

NEUTRON TEMPORAL DIAGNOSTIC FOR HIGH-YIELD DT CRYOGENIC IMPLOSIONS ON OMEGA

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A next-generation neutron temporal diagnostic (NTD) capable of recording high-quality data for the highest anticipated yield cryogenic DT implosion experiments was recently installed at the Omega Laser Facility. A high-quality measurement of the neutron production width is required to determine the hot-spot pressure achieved in inertial confinement fusion experiments—a key metric in assessing the quality of these implosions. The design of this NTD is based on a fast-rise-time plastic scintillator, which converts the neutron kinetic energy to 350- to 450-nm-wavelength light. The light from the scintillator inside the nose-cone assembly is relayed ~16 m to a streak camera in a well-shielded location. An ~200× reduction in neutron background was observed during the first high-yield DT cryogenic implosions compared to the current NTD installation on OMEGA. An impulse response of $\sim 40 \pm 10$ ps was measured in a dedicated experiment using hard x rays from a planar target irradiated with a 10-ps short pulse from the

OMEGA EP laser. The measured instrument response includes contributions from the scintillator rise time, optical relay, and streak camera.

I. INTRODUCTION

The temporal history of the neutron production in inertial confinement fusion (ICF) experiments¹ is an important diagnostic signature. In ICF experiments, shells filled with deuterium (D_2) or a deuterium–tritium (DT) mixture are compressed by either direct laser illumination,² soft x-ray radiation in a laser-heated hohlraum,³ or strong magnetic fields⁴ to conditions under which thermonuclear fusion occurs. The temporal width of the neutron signal is usually of the order of 100 ps. Experimental signatures from the temporal history of the neutron production are the rising edge of the measured neutron rate, which is influenced by the shock transit through the capsule;⁵ the peak of the neutron rate (bang time),⁶ a measure of the energy absorbed in the imploding shell; and the trailing edge of the neutron rate that encodes information about material mixing during the stagnation phase of the implosion.⁷

Time-resolved neutron measurements on ICF experiments generally use either a scintillator to convert the neutron energy into visible light⁸ or chemical-vapor–deposition (CVD) diamond detectors,⁹ which convert the neutron energy directly into an electrical charge. The light from the scintillator is either converted into an electrical signal using a fast photomultiplier tube (PMT) or recorded on a fast optical streak camera.^{10,11} The PMT or CVD–based neutron bang-time diagnostics^{12–16} do not have the temporal resolution to resolve the details of the neutron pulse; they measure solely the neutron

bang time. Only the streak-camera–based neutron temporal diagnostics (NTD)^{10,11} are capable of resolving the details of the neutron temporal history.

High-performance, layered cryogenic DT implosions¹⁷ on the OMEGA laser¹⁸ at the University of Rochester’s Laboratory for Laser Energetics (LLE) present a particular challenge to measure the neutron history because of the high-DT neutron yields ($\sim 5 \times 10^{13}$) and the short neutron-production width of the order of ~ 50 ps. The size of the cryogenic target shroud system¹¹ prevents placing the scintillator of the NTD system mounted in port H5 of the OMEGA target chamber (H5-NTD) closer than 20 cm to the target to minimize Doppler broadening of the neutron pulse, which severely compromises the time resolution of this system. A dedicated neutron temporal diagnostic for D₂-filled cryogenic explosions (cryoNTD)¹¹ was developed at LLE to provide high-resolution neutron-emission measurements but the placement of the streak camera close to the target chamber prevents recording data at high-DT yields because of the excessive neutron background. This article describes the setup of a new NTD system at LLE designed for high-performance, layered DT cryogenic implosions mounted in port P11 of the OMEGA target chamber (P11-NTD). In Sec. II the setup of the system is presented. The scintillator can be inserted as close as 9 cm from the target in cryogenic experiments without interfering with the cryogenic target systems and up to 3 cm on room-temperature spherical implosions without interfering with OMEGA laser beams. The streak camera is placed in a well-shielded location >10 m from the target, with an ~ 16 -m-long optical relay system transporting the optical signal from the scintillator to the streak camera. The performance of the shielding setup is reported in Sec. III. The

temporal impulse-response calibration procedure of the P11-NTD system is presented in Sec. IV and the analysis of the first experimental results is shown in Sec. V.

II. SET UP OF THE DETECTOR SYSTEM

A CAD drawing of the P11-NTD system setup is shown in Fig. 1. The front-end scintillator insertion mechanism is re-entrant into the OMEGA target chamber. A 6-mm-diam, 1-mm-thick plastic scintillator (Bicron BC422) (Ref. 19) is placed in a tungsten-alloy-shielded nose cone,¹⁰ which can be inserted between 2 cm and 25 cm from the target. The first section of the optical relay system is housed inside the front end. The second section of the optical relay, the Target Bay wall periscope, is mounted to the OMEGA Target Bay shield wall. The optical path then leads from the OMEGA building into the OMEGA EP plenum, where the Rochester Optical Streak System (ROSS)²⁰ camera is mounted on an optical table.

A. Neutron shielding

Historically, the streak camera of a NTD system has been placed close to the target chamber to minimize the length of the optical relay system.^{10,11} This approach works very well for moderate yields ($<1 \times 10^{13}$ neutrons), but does not provide enough shielding to suppress the backgrounds for the high-DT neutron yields (up to 5×10^{13}) produced in cryogenic DT implosions on OMEGA.¹⁷ To improve the shielding, the streak camera for the P11-NTD was placed behind the primary shield wall of the OMEGA target area in the OMEGA EP plenum area (see Fig. 2). This location provides a standoff distance to the target of ~ 11.4 m, with ~ 1.7 m of concrete in the direct line of

sight, which goes through the OMEGA Target Bay floor, the OMEGA Target Bay retaining wall, and a brick facing wall. It is well known that the performance of a neutron shielding system depends not only on the shielding thickness in the direct line of sight, but also on the number and area of openings like doors and holes in the shielded volume, which allow scattered neutrons to escape the target area.²¹ Since there is a large ~1-m-diam hole under the target chamber, a ~1-m-diam beam tube that carries the OMEGA EP laser pulse from OMEGA EP to OMEGA for joint experiments²² and a number of doors into the room under the target area, the performance of this shielding will be worse than an evaluation using the thickness of the direct line of sight would indicate,²³ which gives an attenuation $>10^5$.

B. Optical system

With the location of the streak camera in a separate building, a relatively complex optical path of 16.2-m length had to be designed. The light collection and transfer system (Fig. 2) transports the light from the scintillator to the input plane of ROSS. A fast three-element $f/2$ lens system collects the light from the scintillator with high efficiency. An optical system using a movable zoom lens and a field lens relays the light from the scintillator to an intermediate image plane outside the target chamber. The location of the zoom lens is remote controlled and adjusted automatically as a function of nose cone position to keep the location of the intermediate image plane fixed. A four-stage optical relay, each consisting of an achromatic relay lens and a field lens, transports the light from the first intermediate image plane to an image plane close to the ROSS camera on the optical table in the OMEGA EP building. A three-element achromatic $f/4$ lens system

focuses the light from the last image plane onto the photocathode of the ROSS. Since the optical path is not a straight line, seven turning mirrors were required to relay the light from the target chamber through the OMEGA shield wall into the OMEGA EP building. High-quality broadband antireflective (AR) coatings were used on the lenses with a typical loss of $\sim 0.3\%$ per surface and dielectric high-reflective (HR) coatings were used on the mirrors with a reflectivity of $>99.5\%$ over the full spectral width of the scintillator emission from ~ 350 nm to 450 nm (Ref. 19). The total transmission of the system was estimated to be $\sim 55\%$, with $\sim 20\%$ losses in the lens material, $\sim 20\%$ in the AR coatings, and $\sim 5\%$ in the HR coatings. The large collection angle of the $f/2$ collection optics ($\sim 4\%$ of 4π) and the low losses of the transport system make it possible, given the 10% quantum efficiency of the S20 photocathode of the streak camera,²⁰ that at least four photoelectrons are produced per 1 MeV of energy the neutron transfers to the scintillator, which produces of the order of 2000 photons.²⁴ Measurements on low-yield implosion experiments have shown that 2.45-MeV D–D fusion neutrons can be reliably detected at a yield of 2×10^9 with the scintillator at 3 cm from the target.

Even though the optical system is corrected for chromatic aberrations, the chromatic velocity dispersion caused by the change in index of refraction with wavelength will introduce a broadening of the impulse response. Using published values for the index of refraction²⁵ of the glasses used in the optical system, this effect was estimated for the optical ray passing through the center of all optics to broaden the full width at half maximum (FWHM) of the instrument response by ~ 8 ps given the spectrum of the scintillator light emission. This value should be considered an upper limit since

most of the light passes through thinner glass than the center ray, and consequently experiences less chromatic velocity dispersion.

In addition to the signal from the scintillator, light from the OMEGA fiducial system is delivered via an optical fiber and imaged onto the streak camera using an optical system internal to the ROSS camera. The OMEGA fiducial consists of a series of eight pulses spaced 548 ps apart and is amplified separately from the main laser pulse, split, and distributed to various diagnostic instruments for precision timing. This fiducial is also recorded on the P510 ultraviolet streak camera,²⁶ which measures the laser pulse shape. The common optical fiducial serves as a reference for both the neutron signal and the laser pulse, thereby enabling accurate timing of the NTD signal.

A similar system to the one that images the OMEGA fiducial on the photocathode is used to image the light from a 2-GHz comb generator onto the ROSS photocathode. The signal from this comb generator can be used to linearize the sweep speed of the streak camera.

III. SHIELDING PERFORMANCE

Figure 4(a) shows the charge-coupled-device (CCD) image recorded by the P11-NTD diagnostics from a high-yield DT cryo shot (2.6×10^{13} neutrons). On the top of the image, the first four of the eight fiducial pulses are visible and six of the pulses from the 2-GHz comb generator are seen at the bottom. The CCD image shows very little background in comparison with the CCD image recorded with the previous-generation NTD system, called H5-NTD [see Fig. 5(a)], at the same yield level. The H5-NTD diagnostics also uses a ROSS streak camera, which is mounted ~ 3 m from the target in

the Target Bay, shielded by 50 cm of CH in the direct line of sight and 10 cm of CH in all other directions. Figures 4(b) and 5(b) show the respective horizontal lineouts through the signals summed over the whole vertical width. Since the scintillator has a very fast rise time of <20 ps and a decay time of ~ 1.2 ns, the neutron-production history information is encoded in the leading edge of the pulse. The most-prominent feature of the background on the H5-NTD signal is a spike at ~ 2.5 ns, which is most likely caused by scattered neutron background present during the retrace of the streak, which starts a few microseconds after the sweep. The signal-to-noise on the P11-NTD system is ~ 50 , which is an $\sim 200\times$ improvement over H5-NTD with a signal-to-noise of ~ 0.25 at this yield level. As expected, this improvement is less than the difference in the line-of-sight shielding and solid angle ($10\times$ improvement resulting from distance) would indicate.

IV. IMPULSE-RESPONSE CALIBRATION

The impulse response of the full P11-NTD including the scintillator, optical transport, and streak camera was measured using x rays from a target illuminated by a short laser pulse (10 ps) from OMEGA EP (see Fig. 6). The shielding from the 2-mm-thick tungsten alloy nose cone allows only hard x rays (>200 keV) to interact with the scintillator. Hard x rays are a reasonable substitute for neutrons to generate light in the scintillator because they interact mostly via Compton scattering in the CH scintillator substrate, which generates fast electrons. These >100 -keV electrons generate electron-hole pairs similar to the MeV protons produced by the elastic scattering from an incident neutron. Even though the electron-hole pair density for the fast electron is significantly lower than for a proton because of the difference in stopping power, it is a better

substitute for the neutron interaction compared to exciting the scintillator by UV irradiation, which interacts mostly with the dyes in the scintillator.²³

For the calibration, the OMEGA EP laser was defocused to spot sizes between 150 and 175 μm and the pulse energy was reduced to ~ 400 J to optimize the signal on the P11-NTD streak camera. The target was an Au foil of $500 \times 500 \times 10\text{-}\mu\text{m}^3$ size. Figure 7(a) shows the temporal history of the signal from four laser shots with different focal-spot conditions for a 3-ns streak-camera sweep window. This signal is obtained by removing the effect of the long scintillator decay from the recorded signal using a “physical-modeling” approach for the deconvolution.¹¹ The signal n_i at the pixel location i is given as the recorded signal s_i minus the sum of all earlier neutron signals, which decay exponentially at the scintillator fall time τ , with Δt_p as the time separation of two pixels:

$$n_i = s_i - \sum_{j=0}^{i-1} n_j \exp\left[\frac{-(i-j) \times \Delta t_p}{\tau}\right] \quad (1)$$

The signals from the x-ray calibration show a stable center part of approximately Gaussian shape with a FWHM of $\sim 50 \pm 2$ ps, a shoulder at the start of the signal, and a tail, which both vary with focus condition [see Fig. 7(a)]. The shoulder ahead of the main pulse could be caused by Cherenkov radiation from MeV Compton-scattered electrons in the $f/2$ collection system since a MeV electron gains ~ 20 ps/cm on light in glass. The tail after the pulse could be from subrelativistic electrons generated in the laser–target interaction hitting the high-Z nose cone, generating hard x-ray bremsstrahlung. Both of

these effects would scale with laser intensity since the slope of the electron energy distribution is steeper for a lower laser intensity, which corresponds to a smaller number of high- and medium-energy electrons.

A single shot was taken with a faster sweep speed corresponding to a 1.5-ns sweep window [see Fig. 7(b)]. Because of the degraded signal-to-noise ratio a stable fit of a Gaussian to the peak of the signal is no longer possible; several different fits with 30- to 40-ps FWHM are consistent with the data.

To infer the impulse response of the P11-NTD system, the width of the x-ray pulse must be subtracted. Since there is no independent measurement of the x-ray pulse duration, simple estimates must be used. A good estimate of the minimum x-ray pulse duration is ~ 15 ps because the laser pulse is ~ 10 ps long and the hot electrons generated in the laser-target interaction typically have a lifetime of a few picoseconds.²⁷ The maximum pulse duration cannot be longer than the shortest measured pulse duration with the 1.5-ns sweep of ~ 35 ps. Consequently, a reasonable estimate of the x-ray pulse duration is 25 ± 10 ps. Subtracting the x-ray pulse in quadrature from the measured FWHM of the signal yields an impulse response of $\sim 40 \pm 10$ ps for the 3-ns sweep window and $\sim 25 \pm 10$ ps for the 1.5-ns sweep window, respectively.

V. DATA ANALYSIS

Figure 8 shows the inferred neutron rate from the deconvolved P11-NTD signal recorded on a recent DT cryogenic implosion on OMEGA with a neutron yield of $\sim 4 \times 10^{13}$. The measured neutron temporal history is broadened by several different mechanisms, which must be subtracted to measure the actual width of the neutron pulse

from the target. Broadening the neutron energy spectrum caused by the high temperature of the thermonuclear plasma leads to an arrival time spread in the scintillator for DT neutrons.¹⁰

$$\Delta t_T^{\text{DT}} = 122\sqrt{T} \times d, \quad (2)$$

where Δt_T^{DT} is the FWHM of the spread in picoseconds, d is the target-to-detector distance in meters, and T is the neutron-averaged ion temperature in keV. For a 10-cm distance of the P11-NTD scintillator to the target, this effect broadens the signal by ~ 25 ps at 4-keV ion temperature, which is typical for most of the high-yield cryo implosions on OMEGA. Additionally, the finite neutron transit time through the scintillator $\Delta t_s = \Delta x / v_n$ broadens the signal by $\Delta t_s^{\text{DT}} = 20$ ps for a scintillator thickness of $\Delta x = 1$ mm and a DT neutron speed of $v_n = 5.12$ cm/ns. Since the shape of the neutron rate is not far from a Gaussian, the impulse response of the instrument, the thermal broadening, and the transit time spread can be subtracted from the measured FWHM of the signal in quadrature to infer the actual neutron pulse width. For a measured FWHM of the neutron signal of 82 ± 2 ps, the resultant neutron pulse width is calculated to be 65 ± 6 ps.

An alternative method of interpreting the experimental data is to convolve the calculated neutron rate from a simulation with the experimental broadening and compare it to the measured signal. Figure 8 shows the comparison of the results of a 1-D *LILAC* simulation of the cryogenic implosion¹⁷ convolved with the experimental broadening

and the P11-NTD data. Since the absolute timing of the NTD instruments is typically of the order of 50 ps (Ref. 11), the simulation data was shifted by ~ 20 ps earlier to better align with the rising edge of the experimental data. The NTD neutron rate was absolutely calibrated using the measured total yield from the standard OMEGA neutron diagnostics. The simulation matches the experimental data very well on the rising edge over more than one order of magnitude in neutron rate. The experimental and simulated neutron rates start to deviate from each other close to the peak of the neutron pulse, with the experimental rate significantly lower than the simulation. This deviation is believed to be caused by 3-D effects, which mix cold material into the hot core plasma, quenching the neutron production rate earlier than expected in the 1-D simulations.⁷

VI. SUMMARY AND OUTLOOK

A new neutron temporal diagnostic (P11-NTD) was developed to measure the temporal history of the neutron production in high-yield, high-performance cryogenic DT implosions on OMEGA. The ROSS streak camera recording system was placed ~ 11 m from the target chamber center behind the primary shield wall, which reduced the neutron background by a factor of ~ 200 . The remote location of the streak camera required the construction of a complex 16.2-m-long image relay to transport the light from the scintillator to the streak camera. The impulse response of the P11-NTD system was measured using hard x rays generated from the interaction of the 10-ps OMEGA EP laser pulse with an Au target. With the standard 3-ns sweep window an impulse response of $\sim 40 \pm 10$ ps was inferred, which allows for measuring the ~ 65 -ps FWHM neutron pulses with an accuracy of $\sim 10\%$. Preliminary measurements of the impulse response of

the system using a 1.5-ns sweep window showed an improved impulse response of $\sim 25 \pm 10$ ps, which would enable the P11-NTD to measure ~ 50 -ps FWHM neutron pulses with $\sim 10\%$ accuracy once this mode of operation is fully validated.

The technique of placing the streak camera of a NTD system outside the bio shield could be relatively easily adapted to larger ICF facilities like the National Ignition Facility (NIF)²⁸ or Laser Mégajoule (LMJ).²⁹ With a typical distance of the shield wall of ~ 15 m from the target, an NTD on these facilities would need an ~ 20 -m-long optical relay, which could be designed without compromising the temporal resolution for sub-ignition experiments where the temporal broadening caused by ion temperature is small [see Eq. (2)]. Given the much-higher neutron yields at the NIF or LMJ, the constraints on the optical transmission of the relay system are significantly relaxed and a narrowband (2- to 10-nm) optical filter at the peak of the scintillator emission spectrum could be used to minimize the chromatic group velocity dispersion. The larger backgrounds caused by x rays from laser-plasma instabilities and n-gamma interactions with the hohlraum target used in these facilities could make neutron-rate measurements challenging.

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FIGURE CAPTIONS:

FIG. 1. A CAD drawing of the P11-NTD detector system integrated into the Omega Laser Facility. A front-end system re-entrant into the target chamber positions the scintillator distances between 2 to 25 cm from the target. An optical relay partially housed in the Target Bay wall periscope structure transports the scintillator light through a penetration in the OMEGA shield wall to a ROSS streak camera in the OMEGA EP plenum.

FIG. 2. A CAD drawing of the P11-NTD shielding setup. The ROSS streak camera is placed 11.4 m from the target. The 60-cm-thick OMEGA target area floor and 80-cm-thick Target Bay shield wall provide most of the neutron shielding.

FIG. 3. A Drawing of the optical layout of the relay optics. A fast three-element $f/2$ lens system collects (CL) the light from the scintillator. A zoom (ZL) and field lens (FL0) relay the light through the vacuum window (VW) to an intermediate image plane (IP0). A four-stage optical relay, each consisting of an achromatic relay lens (RL1–4) and a field lens (FL1–4), transports the light from the first intermediate image using seven mirrors (M1–M7) to a second image plane (IP1). A three-element focus lens system (FS) focuses the light onto the slit of the streak camera.

FIG. 4. (a) A charge-coupled-device (CCD) image from P11-NTD from a high-yield DT cryo shot (2.6×10^{13} neutrons) (b) a horizontal lineout through the signal summed over the whole vertical width.

FIG. 5. (a) A CCD image from H5-NTD from a high-yield DT cryo shot (2.6×10^{13} neutrons), (b) horizontal lineout through the signal summed over the whole vertical width.

FIG. 6. Setup of the calibration of the P11-NTD impulse response using x rays from an Au target illuminated by a short OMEGA EP laser pulse (10 ps). The 2-mm-thick Hevimet nose cone allows only hard x rays (>200 keV) to interact with the scintillator.

FIG. 7. Unfolded P11-NTD signals from the impulse response calibrations. (a) With a 3-ns sweep window at different focus conditions of the short-pulse laser. A 50-ps FWHM Gaussian fit (dashed line) matches the central part of the signal well. (b) With a 1.5-ns sweep window; both a 30-ps (dashed line) and a 40-ps Gaussian (dotted line) are shown.

FIG. 8. Unfolded P11-NTD signal from a high-yield cryo shot (neutron yield of $\sim 4 \times 10^{13}$), compared to results from 1-D *LILAC* hydro simulations.