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25-ps Neutron Detector for Measuring ICF-Target Burn History

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25-ps neutron detector for measuring ICF-target burn history

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Abstract

We have developed a fast, sensitive neutron detector for recording the fusion reaction-rate history of inertial-confinement fusion (ICF) experiments. The detector is based on the fast rise-time of a commercial plastic scintillator (BC-422) and has a response < 25 ps FWHM. A thin piece of scintillator material acts as a neutron-to-light converter. A zoom lens images scintillator light to a high-speed (15 ps) optical streak camera for recording. A retractable nose cone positions the scintillator between 1 and 50 cm from a target. A simultaneously recorded optical fiducial pulse allows the streak camera time base to be calibrated relative to the incident laser power. Burn histories have been measured for deuterium-tritium filled targets with yields ranging between 10^8 and 2×10^{13} neutrons.

1. BACKGROUND

Several neutron detectors used for measuring the burn-history of ICF targets have been reported.¹⁻⁴ This article describes a fast (25 ps), sensitive, neutron detector developed specifically for measuring the fusion reaction-rate history of ICF targets. We begin with a review of detector characteristics required for making a burn-history measurement. Then, we describe our detector and present examples of measured burn histories.

In ICF experiments, targets filled with deuterium (DD) or a deuterium-tritium (DT) mixture are heated and compressed to conditions under which thermonuclear fusion occurs. At Livermore, we irradiate targets with up to 30-kJ of 0.351- μ m light from the 10-beam Nova laser.⁵ During the plasma confinement time which is on the order of 100 ps⁶, fuel atoms undergo fusion, releasing energetic charged particles, neutrons, and photons. We are interested in the fusion reaction rate relative to the incident laser energy because it is a sensitive indicator of our ability to accurately model energy transport between laser and target.

The reactions of interest in ICF experiments are

where the particle energy is indicated in parentheses. Spectra for each fusion product is nearly monoenergetic. The charged particles are slowed by coulomb interactions with plasma ions and electrons before leaving the fuel. Most neutrons, however, escape from the target without collision. Thus, the neutron temporal distribution at a point outside the target preserves burn history information with a time-of-flight delay. For this reason, burn history may be measured with a fast neutron detector some distance outside the target. Since confinement

times are on the order of 100 ps, a detector with time resolution on the order of 20 ps is highly desirable.

Temporal resolution of a neutron-based measurement is limited by the plasma ion temperature, the target-to-detector distance, and the detector thickness. Thermal motion of the reacting plasma ions causes a Doppler broadening of the neutron energy spectrum.⁷ For neutrons leaving a target at the same instant, the energy distribution causes a spread Δt_T in their arrival times at a detector. The spread is given by

$$\Delta t_T = \left\{ \begin{array}{c} 778 \\ 122 \end{array} \right\} \sqrt{T} \times d \left\{ \begin{array}{c} \text{for DD neutrons} \\ \text{for DT neutrons} \end{array} \right\}, \quad (2)$$

where Δt_T is the FWHM in ps, d is the target-to-detector distance in meters and T is the plasma ion temperature in keV. To keep this time spread small, the detector must be placed close to the target. For example, to keep Δt_T below 20 ps for a 1-keV plasma requires $d < 2.6$ cm for DD neutrons and $d < 16.4$ cm for DT neutrons.

A neutron detector must also be thin to achieve 20-ps response. In a thick detector, there is uncertainty in the neutron interaction point. This results in a corresponding uncertainty in the instant of the interaction which is given by $\Delta t_x = \Delta x/v_n$ where Δx is the detector thickness and v_n is the speed of the neutrons. For 20-ps resolution, detector thickness must be less than 1 mm for DT neutrons and less than 0.4 mm for DD neutrons.

The less stringent distance and thickness requirements for 14-MeV DT neutrons are a distinct advantage for making burn history measurements with DT-filled capsules. Furthermore, the larger fusion cross section for DT neutrons results in a DT-neutron yield nearly 100 times greater than for a hydrodynamic equivalent DD-filled target, and thereby reduces statistical uncertainty in measurements.

2. DETECTOR

Our detector is based on the fast rise time of a plastic scintillator. A thin piece of BC-422⁸ converts neutron kinetic energy to light. As neutrons pass through the scintillator, some of them have elastic collisions with hydrogen nuclei. The resulting recoil protons quickly transfer their kinetic energy to luminescent states in the scintillator. For BC-422 the light output has a rise time < 20 ps and a decay time of ~ 1.2 ns. The temporal distribution of the emitted light is the convolution of the neutron temporal distribution with the scintillator response. Burn history information is encoded in the leading edge of the light pulse. A fast optical streak camera (< 15 ps FWHM) records the signal.⁹

Figure 1 shows the scintillator configuration. A 6-mm diam, 1-mm thick piece of BC-422 is housed in a Hevimet (90% tungsten) nose cone. The front of the nose cone, which is 3mm thick, shields the scintillator from target x rays, scattered laser light, and target debris. An aluminized mirror deposited on one surface of the scintillator doubles the light output directed towards the streak camera. A piece of lead glass shields the back side of the scintillator from scattered x rays. The nose cone design allows the scintillator to be positioned within 1 cm of a target.

Figure 2 shows the detector system. A retractable nose cone positions the scintillator at any point between 1 and 50 cm from the target. An achromatic f/2 zoom lens relays the scintillator image along a 4-m optical path to the S-20 photocathode of the streak camera. This arrangement allows the camera to be outside the chamber. Lens coupling produces minimal temporal dispersion. In contrast, a 4-m coupler made of graded-index optical fibers would produce about 80 ps of dispersion for the 350- to 450-nm scintillator light. Baffling and a light shield prevent scattered laser light from entering the lens system. Scintillator light passes through a glass

window at the vacuum chamber wall. Components inside the chamber can operate at either vacuum or atmospheric pressure. The streak camera image is recorded with a CCD camera. The relatively long distance between target and streak camera is an advantage of this configuration. Background caused by target x rays and neutrons interacting with the streak camera or the CCD decreases inversely with the square of the distance.

Besides the neutron signal, the streak camera also records an optical fiducial pulse. The laser facility generates a 100-ps, 0.53- μm , optical fiducial that is split and distributed to various diagnostic instruments via optical fibers. We insert a 527-ps etalon into the fiducial path to form a series of evenly spaced pulses. The first pulse is a timing reference required to temporally relate the neutron signal to the laser power recorded with other streak cameras. The pulse train provides a calibration check for the time base. Optical fiducial amplitude, timing, and pulse shape are easily controlled because they are independent of target type, incident laser energy, and target-to-detector distance. This is not the case when target-generated x rays are used as the fiducial.

3. REACTION-RATE MEASUREMENTS

Excellent data have been recorded with the instrument. Figure 3a shows a sample image recorded with the scintillator 2 cm from a target producing 6×10^8 DT neutrons. Figure 3b shows image exposure versus time averaged across the spatial extent of the neutron signal. Streak camera flat-field and time-base corrections are included in the signal processing. Information about the target burn history is encoded in the leading edge of the pulse.

The actual neutron temporal distribution is obtained by deconvolving the effect of the scintillator decay from the recorded neutron signal. This fast signal, which is shown in Fig. 4a, is approximately the derivative of the recorded signal. This fast pulse actually represents the convolution of the

neutron temporal distribution with the streak camera response and the derivative of the scintillator rise time. Since rise time and camera response are both < 20 ps, the fast pulse is a good representation of the fusion reaction rate. The quality of the deconvolution is checked by convolving the fast pulse (Fig. 4a) with the exponential decay and comparing the result with the original lineout (Fig. 3b). This is done in Fig. 4b.

Examples of both x-ray and reaction-rate histories are presented in Figs. 5 and 6. For each case, effect of the exponential decay has been deconvolved and the radiation signal has been temporally related to the incident laser power using the fiducial pulse and an appropriate time-of-flight correction. Absolute timing is done with a precision of ± 10 ps.¹⁰ Response to a short, 20-ps burst of x rays demonstrates the scintillator speed and the detector system response (Fig. 5a). This signal was obtained for a gold disk target irradiated with a 20-ps laser pulse containing 70 J of 0.53- μ m light. Such targets produce gold M-band x rays (2.5 - 4 keV) that pass through a 15-mil Al window that replaces the 3-mm thick Hevimet window on the nose cone. The measured 31-ps FWHM signal represents the system response convolved with the 20-ps x-ray pulse. Timing calibrations are typically done with 100-ps laser pulses on gold targets (Fig. 5b).

Reaction-rate history for two DT-filled targets is shown in Fig. 6. These examples demonstrate the capability of the detector over a wide range of neutron yields and burn widths. In each case, neutron yield from an independent measurement was used to determine the magnitude of the reaction rate. Burn histories have been recorded for targets whose yields range from 10^8 to 2×10^{13} DT neutrons. Burn widths have ranged from 60 to over 200 ps.

We have developed and demonstrated a fast, sensitive neutron detector for measuring the burn history of ICF targets. Fusion reaction rates can be measured with a resolution of 25 ps for DT-filled targets producing as-few-as 10^8 neutrons. An optical fiducial pulse allows the time base of the neutron

signal to be related to the incident laser power with a precision of ± 10 ps. This detector represents a significant step forward in our ability to measure reaction-rate history for ICF targets.

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FIGURE CAPTIONS

- FIG. 1. Detector nose cone configuration. Scintillator must be thin and close to the target to control temporal dispersion.
- FIG. 2. Neutron detector system. Scintillator converts neutron kinetic energy to light. Zoom lens relays light to streak camera for recording.
- FIG. 3. Neutron signal. (a) Streak camera image recorded for an indirect-drive target producing 6×10^8 DT neutrons. (b) Average neutron-signal intensity versus time. Burn history is encoded in leading edge of pulse. Pulse tail shows the characteristic decay of the scintillator.
- FIG. 4. (a) Neutron temporal distribution. The effect of scintillator decay has been deconvolved from neutron signal shown in Fig. 3b. (b) Deconvolution check. Fast signal in (a) convolved with exponential decay (dashed line) compared with original data from Fig. 3b (solid line).
- Fig. 5. X-ray measurements. (a) Response to 20-ps pulse demonstrates system speed. (b) Typical calibration signal.
- Fig. 6. Examples of reaction-rate measurements: (a) Indirect-drive target producing 2×10^9 DT neutrons, $d = 4$ cm. (b) Direct-drive target producing 1×10^{12} DT neutrons, $d = 10$ cm..

Figure 1
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Figure 2
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