langle \rho \Delta R \rangle,$$

where σ is the cross section for the ${}^{28}\mathrm{Si}(n,p){}^{28}\mathrm{Al}$ reaction ($0.250b$), f is the fraction of Si ions in the shell, A_w is the average atomic weight of the shell, and A_0 is Avogadro's number. The value of N_s^* is determined from the number of coincidence decays N_c detected over a time Δt, commencing a time t after the shot by

$$N_s^* = N_e / \eta_c \eta_d e^{-\lambda t} (1 - e^{-\lambda \Delta t}),$$

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/mm, and thus for a signal of ten counts recorded over a 5-min interval, a minimum value of the Y_n $\langle \rho R \rangle$ product of $\sim 10^7$ neutron-g/cm^2 is detectable.

In the measurement of the fuel $\langle \rho R \rangle$, 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 deployed in Ta-filtered cells subtending a total solid angle $\Delta\Omega \sim 1\%$. The total number of scattered fusion particle ions (Q) is related to the fuel conditions by[14]

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

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[14]

$$N_t^* = \frac{0.18}{4\pi} \Delta\Omega \epsilon \langle \rho_R \rangle Y_n,$$

where ϵ is the fraction of particles that can produce a signal in the CR-39 and is determined from analysis of its response characteristics, filter transmission functions, and other factors.[15] This simply deployable technique renders 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 intermediate high density (i.e., 50× liquid density) goals. With the fabrication of cryogenic polymer shell targets, which should provide optimum high-density performance, knock-on-ion spectrometry will again become a valid $\langle \rho R \rangle$ diagnostic.

An alternative approach to the measurement of the fuel $\langle \rho R \rangle$, currently under investigation, which 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 ${}^{80}\mathrm{Kr}(n,2n){}^{79m}\mathrm{Kr}$ 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 it 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 sufficiently small so as not to impair target performance ($<10^{-3}$ 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 the neutron generation in fusion targets which are of value in determining the target performance, and in comparing the latter to hydrodynamic code simulations are the emission time and duration of the neutrons, and an estimate of the region in the compressed fuel from which they occur. 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 (Ref. 6); insufficient to resolve the thermonuclear burn time for most fusion targets. Several approaches have been proposed or are currently under investigation to provide temporal resolution on the picosecond range.[17–20]

A knowledge of the extent of the thermonuclear burn region is important to determine the fraction of the compressed fuel region contributing to neutron generation, to assessing the local fuel conditions, and to determining the symmetry of the implosion. Several approaches to imaging the neutrons directly have been proposed, including the use of pinhole imaging, zone plate imaging,[21] and penumbral imaging.[22] All these techniques are limited in sensitivity. Nonetheless, we can expect to see exploratory studies in the near future with high yield targets producing neutron fluences in excess of 10^{11}. Additionally, for these types of targets, demonstrated techniques[23] of measuring the burn region by zone plate imaging of the α particles is 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 now providing conditions conducive for 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, nor compared with the predictions of hydrodynamic code simulations, without the simultaneous deployment of many of these diagnostics.

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