A new neutron time-of-flight detector for yield and ion-temperature measurements at the OMEGA Laser Facility

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A new neutron time-of-flight (nTOF) detector for deuterium-deuterium (DD)-fusion yield and ion-temperature measurements was designed, installed, and calibrated for the OMEGA Laser Facility. This detector provides an additional line of sight for DD neutron yield and ion-temperature measurements for yields exceeding 1×10^{10} with higher precision than existing detectors. The nTOF detector consists of a 90-mm-diam, 20-mm-thick BC-422 scintillator and a gated Photek photomultiplier tube (PMT240). The PMT collects scintillating light through the 20-mm side of the scintillator without the use of a light guide. There is no lead shielding from hard x rays in order to allow the x-ray instrument response function of the detector to be measured easily. Instead, hard x-ray signals generated in implosion experiments are gated out by the PMT. The design provides a place for glass neutral-density filters between the scintillator and the PMT to avoid PMT saturation at high yields. The nTOF detector is installed in the OMEGA Target Bay along the P8A sub-port line of sight at a distance of 5.3 m from the target chamber center. In addition to DD measurements, the same detector can be used to measure the neutron yield and ion temperature from deuterium-tritium (DT) implosion targets in the 5×10^{10} to 2×10^{12} yield range. The design details and the calibration results of this nTOF detector for both D_2 and DT implosions on OMEGA will be presented.

I. INTRODUCTION

In an inertial confinement fusion (ICF)[1] experiment, a capsule filled with deuterium (D_2) or a deuterium–tritium (DT) fuel is heated by either direct laser illumination or soft x-ray radiation in a laser-heated hohlraum. The target is compressed to conditions under which thermonuclear fusion occurs. The neutron yield and average ion temperature are two of the most important observables from the ICF implosion experiment. Many ICF facilities[2,3] use neutron time-of-flight (nTOF) diagnostics to measure both the DD and DT neutron yield and the ion temperature along different lines of sights, including OMEGA. Until recently, however, only two nTOF detectors on OMEGA called 5.4-m nTOF[4] located at 5.4 m from target chamber center (TCC) in sub-port H10G line of site (LOS) with $\theta = 84.98°$ and $\phi = 311.76°$ (where θ and ϕ are the polar and azimuthal angles of the port in the target chamber coordinate system) and 12-m nTOFL[5] located at 12.4 m from TCC in sub-port H8A LOS with $\theta = 87.86°$ and $\phi = 161.24°$, measured the DD yield and ion temperature above 2×10^{10} yield. To provide an additional line of sight and to increase the yield range of DD measurements, a new nTOF detector was designed, manufactured, and installed on OMEGA. This paper describes this new detector, its calibration, and its performance for both DD and low-yield DT measurements.

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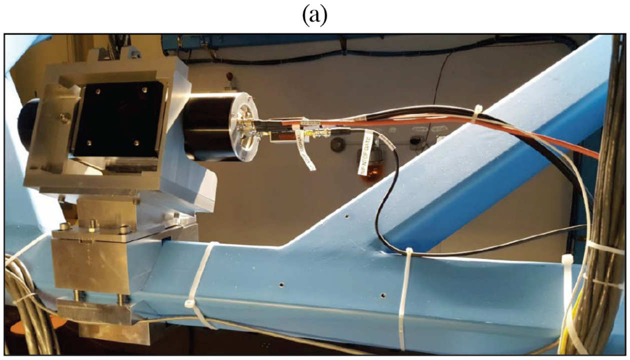
II. EXPERIMENTAL SETUP

The new nTOF detector shown in Fig. 1(a) has a 90-mm-diam, 20-mm-thick BC-422 scintillator in a light-tight aluminum box with thin windows matching the scintillator diameter. The BC-422 scintillator has a sharp rise time and an exponential decay constant of 1.4 ns. The scintillator thickness of 20 mm corresponds to a 0.92-ns transit time for DD neutrons and provides a good match between scintillator decay and transit time through the scintillator. There is no lead shielding protecting the scintillator from hard x rays. The x-ray signal can be recorded and the x-ray instrument response function can be measured. Two photomultiplier tube (PMT) housings originally designed for the nTOF20-IgnLo detectors on the NIF (see Fig. 1 in Ref. 2) are attached to a scintillator box on opposite sides. The PMT's face the 20-mm side of the scintillator without an intermediate light guide between the scintillator and the PMT. To compensate the lower light collection efficiency from the side in comparison with a scintillator directly attached to the PMT photocathode, the scintillator diameter was increased to 90 mm. The scintillator volume of the new nTOF detector is more than 5 times larger than 40 mm × 20 mm BC-422 scintillator in the 12-m nTOFL detector. There is a light-tight compartment with slots for glass neutral-density (ND) filters or aluminum plates with holes between the scintillator and the PMT. These ND filters were successfully operated on the NIF during the National Ignition Campaign.

Up to two PMT's can be used with this detector, but currently only one gated Photek[6] microchannel plate photomultiplier tube (MCP-PMT) PMT240 is deployed. This PMT has a 40-mm-diam photocathode, two MCP's, and provides a gain of up to 1×10^6. To gate out the implosion x-ray signal, a Photek GM10-50B cathode gating module is used. This is not the fastest gating module available from Photek, but it is sufficient for this application. For DD measurements the PMT240 is operated at a bias voltage of –4.4 kV, corresponding to a PMT gain of 2×10^5. A 20-m-long LMR-400 cable connects the PMT nTOF detector to a 1-GHz, 10 GS/s Tektronix DPO7104 oscilloscope. A resistive power divider splits the detector signal among the four oscilloscope channels with different sensitivity settings to increase the dynamic range of the recording system. Since practically all OMEGA Target Chamber sub-ports are used by different diagnostics, it is very difficult to find a new LOS for new nTOF detectors. Therefore, the new nTOF detector was installed in the P8A LOS with $\theta = 109.57°$ and $\phi = 90.00°$ previously used for calibration of the NIF nTOF detectors[2] on OMEGA. The distance of 5.3 m from TCC is determined by the structural support for the detector, see Figure 1(b). Neutrons from TCC are coming from the left on Fig. 1(b) perpendicular to the face of the nTOF detector. This detector was named P8A 5.3-m nTOF.

(a)



(b)

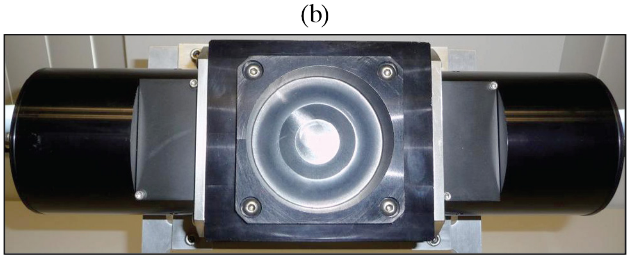


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FIG. 1. Photos of (a) the new nTOF detector on a test bench and (b) the P8A 5.3-m nTOF in the OMEGA Target Bay.

III. DD NEUTRON MEASUREMENTS

One of the first tests that was performed with P8A nTOF was a measurement of the effectiveness of the gate suppression of the hard x-ray signal from an implosion. An ungated large hard x-ray signal can deplete the charge of the MCP inside the PMT, therefore affecting the PMT gain, and compromise the neutron measurement. Figure 2 compares two OMEGA shots with very similar hard x-ray signals; one with the PMT gate "off" and one with the PMT gate "on." In shot 96431 the gate was turned off and P8A nTOF recorded a 135.45-pC charge from hard x rays. In shot 96432 the gate was turned on and P8A nTOF recorded 9.56-pC charge from hard x rays, about 7% of the original hard x-ray signal. The gate produces a 250-V pulse that prevents photoelectrons from the photocathode from reaching the MCP. The residual 7% of charge can be explained by a small percent of photons with enough energy to overcome the 250-V bias gate or produced by direct interaction of x-rays with the MCP inside the PMT. If a signal is produced by direct interaction of x-rays with the MCP, then the gate will have no effect.

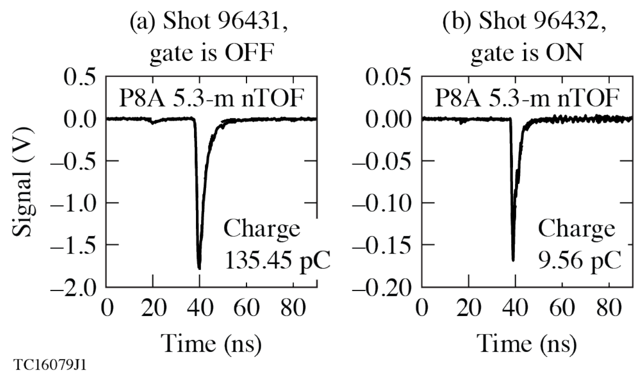

FIG. 2. (a) The x ray in shot 96431 recorded by P8A nTOF with gate "off," and (b) the x ray in shot 96432 recorded by P8A nTOF with gate "on."

Figure 3 shows the typical scope trace from P8A nTOF for the DD shot 98130 with yield 2.15×10^{11}. In all scope traces in this paper, the signal amplitude recorded on the oscilloscope was corrected to take into account the splitter. After such correction, the signal amplitude corresponded to the PMT output. The residual x-ray peak from PMT is seen at ~40 ns, the end of gate pulse is at ~100 ns, and the neutron signal is recorded at ~260 ns. After the gate pulse ended, there is a small signal from a tail of scintillator light decay from the x-ray pulse. The total charge from x rays in the PMT and from the scintillator light decay is small compared with the neutron signal and it does not affect the DD neutron measurements. A comparison of the neutron signals from three DD nTOF detectors on OMEGA for the same shot 96568 with a yield of 5.5×10^{10} and an ion temperature of 3.8 keV is shown in Fig. 4. The PMT gain of the 5.4-m nTOF and 12-m nTOF detectors was 1.0×10^6, the PMT of the P8A nTOF has gain of 2×10^5. From Fig. 4 it is obvious that the P8A nTOF is more sensitive than the 5.4-m nTOF and 12-m nTOFL detectors. The P8A nTOF has a larger scintillator volume and records more neutron interactions than the other two detectors. All nTOF detectors that are located in an un-collimated LOS in the Target Bay have a tail after the main neutron signal, which is created by re-scattered neutrons in the target chamber and surrounding structures which arrive at the nTOF scintillator later in time.

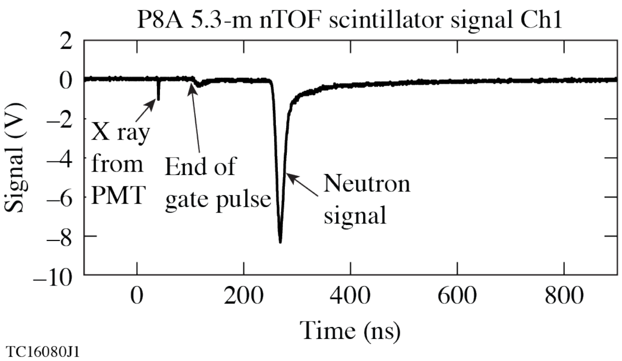

FIG. 3. A scope trace from P8A nTOF for DD shot 98130 with a yield 2.15×10^{11}.

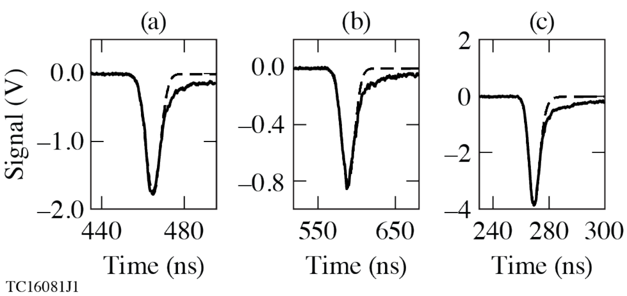

FIG. 4. Comparison of neutron signals from three nTOF detectors: (a) 5.4-m nTOF, (b) 12-m nTOF, (c) P8A 5.3-m nTOF for shot 96568 with yield 5.5×10^{10}.

The measured neutron signal from all three nTOF detectors was fit with a convolution of a Gaussian and an exponential decay function, as described in Ref. 7. In order to remove re-scattering tail from the fit, the fit was performed up to 50% of the falling slope of the signal. The fit is shown in plots on Fig. 4 as a dashed line.

The fitting parameters for the P8A nTOF detector were adjusted so that the ion temperature matches the ion temperature measured by the 12-m nTOFL detector. To reduce the statistical error in the ion temperature measurement from the 12-m nTOFL detector, only shots with a yield exceeding 1×10^{10} were selected for this calibration. Figure 5(a) shows the ion temperature measured by the P8A nTOF versus the ion temperature measured by the 12-m nTOFL detector with the line $y = x$ plotted for comparison. The ratio of ion temperatures measured by these two detectors is shown in Fig. 5(b). The standard deviation for the ion temperature ratio is 4.7%. If we assume the same measurement precision for both detectors, then the ion temperature shot-to-shot precision for a single detector will be 3.3%.

The DD yield calibration of P8A nTOF against 12-m nTOF is shown in Fig. 6. Once again, only shots with yields exceeding 1×10^{10} were selected for the calibration. Figure 6(a) shows the charge of the neutron signal from P8A nTOF plotted versus the DD yield from 12-m nTOF. The line in Fig 6(a) is the linear fit of the data that is forced to go through the point (0,0). Figure 6(a) demonstrates a good linearity of the P8A nTOF detector signal for DD yields up to 4×10^{11}. The data on Fig. 6 were recorded without an ND filter. When an ND filter is used there is practically no upper limit in DD yield measurement for the P8A nTOF detector. Figure 6(b) shows the ratio of the yields from the two detectors as a function of the shot number. The standard deviation of the yield ratio is 3.4%. If we assume the same measurement precision for both detectors, then the yield shot to shot precision for a single detector will be 2.4%.

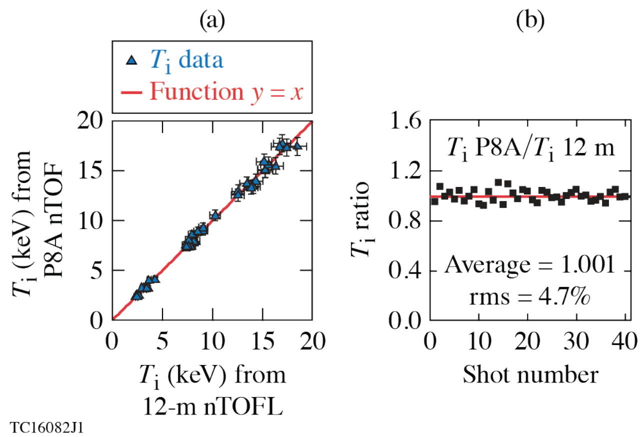

FIG. 5. (a) Ion temperature from P8A 5.3-m nTOF versus ion temperature from 12-m nTOFL and (b) the ratio of ion temperatures from P8A 5.3-m nTOF and 12-m nTOFL detectors.

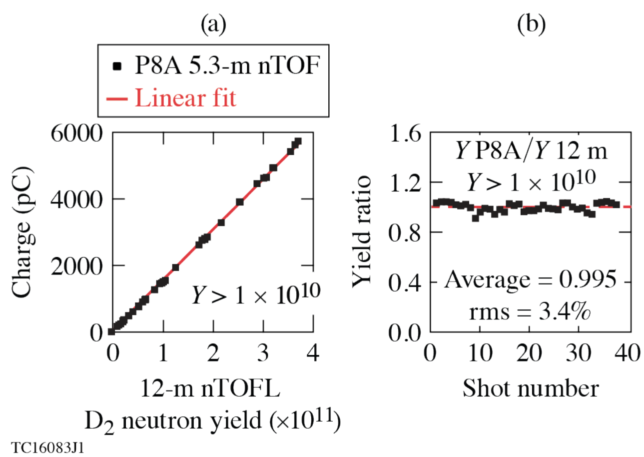

FIG. 6. (a) DD neutron calibration of P8A 5.3-m nTOF against 12-m nTOFL and (b) the ratio of DD yield measured by P8A 5.3-m nTOF and 12-m nTOFL.

IV. DT NEUTRON MEASURMENTS

Most of the Laboratory for Laser Energetics implosion campaigns are designed for DT yields in the range from 1×10^{13} to 1×10^{14} and recently for yields above 3×10^{14}. Therefore, the DT nTOF detectors on OMEGA were designed for such high yields. External OMEGA users, however, sometimes require DT yield measurements from 5×10^{10} to 1×10^{12}. In this yield range the standard DT nTOF detectors on OMEGA (12-m nTOF and 15.8-m nTOF) have poor neutron/photon statistics, low signal level, and are affected by EMP noise that makes it impossible to use these detectors for low DT yield. Example signals showing these issues are shown in Fig. 7(a) and Fig. 7(b). We have adjusted the PMT high-voltage setting of P8A nTOF from –4.4 kV for DD operation to –3.6 kV, corresponding to a PMT gain of 6×10^3 for the DT operation. An example of a high-quality neutron signal from P8A nTOF for a DT shot 96633 with a yield of 2.4×10^{11} and an ion temperature of 9.8 keV is shown in Fig. 7(c).

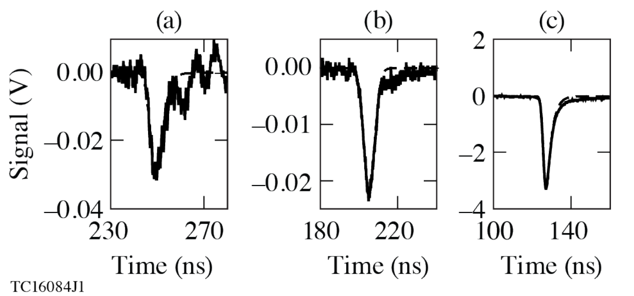

FIG. 7. Comparison of neutron signals from three nTOF detectors: (a) 12-m nTOF, (b) 15.8-m nTOF, (c) P8A 5.3-m nTOF for DT shot 96633 with yield 2.4×10^{11}.

The P8A nTOF was calibrated in DT yield against the Cu activation diagnostic. The OMEGA Cu activation diagnostic is an exact copy of the original LLNL Cu activation diagnostic[8] with simplified and improved lead shielding. The LLE Cu diagnostic has better than 5% absolute DT yield accuracy[9].

Figure 8(a) shows the charge of the neutron signal from P8A nTOF plotted versus the DT yield from Cu activation. The straight line in Fig. 8(a) is a linear fit of the data that is forced to go through the point (0,0). Figure 8(a) demonstrated that P8A nTOF is linear in the desired DT yield range from 5×10^{10} to 1×10^{12}. Figure 8(b) shows the ratio of the yields from the two detectors as a function of shot number. The standard deviation for the yield ratio is 2%.

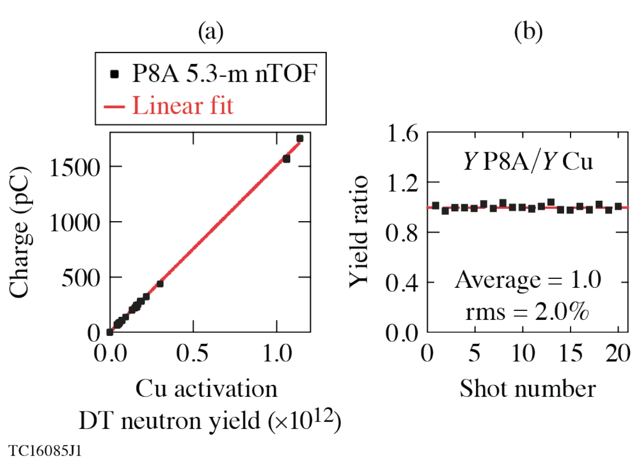

FIG. 8. (a) DT neutron calibration of P8A 5.3-m nTOF against copper activation and (b) the ratio of DT yield measured by P8A 5.3-m nTOF and copper activation.

If we assume the same measurement shot to shot precision for both detectors, then the yield standard deviation for a single detector shot-to-shot precision will be better than 1.5%. The absolute DT yield accuracy (systematic uncertainty) is determined by absolute Cu activation DT calibration accuracy and is about 5%.

The P8A nTOF was also calibrated in DT ion temperature against the 22-m nTOF Petal detector. There are two identical so-called Petal nTOF detectors on OMEGA in different LOS, one along port P7 at 13 m from TCC and one along port H10 at 22 m from TCC. The design of the Petal nTOF detector and a timing calibration of the 13-m Petal nTOF are described in Ref. 10. The calibration of the 22-m nTOF Petal was very similar. The 13-m Petal nTOF is more sensitive than 22-m Petal nTOF, but during these low yield DT shots it was blocked by another diagnostic. This forced us to use the 22-m Petal for the DT ion temperature calibration. Figure 9(a) shows the ion temperature from P8A nTOF versus the ion temperature measured by 22-m nTOF Petal with the line $y = x$ plotted for comparison. The ratio of ion temperatures from these two detectors is shown in Fig. 9(b). The standard deviation for the ion temperature ratio is 6.2% and it is primary determined by the poorer neutron statistics in the 22-m nTOF Petal detector.

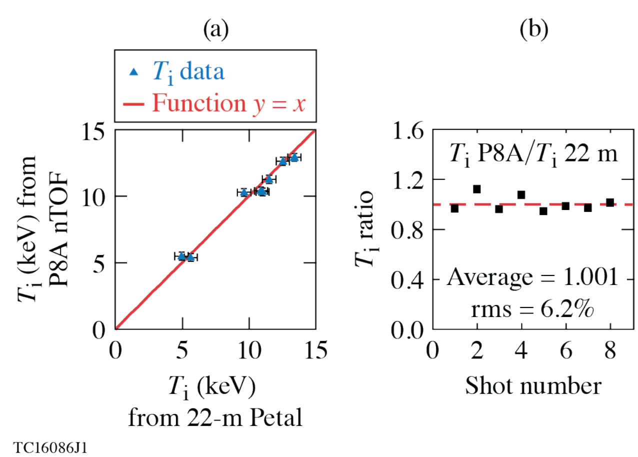

FIG. 9. (a) Ion temperature from P8A 5.3-m nTOF versus ion temperature from 22-m nTOF Petal and (b) the ratio of ion temperatures from P8A 5.3-m nTOF and 22-m nTOF Petal detectors.

V. SUMMARY

A new nTOF detector was installed and calibrated on the OMEGA Laser System. This detector is now a standard OMEGA diagnostic for DD neutron yield above 1×10^{10} and DT yields from 5×10^{10} to 2×10^{12}.

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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REFERENCES

[1] J. D. Lindl, *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive* (Springer, New York, NY, 1998).
[2] V. Yu. Glebov *et al*., Rev. Sci. Instrum. **81**, 10D325 (2010).
[3] V. Yu. Glebov *et al*., Rev. Sci. Instrum. **92**, 013509 (2021).
[4] M. A. Russoto and R. L. Kremens, Rev. Sci. Instrum. **61**, 3126 (1990).
[5] V. Yu. Glebov *et al*., Rev. Sci. Instrum. **75**, 3559 (2004).
[6] http://www.photek.com
[7] T. J. Murphy, R. E. Chrien, and K. A. Klare, Rev. Sci. Instrum. **68**, 610 (1997).
[8] Laser Program Annual Report-1976, Lawrence Livermore Laboratory, Rept. UCRL-50021-76, 3-105 (1976).
[9] O. Landoas *et al*., Rev. Sci. Instrum. **82**, 073501 (2011).
[10] O. M. Mannion *et al*., Rev. Sci. Instrum. **89**, 10I131 (2018).