A Novel Photomultiplier Tube Neutron Time-of-Flight Detector

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A traditional neutron time-of-flight (nTOF) detector used in inertial confinement fusion[1] usually consists of a scintillator optically coupled to a photomultiplier tube (PMT). For accurate ion-temperature measurements in DT implosions, a scintillator- and PMT-based detector must use a fast scintillator and fast microchannel plate (MCP) PMT. Even with the fastest scintillators, the scintillator light decay significantly contributes to the instrument response function (IRF) of the nTOF detector. A novel PMT nTOF detector developed at LLE has a MCP photomultiplier tube in a housing without a scintillator. This PMT nTOF detector is less sensitive than a traditional nTOF detector with a scintillator and can be used only in high-yield (typically larger than 10^{13} DT) implosions. Eliminating the scintillator removes the scintillator decay from the IRF and makes the detector faster. The PMT nTOF is the fastest nTOF detector currently in use on OMEGA.

The PMT nTOF detector made of Photek[2]—a PMT110 gated photomultiplier with a 10-mm-diam photocathode and a single-stage MCP—was tested at 5.6 m from the target in the P2 open line of sight (LOS) on OMEGA. The nTOF signal was recorded on a 2.5-GHz, 10-GS/s Keysight DSOS254A oscilloscope. The measured neutron temporal trace signal was fit with a convolution of a Gaussian and an exponential decay function, as described in detail in Ref. 3. The fit was performed at up to 50% of the falling slope of the signal.

To determine if the measured neutron signal originates in the window or in the MCP, a comparison test was performed of the PMT nTOF with no gate and with a gate (see Fig. 1). The electronic gate energizes the PMT at select times to discriminate unwanted signals. During the shot with the gate, the Photek gate unit produces a 250-V pulse that prevents photoelectrons from the photocathode from reaching the MCP. If a neutron signal is produced by direct interaction of neutrons with the MCP, the gate will have no effect.

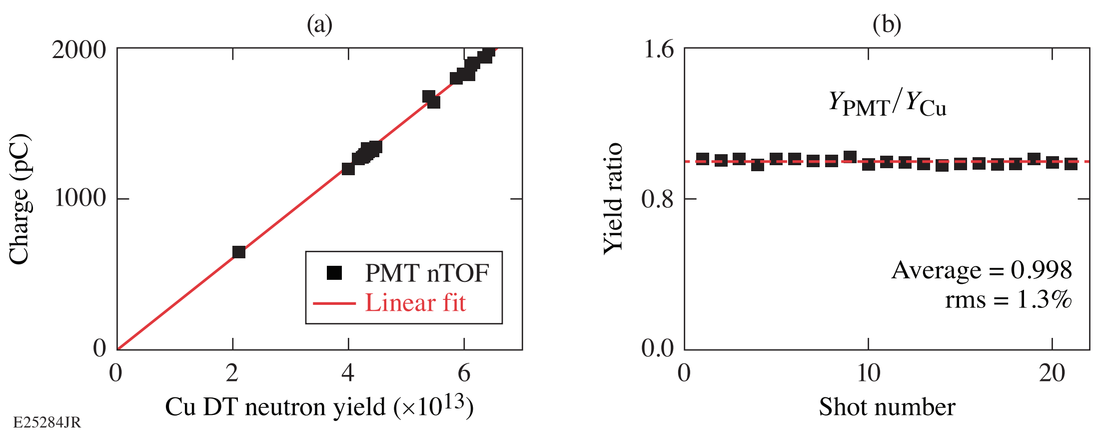

Figure 1
(a) The neutron signal in shot 91551 with a yield of 3.7×10^{13} recorded by a PMT nTOF with no gate; (b) the neutron signal in shot 91547 with a yield of 4.1×10^{13} recorded by a PMT nTOF with a gate.

However, in shot 91551 with a DT yield of 3.7×10^{13} and no gate pulse in the PMT, the neutron pulse charge was 223.10 pC, and in shot 91547 with a DT yield of 4.1×10^{13} and with a gate pulse in the PMT, the neutron pulse charge was 5.25 pC. One can calculate from the yields and charges of these two shots that only 2% of the neutron signal is produced by direct interaction with the MCP, and the remaining 98% of the neutron signal in the PMT nTOF is produced by photoelectrons from the photocathode. The photoelectrons are produced in the PMT fused-silica window in many complex nuclear processes[4] ranging from (n,γ) interactions and following Compton scattering to "knock-on" O^{16} and Si^{28} ions that produce low-energy electrons during slowdown.

The PMT nTOF detector based on Photek[2] PMT140 was permanently installed on the wall of the OMEGA Target Bay's southeast corner in the P4F line of sight at 15.9 m from the target with 10-mm-thick lead shielding in front. At 15.9 m, the PMT140 is operated at –4.2 kV, corresponding to a PMT gain of 400. The PMT nTOF in this location is capable of measuring DT yields from 1×10^{12} to 3×10^{14}. The PMT nTOF at the 15.9-m location was yield calibrated against the copper activation diagnostic as shown in Fig. 2(a). The ratio of DT neutron yields measured by the PMT nTOF and the copper activation are shown in Fig. 2(b). The measured neutron yield shot-to-shot precision of the PMT nTOF at the 15.9-m location is better than 1.3%.

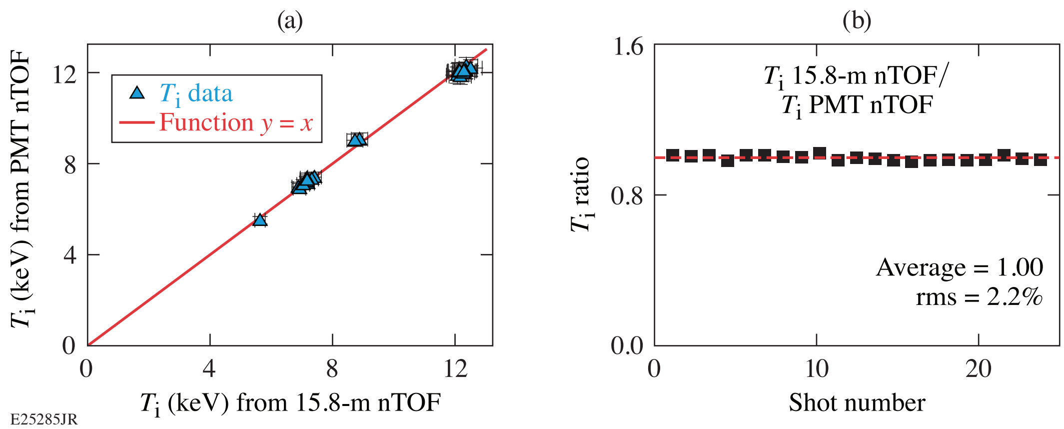

Figure 2
(a) DT neutron calibration of the 15.9-m PMT nTOF against copper activation; (b) the ratio of DT yield measured by the 15.9-m PMT nTOF and copper activation.

For ion-temperature calibration of the 15.9-m PMT nTOF, we used a traditional 15.8-m nTOF detector with a 40-mm-diam, 20-mm-thick BC422Q scintillator coupled to a PMT140 and located at 15.8 from target chamber center (TCC). Both detectors use the same type of PMT, the same scopes (located at a similar distance from the target), and the same 10-mm lead front shielding. The only difference between the two nTOF detectors is whether or not a scintillator is included. The fitting parameters of the PMT nTOF detector at the 15.9-m location were adjusted to match the ion-temperature measurements of the 15.8-m nTOF detector recorded in room-temperature, thin-shell targets with high-adiabat implosions in which the ion-temperature distribution is considered isotropic. Figure 3(a) shows the ion temperature measured by the PMT nTOF versus the ion temperature measured by the 15.8-m nTOF. The ratio of ion temperatures measured by these two similar independent detectors is shown in Fig. 3(b). The standard deviation for the ion temperature ratio is 2.2%, which corresponds to the standard deviation for a single detector of 1.56%. Therefore, the ion temperature measurement precision of the 15.9-m PMT nTOF is 1.6%.

Two additional fast nTOF detectors were constructed along opposing (antipodal) lines of sight to complete a suite of nTOF detectors on OMEGA for hot-spot flow-velocity measurements.[5] The H4D and H17E lines of sights were selected for nTOF detector deployment. Since hot-spot flow-velocity measurements require[5] timing uncertainties <100 ps, the fastest PMT nTOF based on 10-mm-diam MCP PMT's were selected for these antipodal nTOF's. Two 10-mm-diam Hamamatsu[6] MCP PMT's were available at LLE: one ungated R3809U-52 and one normally gated "OFF" R5916U-50. To record x-ray IRF from the Hamamatsu PMT during OMEGA timing-calibration shots, each detector has a 1-mm-thick aluminum front PMT housing and each OMEGA sub-port has a 5-mm aluminum window. The ungated R3809U-52 PMT was installed in the H4D LOS at 10.4 m from TCC, and the gated R5916U-50 PMT was installed at the H17E 4.9-m location. Both detectors were installed with their faces perpendicular to the LOS of the TCC.

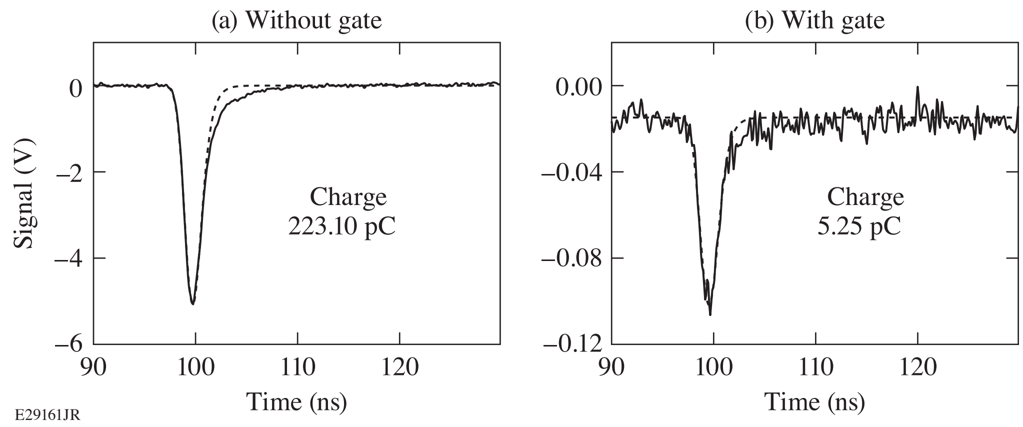

Figure 3
(a) Ion temperature from the 15.9-m PMT nTOF versus ion temperature from the 15.8-m nTOF; (b) the ratio of ion temperatures from the 15.8m nTOF and 15.9-m PMT nTOF detectors.

The neutron IRF is very important for accurate measurement of the neutron energy and hot-spot flow velocity[5] in DT implosions. Since, in the absence of the short impulse of 14-MeV neutrons, it is impossible to measure neutron IRF directly, a two-step process described in detail in Ref. 7 was used. During the first step, an x-ray IRF was experimentally measured, and during the second step, the neutron IRF was constructed by correcting x-ray IRF for the DT neutron propagation time modeled in MCNP (Monte Carlo neutron particle code). The x-ray IRF's for the H4D and the H17E PMT nTOF detectors were measured with a 100-ps laser pulse on a gold target. Both detectors have a subnanosecond x-ray IRF: the H4D nTOF has 540±20 ps FWHM and the H17E nTOF has 360±12 ps FWHM. The uncertainty on the IRF FWHM is taken from the standard error of the mean FWHM from the set of IRF measurements. The 14-MeV neutrons' propagation time through a 3.2-mm-thick PMT window is very short (62 ps), and convolution of an x ray with MCNP simulation is practically the same as an x-ray IRF. Using the constructed neutron IRF, the hot-spot flow velocity in DT fusion experiments can be determined from the H4D and the H17E PMT nTOF signals using a forward-fitting method.[7] The H4D and H17E forward fits for shot 95201 with a yield of 1.1×10^{14} and T_i of 4.3 keV are shown in Fig. 4. The PMT nTOF detector in the H17E location has a negligible background, and a good fit is achieved with only the IRF. The PMT nTOF detector in the H4D location has an additional gamma background from (n,γ) interactions with the Target Bay wall. For proper fitting of a neutron peak, a modified Gaussian background contribution is included in the forward fit and determined on each shot [see Fig 4(a)]. The operational yield range for the H4D and H17E PMT nTOF detectors is from 1×10^{13} to 2×10^{14}. The commissioning of the H4D and H17E PMT nTOF detectors completed the suite of nTOF detectors on OMEGA for hot-spot motion measurements.[5]

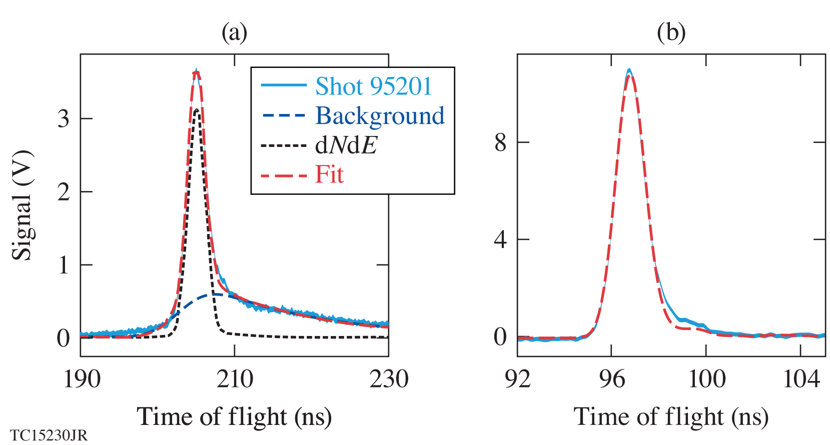

Figure 4
The forward fits of neutron signals from (a) H4D and (b) H17E nTOF detectors.

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