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This paper was prepared for submittal to the
10th Topical Conference on High Temperature Plasma Diagnostics
Rochester, NY
May 8-12, 1994

May, 1994

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Ion Temperature Measurement of Indirectly-Driven Implosions Using a Geometry-Compensated Neutron Time-of-Flight Detector

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A geometry-compensated neutron time-of-flight detector has been constructed and used on Nova to measure ion temperatures from indirectly-driven implosions with yields between 2.5 and 5×10^9 DD neutrons. The detector, which has an estimated response time of 250 ps, was located 150 cm from the targets. Due to the long decay time of the scintillator, the time-of-flight signal must be unfolded from the measured detector signal. Several methods for determining the width of the neutron energy spectrum from the data have been developed and give similar results. Scattered x rays continue to be a problem for low yield shots, but should be brought under control with adequate shielding.

I. Introduction

Measurements of the neutron emission from inertial confinement fusion (ICF) implosions provide sensitive tests of implosion modeling. Measurements of interest include neutron yield, burn history, and neutron energy spectrum.

Current mode neutron time-of-flight detectors are used to measure the neutron yield,¹ ion temperature,²⁻⁴ and neutron emission time⁵ of ICF targets on Nova and other ICF facilities. Current mode neutron time-of-flight detectors consist of a scintillator optically coupled to a photomultiplier tube and placed at a distance from a pulsed neutron source. The thermal broadening of the fusion neutron energy distribution can be measured and the ion temperature of the source region deduced by measuring the width of the neutron pulse. The ion temperature is related to the pulse width by the equation:⁶

$$kT_i = \left(C_1 \frac{FWHM_{tof}}{d} \right)^2 \quad (1)$$

where $C_1 = 1.285$ for DD and $8.197 \text{ m keV}^{1/2}/\text{ns}$ for DT. In this paper, the use of a “geometry-compensated”⁷ neutron time-of-flight detector to make ion temperature measurements from indirectly-driven ICF targets is described. This method allows neutron time-of-flight detectors to take advantage of the speed available from state-of-the-art microchannelplate

photomultiplier tubes and high-bandwidth transient digitizers by reducing the contribution of neutron transit time across the scintillator to the width of the time-of-flight signal. Faster detectors can then be placed closer to the target, allowing ion temperatures to be measured on targets with lower yields than previously possible.

Geometry compensation is a technique⁷ in which the transit time of neutrons across a scintillator is kept small by reducing the thickness of the scintillator while increasing the length in order to keep the volume constant. Since the length of the scintillator is increased, the travel time of light down the scintillator to the photomultiplier tube also increases, so light produced by neutrons interacting in different parts of the scintillator arrives at the PMT with different delay times. To offset this delay, the end of the detector farthest from the PMT is tilted toward the target so that neutrons interacting in that region of the scintillator have a flight time which is shorter by the amount of time necessary for the light to travel the extra length from that region of the scintillator to the PMT. In addition to a delay, there is also dispersion of the light as it travels along the scintillator. The amount of dispersion is dependent on the index of refraction of the scintillator, any cladding it might have, and its length. The angle of tilt is adjusted to optimize the compensation and minimize the contribution of dispersion to the width of the signal.^{7, 8}

II. Detector design

Two geometry compensated neutron time-of-flight detectors have been operated on Nova. The first model⁸ consisted of a 3 mm by 1 cm by 10 cm long quenched scintillator (BC-422Q, 2% benzophenone) coupled to a fast microchannelplate photomultiplier tube (MCP-PMT) (Hamamatsu R2566U-06).

Recently, an improved version of this detector has been put into operation. The new model consists of a 10-cm radius cone-shaped scintillator coupled to the MCP-PMT through a 1-cm diameter light guide (Fig. 1) and placed in a reentrant tube which allows the detector to be positioned between 1.1 and 2.1 m from the target with 0.2 mm resolution. The cone is shallow, with the sides tilted toward the target by 8° , which is calculated to be the optimum angle for DD neutrons using this scintillator.⁸ The volume of the scintillator is 94 cm³, a thirty-fold increase over the first detector. While the light coupling is not as good with the new geometry, the scintillation light is created from a larger number of neutron interactions, resulting in better statistics. The signal is measured using a fast transient digitizer with 5 GHz bandwidth. The gain of the system is adjusted by changing the MCP-PMT bias voltage so that the expected signal will be about 2.5 volts high. By using two digitizers, splitting the signal, and attenuating one branch by a factor of 10, a dynamic range of about 30 in neutron yield is realized with a single detector.

III. Data and unfold techniques

A number of techniques may be used to unfold the neutron time-of-flight signal from the data. The optimum technique depends on the situation and the quality and statistics of the signal.

The simplest unfold method is a derivative method. If the rise time of the signal is much shorter than the decay of the scintillator and the data $F(t)$ is assumed to be the real signal $f(t)$ convolved with an exponential decay with decay constant τ , then the signal is given by⁸

$$f(t) = F(t) + \tau dF / dt. \quad (2)$$

If the signal consists of a number of exponential decays convolved together, these decays may be removed one at a time by repeated use of Eqn. 2.

A second method, useful if the data contains significant noise but the response function and shape of the time-of-flight signal are known and can be parameterized, is to fit of the time-of-flight signal convolved with the response function to the data. For instance, if the data is assumed to consist of the sum of a number of exponential decays $g(t)$ convolved with a Gaussian of width σ (which would contain the time-of-flight width, the burn width, and the PMT/scope response), then the data $F(t)$ can be fit using

$$F(t) = C \sum_n A_n \frac{e^{-t/\tau_n} e^{\sigma^2/2\tau_n^2}}{2\tau_n} \left[1 + \operatorname{erf} \left(\frac{t - \sigma^2/\tau_n}{\sqrt{2}\sigma} \right) \right], \quad (3)$$

where the response function is given by

$$g(t) = \sum_n \frac{A_n}{\tau_n} e^{-t/\tau_n}. \quad (4)$$

This technique is especially useful if the values of the time constants τ_n and the relative amount of each component A_n are known from previous characterizations of the detector. In this case, the function $F(t)$ can be fit using parameters for the integral (C) and width (σ) of the time-of-flight signal.

If the response function of the detector cannot be adequately modeled analytically, or if a measured response function is available, then a Fourier deconvolution technique may be advantageous. The measured signal $F(t)$ can be related to the true time-of-flight signal $f(t)$ and the response function of the detector $g(t)$ through their Fourier transforms

$\tilde{F}(\omega) = \tilde{f}(\omega) \tilde{g}(\omega)$. The Fourier transform of $f(t)$ can therefore be expressed as $\tilde{f}(\omega) = \tilde{F}(\omega) / \tilde{g}(\omega)$.

Problems arise, however, since the detector response $\tilde{g}(\omega)$ drops off at high frequency. Therefore, any high frequency noise in the data $\tilde{F}(\omega)$ will be exaggerated in the deconvolution. To reduce this contribution, one may choose use a filtered deconvolution. One possibility is to use a Wiener filter:⁹

$$\tilde{f}(\omega) = \frac{\tilde{F}(\omega)}{\tilde{g}(\omega)} \left(1 + \frac{\gamma^2}{|\tilde{g}(\omega)|^2} \right)^{-1}. \quad (5)$$

This filter removes contributions to the deconvolution from frequencies for which the response function is small. The parameter γ can be adjusted to select the degree of filtering required.

The geometry-compensated neutron time-of-flight detector has been used to measure the neutron time-of-flight signal from a number of different types of target (Fig. 2). Good signals have been obtained from indirectly-driven deuterium-filled targets yielding less than 3×10^9 DD neutrons (Fig. 2a). Higher quality data is obtained from DT-filled targets (Fig. 2b and c), but at a distance of 1.5 m, the thermal broadening is too small for adequate ion temperature determinations.

The data in Fig. 2a can be analyzed using the methods described in the previous section. The results of this analysis are shown in Fig. 3 and summarized in Table 1. The derivative method (Fig. 3a) was performed on the data after smoothing with three passes of a binomial smoothing filter using Eqn. 2 with $\tau=1.2$ ns. The resulting unfold was then smoothed with three additional passes of the binomial filter.

The results were also analyzed using a parameterized response function convolved with a Gaussian to fit the data. It was assumed that the response function is given by Eqn. 4,

with $t_1=0.6$ ns, $t_2=5.0$ ns, $A_1=0.2$, and $A_2=0.8$. The response was convolved with a Gaussian (Fig. 3b) with the width chosen to give the best fit to the data.

A Fourier deconvolution was performed using the direct-drive DT data (Fig. 2c) as a response function. To reduce the contribution from high frequency noise, values for γ (Eqn. 5) of 1 ns and 3 ns were used (Fig. 3c). The two deconvolutions demonstrate that the larger value of γ results in significant smoothing and spreading of the data, while the unfold using the smaller value shows many of the same features as seen in Fig. 3a derived using the derivative technique.

The three methods yield very similar numbers for the ion temperature for this target (Table 1), with a value of $kT_i=2.0\pm0.1$ keV being consistent with all three methods. Ion temperature measurements from targets with lower yields have been prevented so far by the presence of scattered x rays. At low yield, the bias of the MCP-PMT must be increased to give an adequate signal, however scattered x rays which arrive about 65 ns before the DD neutrons (at 1.5 m) can lead to large signals which remove most of the charge from the MCP-PMT and create oscillations in the signal which persist through the period in which the neutrons arrive. It is expected that increased shielding to scattered x rays will reduce this problem.

This work was performed under the auspices of the U. S.
Department of Energy by the Lawrence Livermore National
Laboratory under Contract No. W-7405-Eng-48.

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Figures

Fig. 1. Cross section of the neutron time-of-flight detector showing the relative placement of the microchannelplate photomultiplier tube (MCP-PMT) and the scintillator. In this figure, the neutrons would be incident from the left.

Fig. 2. Neutron time-of-flight data from (a) an indirectly-driven, deuterium filled target which yielded 2.8×10^9 DD neutrons, (b) an indirectly-driven DT-filled target which yielded 2.7×10^9 DT neutrons, and (c) a directly-driven DT-filled target which yielded 6.3×10^{11} DT neutrons.

Fig. 3. Unfolded data from Fig. 2a using three different methods: (a) derivative method assuming a decay constant of 1.2 ns, (b) the Gaussian which is convolved with a two-component exponential decay ($\tau_1=0.6$ ns, $\tau_2=5$ ns) to obtain the best fit to the data, and (c) a Fourier deconvolution using the DT data from Fig. 2c as a response function using values of $\gamma=1$ ns (solid line) and $\gamma=3$ ns (dashed line).

Table

Table 1. Ion temperatures derived from the unfolded neutron time-of-flight data are consistent with $kT_i=2.0\pm0.1$ keV, except in the case of the Fourier transform with the larger smoothing parameter, which gives too wide an unfold.

Unfold Method		$FWHM_{\text{tof}}$ (ns)	kT_i (keV)
Derivative		1.68	2.07
Convolved fit		1.64	1.97
Fourier transform	$\gamma=1$ ns	1.64	1.97
	$\gamma=3$ ns	1.96	2.82

figure 1

figure 2

figure 3

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