Prototypes of NIF Neutron Time-of-Flight Detectors Tested on OMEGA

Introduction

The National Ignition Facility[1] (NIF) is a 2-MJ, 192-beam laser system currently under construction at Lawrence Livermore National Laboratory. One of the main missions of the NIF is to achieve thermonuclear ignition of fusion fuel in inertial confinement fusion (ICF).[2] In ICF experiments, primary neutrons are produced in two reactions:

$$\mathrm{D}+\mathrm{D}\rightarrow n(2.45\ \mathrm{MeV})+{}^{3}\mathrm{He}, \tag{1}$$

$$\mathrm{D}+\mathrm{T}\rightarrow n(14.1\ \mathrm{MeV})+\alpha. \tag{2}$$

Neutrons from reaction (1) are referred to as DD neutrons and neutrons from reaction (2) are referred to as DT neutrons.

Every large ICF laser facility, including Nova, OMEGA, and GEKKO, uses neutron time-of-flight (nTOF) systems to measure neutron yields and ion temperatures. Such nTOF systems are usually based on current-mode detectors consisting of a fast plastic scintillator optically coupled to a fast photomultiplier tube (PMT). A high-bandwidth transient digitizer records the signal. These systems, which are relatively inexpensive, have a large dynamic range and a fast time response. The nTOF detectors are reliable, and the information they record is fundamental to most ICF implosion experiments. It is for these reasons that the nTOF system was identified as a "core" diagnostic[3] for the NIF.

The 30-kJ, 60-beam OMEGA laser system[4] is currently the only facility that produces sufficient ICF neutrons for developing and testing prototype nTOF detectors for the NIF. Several nTOF detector prototypes have been built and tested on OMEGA. Based on the results of these tests, a set of nTOF detectors is proposed for use on the NIF to measure ion temperature and DD and DT neutron yields from 10^9 to 10^{19}.

NIF nTOF Detector Requirements

The nTOF system for the NIF must measure ion temperatures of implosion targets, ranging from 1 to 50 keV for yields between 10^9 and 10^{19} neutrons. The nTOF system must work in a harsh environment[5] of energetic neutrons, x rays, γ rays, and high electromagnetic pulse (EMP) noise. The main objective of an nTOF system is to measure ion temperature. Because nTOF-detector signals are proportional to the number of neutrons detected, they are easily adapted for simultaneous use as a yield monitor.

The neutrons produced in fusion reactions (1) and (2) are monoenergetic. Center-of-mass motion of the reacting ions causes spectral broadening of these energy lines. Because ICF targets are nearly ideal point sources in both time (<100 ps) and space (<100 μm) and neutrons travel to a detector without collisions, neutron spectra can be measured using the time-of-flight technique. The arrival time at a detector corresponds to the energy of the neutron. The time spread Δt of neutrons arriving at an nTOF detector is given by the following equations:[6]

$$\Delta t = 0.778 d\sqrt{T_i}\quad \text{(for DD)}, \tag{3}$$

$$\Delta t = 0.122 d\sqrt{T_i}\quad \text{(for DT)}, \tag{4}$$

where Δt is the full width at half maximum (FWHM) in nanoseconds, d is target-to-detector distance in meters, and T_i is the ion temperature in keV. The width of a measured signal is the width of the time-of-flight spread added in quadrature with the detector response.[7] To minimize measurement error, the nTOF detector response (FWHM) should be much less than the neutron temporal broadening being measured. For scintillator- and PMT-based detectors, this requirement leads to the use of fast microchannel-plate (MCP) PMT's with time resolutions of a few hundred picoseconds (FWHM).

The scintillator used in an nTOF detector must also be fast. Bicron's[8] ultrafast BC-422 scintillator has a rise time of less than 20 ps[9] and an exponential decay constant of 1.4 ns. The quenched version of the scintillator, BC-422Q, has a two-component decay with time constants of about 0.6 and 5 ns. In addition, the nTOF detector-response function includes the transit time of the neutrons across the thickness of the scintillator. A 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. The cables and digitizer also contribute to detector response. A cable with a 3-GHz bandwidth and a 1-GHz or faster oscilloscope contributes relatively small dispersion to temperature measurements.

X rays and γ rays from an ICF implosion generate background[10] in nTOF detectors that can saturate a PMT and distort the neutron signal, causing errors in ion temperature and yield measurement. Shielding is therefore required to reduce the x-ray and γ-ray fluence entering PMT-based nTOF detectors. Lead-shielding thickness is limited to <30 mm to avoid neutron scattering that would appear as signal broadening in the detector. High-yield DT implosions create MeV γ rays from (n,γ) interactions in the target, target positioner, nearby diagnostics, and the target chamber walls. This γ-ray background is proportional to the DT neutron yield and will be very high at expected NIF yields. It is difficult to shield MeV γ rays without also shielding the energetic neutrons. New techniques[10] like single-stage MCP PMT's and chemical-vapor-deposition (CVD) diamonds,[11] which are less sensitive to MeV γ rays, are recommended for the NIF.

nTOF Detector Locations on the NIF

The optimum placement[12] of nTOF detectors is determined by a tradeoff between decreased time resolution at small distances from the target and a smaller statistical sample of detected neutrons at longer distances. It can be shown[13] that the number of neutrons needed to achieve a given statistical uncertainty should be a factor of 2 larger over that predicted by Poisson statistics. Therefore, in our design, we require at least 200 neutron interactions in the nTOF detectors to achieve 10% statistical uncertainty, which puts a restriction on detector location. Another requirement is that, at the lowest yields, the nTOF detector should provide a neutron signal with an amplitude five to ten times higher than the EMP noise of the system. The highest-measurable yield is determined by PMT saturation. The signal from a modern MCP PMT is linear to ~3 nC of integrated charge for low-repetition pulses. This was taken into account in estimating yield limits. A combination of the optimization[12] of the detector locations combined with background considerations provides several natural locations for nTOF detectors on the NIF.

Placing a detector outside the target chamber wall at 5 m from the target avoids vacuum interface and tritium contamination problems. A 5-m flight path is adequate for ion-temperature measurements. At this location the nTOF detector will not be affected by scattered neutrons and (n,γ) interactions with the target chamber. The EMP noise at the OMEGA target chamber is 2 to 20 mV, depending on shot and detector design. The EMP noise at the NIF target chamber will most likely be higher; therefore, at least a 500-mV signal is required at the target chamber wall. This location should be used only for D_2 implosions and low-yield DT shots as described in the next section and Table 99.IV.

Another natural location for nTOF detectors is outside the NIF target bay shield wall against existing, predrilled holes. The 2-m-thick concrete walls of the target bay can be used as shielding against scattered neutrons and γ rays. There are several such locations at the NIF where detectors can be placed 17 m to 20 m from the target. The digitizing oscilloscopes can be placed nearby, thereby shortening the signal and HV cables and decreasing EMP noise pickup. The EMP noise in this location should be much less of a problem than at the target chamber wall; therefore, the minimum signal requirement in this location is 100 mV.

The 20-m standoff distance is not adequate for pre-ignition and ignition targets producing 10^{17} to 10^{19} neutrons. Most of the nTOF detectors located 20 m from the target will saturate at such yields. The high neutron flux can also damage an oscilloscope and PC. Another location as far away from the target as possible with a clean flight path is needed for the ignition campaign. There is a line of sight at $\theta = 64°$ and $\phi = 275.62°$ with an opening in the target bay wall that exits outside the building just above the roof of the diagnostic building. The nTOF detectors can be installed on the roof of the diagnostic building at about 40 m from the target.

OMEGA Performance Scaled to the NIF

Three different types of fast detectors were used for the NIF nTOF prototype tests on OMEGA. The most-sensitive nTOF detector consists of a BC-422 scintillator coupled to a two-stage MCP PMT. The PMT has a response time of about 250 ps (FWHM), a gain up to 10^6, and a 40-mm-diam photocathode. Detectors based on a two-stage MCP PMT are relatively sensitive to hard-x-ray and γ-ray background and are good for relatively low (10^9 to 10^{11}) neutron-yield NIF implosions, in which x-ray and γ-ray background is low as well. The first prototype has a 40-mm-diam, 20-mm-thick BC-422 scintillator coupled to a Photek[14] PMT240 PMT. To protect the prototype from the x-ray and γ-ray background inside the OMEGA Target Bay, it was heavily shielded on all sides by a thick lead housing (Fig. 99.72). The prototype was installed in the OMEGA Target Bay at 12.4 m from the target and connected by a 12-m-long LMR-400 cable to a 1-GHz Tektronix 684 oscilloscope. A Mini-Circuits model 15542 resistive splitter divides the detector signal between two oscilloscope channels with different sensitivity settings to increase the dynamic range of the recording system. The prototype was tested on D_2 implosions on OMEGA and calibrated against the standard suite of neutron diagnostics. Figure 99.73 shows a typical scope trace of the neutron signal taken for a shot yielding 1.2×10^{11} DD neutrons and having a $T_i = 4.1$ keV. The measured signal was fitted by a convolution of a Gaussian and an exponential decay, as described in detail in Ref. 7. Scaled to the 5-m distance on the NIF chamber wall, this detector will have ~200 neutron interactions and produce a signal amplitude of 500 mV for a DD yield of 1×10^9 neutrons. This detector installed on the NIF target chamber wall will be sensitive to DD and DT neutron yields from 5×10^8 to 5×10^{10}. Using relations derived by Lerche,[12] it is estimated that, at 5 m, this detector can measure ion temperature with 15% accuracy for 10^9 DD neutrons at 1 keV. Better than 10% accuracy is possible at higher yields or higher ion temperatures.

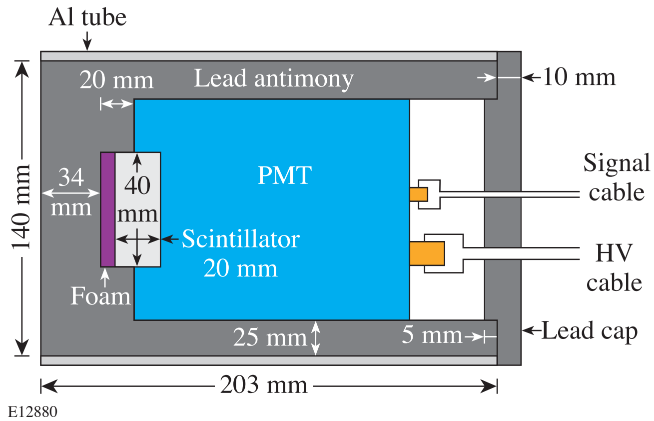

Figure 99.72
Schematic of the single-stage and two-stage MCP PMT nTOF prototypes tested on OMEGA at 12.4 m from the target.

Table 99.IV: Proposed set of nTOF detectors required for DD and DT temperature measurements for yields between 10^9 and 10^{19} neutrons.

N	Distance	Scintillator/ Wafer Size	Type	PMT	Yield Range
1	5 m	40 mm × 20 mm	BC-422	2 MCP	1×10^9 to 5×10^{10}
2	5 m	40 mm × 20 mm	BC-422	1 MCP	1×10^{10} to 5×10^{11}
3	5 m	10 mm × 1 mm	CVD diamond		5×10^{12} to 1×10^{15}
4	20 m	40 mm × 20 mm	BC-422	1 MCP	1×10^{11} to 5×10^{12}
5	20 m	40 mm × 20 mm	BC-422Q	1 MCP	1×10^{12} to 1×10^{14}
6	20 m	10 mm × 1 mm	CVD diamond		1×10^{14} to 5×10^{16}
7	40 m	10 mm × 5 mm	BC-422Q	1 MCP	1×10^{14} to 1×10^{16}
8	40 m	10 mm × 1 mm	CVD diamond		5×10^{14} to 1×10^{17}
9	40 m	2 mm × 0.5 mm	CVD diamond		2×10^{16} to 1×10^{19}

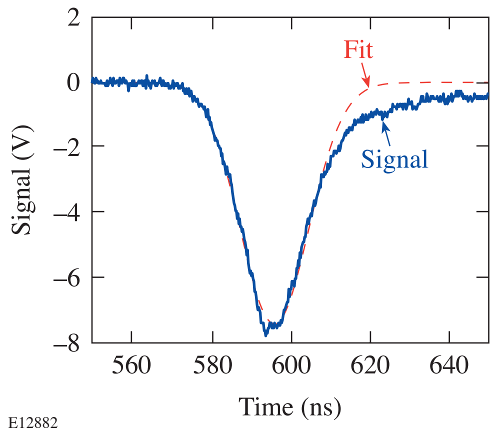

Figure 99.73
Neutron signal recorded for the two-stage MCP PMT prototype on D_2 shot 33949: yield = 1.2×10^{11} and T_i = 4.1 keV. The fit is a convolution of a Gaussian shape and a scintillator exponential decay.

The second nTOF detector designed for the NIF consists of a BC-422 or BC-422Q scintillator coupled to a single-stage MCP PMT. This PMT has a slightly faster response time of about 200 ps (FWHM), a gain up to 10^3, and a 40-mm-diam photocathode. The single-stage MCP PMT is less sensitive (by a factor of about 10^3) to x-ray and γ-ray background but has less gain by the same factor. Two versions of this detector were tested on OMEGA: The first version was designed to determine the maximum sensitivity achievable using a single-stage MCP Photek PMT140 PMT, coupled to a 20-mm-thick, 40-mm-diam BC-422 scintillator. It has 14-mm lead shielding in front and a 5-mm aluminum housing on all other sides. This prototype was tested on the OMEGA chamber wall, 1.65 m from the target, with DD implosions and calibrated against the standard neutron diagnostics. Figure 99.74 shows a typical oscilloscope trace of a neutron signal from this detector (DD yield of 6.7×10^{10} neutrons and T_i = 3.2 keV). This detector installed on the NIF target chamber wall will detect ~1900 neutron interactions and produce a 500-mV signal for a DD yield of 1×10^{10} neutrons. The same detector installed outside the NIF target bay at 20 m from the target will have ~1700 neutron interactions and produce a 450-mV signal for a DD yield of 1×10^{11}.

The second version of the single-stage MCP PMT system was designed to test upper-yield limits of such detectors. This prototype had a 40-mm-diam, 20-mm-thick BC-422Q (1% benzephenone) quenched scintillator, coupled with a Photek PMT140 PMT, and operated at a gain of 5×10^2. The detector was placed in a lead housing identical to that shown in Fig. 99.72 and installed in the OMEGA Target Bay at 12.4 m from the target, next to the two-stage MCP PMT prototype. This prototype was tested with DT implosions and calibrated against copper activation measurements. A scope trace of a neutron signal is shown in Fig. 99.75 (DT neutron yield of 5.0×10^{13} and T_i = 9.7 keV). If this detector is installed outside the NIF target bay at 20 m from the target, it will be sensitive to DT yields from 10^{12} to 10^{14} neutrons.

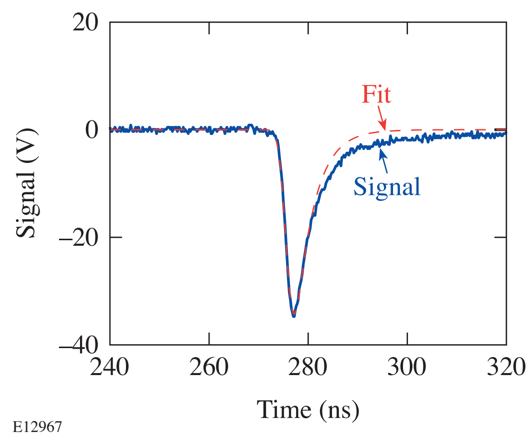

Figure 99.74
Neutron signal recorded for the singe-stage MCP PMT prototype on D_2 shot 33413: yield = 6.7×10^{10} and T_i = 3.2 keV. The fit is a convolution of a Gaussian shape and a scintillator exponential decay.

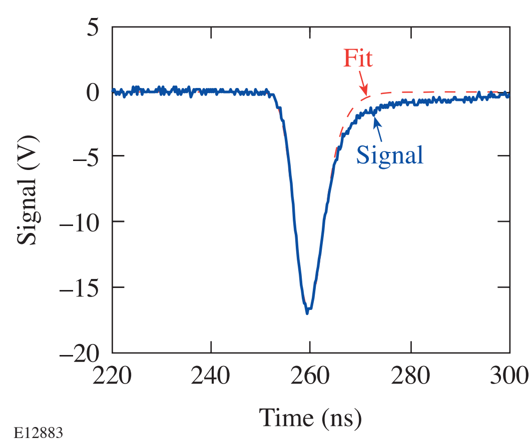

Figure 99.75
Neutron signal recorded for the single-stage MCP PMT prototype on DT shot 33797: yield = 5.0×10^{13} and T_i = 9.7 keV. The fit is a convolution of a Gaussian shape and a scintillator exponential decay.

The third prototype nTOF detector tested on OMEGA used a 10-mm-diam, 1-mm-thick CVD diamond wafer. Diamond detectors have low sensitivity[11] to hard-x-ray and γ-ray background and can be used at very-high DT yields. The CVD diamond detectors also have a larger dynamic range than PMT-based detectors. Such detectors[11] were previously tested inside the OMEGA target chamber. This time, the CVD diamond detector was installed outside the target chamber at 2.8 m from the target and biased at 1 kV. The CVD diamond prototype was tested with DT implosions and calibrated against copper activation. A typical scope trace is shown in Fig. 99.76 (DT yield of 5.0×10^{13} and $T_i = 9.7$ keV). This detector installed on the NIF target chamber wall will be sensitive to DT neutrons over a yield range from 5×10^{12} to 10^{15}. The same detector installed outside the NIF target bay at 20 m from the target will be sensitive to DT yields between 10^{14} and 5×10^{16} neutrons.

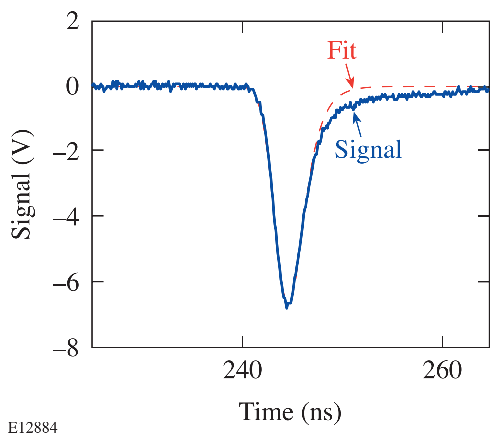

Figure 99.76
Neutron signal recorded for the CVD diamond prototype on DT shot 33797: 5.0×10^{13} and $T_i = 9.7$ keV. The fit is a convolution of a Gaussian shape and an exponential decay.

For pre-ignition and ignition targets on the NIF, less-sensitive detectors are needed about 40 m from the target. Scaled detectors based on a single-stage MCP PMT and a CVD diamond detector are chosen for this purpose. The proposed set of nTOF detectors to measure ion temperature and DD and DT neutron yields between 10^9 and 10^{19} is summarized in Table 99.IV.

The proposed set of detectors is a realistic, cost-effective approach to the NIF nTOF system and based on commercially available components. All of the nTOF detectors and components can be calibrated on OMEGA prior to installation and use on the NIF. The nTOF detector calibrations can be later cross checked against other yield-sensitive diagnostics, such as the PROTEX[15] and activation.[16]

Conclusions

Neutron time-of-flight (nTOF) detectors are part of the NIF core diagnostic suite providing a measurement of ion temperature and yield. Several NIF nTOF detector prototypes have been built and tested with D_2 and DT implosions on OMEGA. Prototypes for low and moderate NIF neutron yields are based on fast plastic scintillators and fast photomultiplier tubes. A third prototype is based on a CVD diamond detector. A set of nTOF detectors is proposed for the NIF to measure ion temperature and DD and DT neutron yields between 10^9 and 10^{19}.

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