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Interpretation of neutron time-of-flight signals from current-mode detectors

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Neutron time-of-flight (nToF) signals from current-mode neutron detectors are often used to determine burn-averaged ion temperature from ICF targets because the spread of the neutron energy distribution is a function of the temperature of the reacting ions. The measured signal will, however, be a convolution of the actual neutron signal, the detector response, and the response of the recording system. In addition, scattered neutrons will arrive at the detector later than unscattered neutrons, further broadening the signal. The ion temperature derived from nToF data depends strongly on the functions used to fit the data or the methods utilized to unfold the neutron energy spectrum. A functional form based on known and measured properties of the detectors is used to fit the integral of the time-of-flight signal, allowing ion temperature derivations from targets with lower neutron yield than previously possible.

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I. Introduction

Current mode neutron time-of-flight detectors have been used to measure the neutron yield [1], ion temperature [2-6], and neutron emission time [7] of ICF targets on Nova, Omega, and other large ICF facilities. A current-mode neutron time-of-flight detector typically consists of a scintillator optically coupled to a photomultiplier tube and placed at a distance from a pulsed neutron source.

Neutrons are usually produced in the reactions $D(d,n)^3\text{He}$ or $T(d,n)^4\text{He}$.

Conservation of energy (mass) and momentum and the large amount of energy released in the reaction results in nearly monoenergetic neutrons being produced at energies of 2.45 MeV (DD reaction) or 14 MeV (DT reaction).

In a reacting plasma, the energy distribution of the neutrons is broadened due to the center-of-mass motion of the reacting ions. For a Maxwellian distribution of ions, the energy distribution of the neutrons is nearly Gaussian. The width 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 arriving at the detector. The pulse width is related to the ion temperature by the equation [8]:

$$\text{FWHM}_{\text{tof}} = \begin{cases} 0.778 \frac{\text{ns}}{\text{m keV}^{1/2}} \\ 0.122 \frac{\text{ns}}{\text{m keV}^{1/2}} \end{cases} \times d \sqrt{kT_i} \quad \begin{matrix} \text{DD} \\ \text{DT} \end{matrix} \quad (1)$$

where d is the distance from the source of neutrons to the detector, kT_i is the temperature of the reacting ions, and FWHM_{tof} is the full width at half maximum of the neutron time-of-flight signal. The optimum placement [9] of time-of-flight

detectors is determined by a tradeoff between decreased time resolution at small distances from the target and smaller statistical sample of detected neutrons at large distance.

II. Response function of current-mode neutron detectors

The measured neutron time-of-flight signal will consist not only of the actual neutron arrival time distribution, but will also include the detector response. Different methods have been used to separate the neutron signal from the response of the detector system including deconvolution [2,4,9], convolution [3], and derivative methods [5,6].

Plastic scintillators have a response which consists of a very short rise time [8] followed by a relatively slow exponential decay or sum of decays. The response of the photomultiplier tube, effect of finite flight path across the scintillator thickness, and the bandwidth of the cabling system and recording instruments is usually approximated as a Gaussian with a width that contributes to the entire system response.

We assume that the measured signal is the convolution of a Gaussian neutron signal given by $f(t;\sigma)$ and the sum of exponential decays $g(t;\tau)$. The function $H(t)$ is a step function so that the exponential zero before the event.

$$f(t;\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{t^2}{2\sigma^2}\right) \quad (2)$$

$$g(t;\tau) = \frac{1}{\tau} e^{-t/\tau} H(t) \quad (3)$$

The convolution of these is given by [6]:

$$\begin{aligned}
h(t; \sigma, \tau) &\equiv f(t; \sigma) \otimes g(t; \tau) \\
&= \frac{\exp(-t/\tau) \exp(\sigma^2/2\tau^2)}{2\tau} \left[1 + \operatorname{erf} \left(\frac{t - \sigma^2/\tau}{\sqrt{2}\sigma} \right) \right]
\end{aligned} \tag{4}$$

Figure 1 shows the effects of convolving exponential decays of various decay constants with a Gaussian. A decay time which is long compared to the width of the Gaussian increases the rise time of the signal, adds a late time tail to the signal, and shifts the maximum of the signal later in time.

Often times, the signal obtained with a current mode detector will have less than satisfactory statistics and will contain statistical noise as well as fluctuations due to digitization noise. In order to fit this data, it is sometimes more reliable to fit the integral of the signal. Here $H(t; \sigma, \tau)$ is the integral of the convolved response given in Eq. 4.

$$\begin{aligned}
H(t; \sigma, \tau) &\equiv \int_{-\infty}^t h(t'; \sigma, \tau) dt' \\
&= \frac{1}{2} \left\{ 1 + \frac{\operatorname{erf}(t/\tau)}{\sqrt{2}\sigma^2/\tau^2} - \exp \left(\frac{x}{\tau} + \frac{\sigma^2}{2\tau^2} \right) \left[1 + \operatorname{erf} \left(\frac{t/\tau - \sigma^2/\tau^2}{\sqrt{2}\sigma^2/\tau^2} \right) \right] \right\}
\end{aligned} \tag{5}$$

Measured signals can have offsets in the baseline. Allowing for this, and for the presence of both a fast decay component (τ_1) and a slow component (τ_2), the following form is used to fit the measured signals:

$$S(t) = A + Bt + C \left[\chi H(t - t_0; \tau_1, \sigma) + (1 - \chi) H(t - t_0; \tau_2, \sigma) \right] \tag{6}$$

The parameters A and B allow for an offset in the signal. C is the integral of the

total neutron pulse (from $-\infty$ to $+\infty$) with the offset removed. χ is the fraction of the signal in the fast decay component (τ_1), the rest is in the slow component (τ_2).

III. Determination of response parameters

The time decays associated with the scintillators may be obtained using experimental data for which the width of the time-of-flight signal is narrow relative to the decay times of the scintillator. DT implosions are better than DD implosions since, as shown in Eq. 1, for a given ion temperature, the DT signals are about a factor of six narrower than for an equivalent DD signal. In addition, DT targets give about a factor of 100 higher neutron yield than DD targets due to the larger DT cross section.

Figure 2 shows a fit of the neutron signal from a DT implosion for a detector located 8.36 m from the target. On the semi-log plot, the two exponential decays are readily apparent. By comparing signals from a number of shots, the exponential decay constants for the scintillator may be determined.

Two detectors have been used simultaneously to measure the time-of-flight signal from ICF targets located 8.36 m from the target ("10-m detector") and 18.33 m ("20-m detector"). The detectors are similarly constructed so that the Gaussian part of the response function of the detectors is assumed to be nearly equal. To determine this contribution, the ion temperature measured using the two detectors can be compared. Since we assume a Gaussian form for non-exponential decay portion of the detector response, the width of the measured signal should be the widths of the actual neutron time-of-flight signal added in quadrature with the detector response.

$$FWHM_{\text{measured}}^2 = FWHM_{\text{neutron}}^2 + FWHM_{\text{response}}^2 \quad (7)$$

Since the ion temperature deduced from the signal is proportional to the square of the width, the measured ion temperature varies from the actual due to the detector response by a constant amount which is a function of the detector response function and the distance of the detector. The response function can be determined if we assume that the detector at 8.36 m and at 18.33 m are identical, by comparing the ion temperatures obtained by the two detectors on the same implosions (Figure 3).

Using equations (1) and (6), we can show that, for DT implosions,

$$kT_{i,\text{measured}} = kT_{i,\text{actual}} + \left(8.197 \frac{\text{m keV}^{1/2}}{\text{ns}} \times \frac{FWHM_{\text{response}}}{d} \right)^2 \quad (8)$$

Using this, and assuming that the response function of the two detectors is the same, we can solve for $FWHM_{\text{response}}$ to get

$$\Delta kT_{i,\text{measured}} = \left(8.197 \frac{\text{m keV}^{1/2}}{\text{ns}} FWHM_{\text{response}} \right)^2 \Delta \left(\frac{1}{d^2} \right) \quad (9)$$

for DT neutrons.

From Figure 3, one sees that the detector at 8.36 m ("10-meter detector") measures about 1.15 keV higher temperature than the detector at 18.33 m ("20-meter detector") using one transient digitizer and 0.5 keV using the other. From equation (8), this gives a $FWHM_{\text{response}}$ of 1.22 ns or 0.81 ns. This illustrates the importance of characterizing the entire system including the data acquisition system, and not simply the detector. From this comparison, we adopt a value of

1.0 ± 0.2 ns for the Gaussian part of the response function of the detector and digitizing system for DT neutrons. The response function for DD neutrons will be wider due to the longer transit time of DD neutrons across the thickness of the scintillator. DD neutrons require 1.1 ns to traverse the 2.4 cm thickness of the scintillator, while DT neutrons require only 0.46 ns. Taking this into account we get response function of about 1.3 ns for DD neutrons.

IV. Comparison of temperature measurements

The integral-fit method for obtaining ion temperature data has been applied to a number of experiments performed on the Nova laser facility utilizing DD-filled capsules (Figure 4). For this analysis, the fast time decay of the scintillators is held fixed at the value obtained from DT measurements. While the slower decay and the fraction of the signal in the slower decay should also remain fixed, the statistics of the signals with typical DD targets is low enough that a more satisfactory fit is obtained by allowing these to be free parameters; however, the value assumed for the slow decay does not have a strong influence on the obtained value of the width of the Gaussian part of the spectrum. The results have been compared to those obtained using a single-hit neutron detector array [11,12] for comparison (Figure 5). The results were obtained for experiments yielding between 2×10^8 and 2×10^9 neutrons. The lower end of the range was determined by the statistics for the current-mode detector. The upper end of the range was set by pulse pile up considerations for the single-hit detector array. The error bars were determined using the statistics of the fit [4,9].

The comparison is in general quite good. The apparent offset in the two results indicates that there may be a further refinement of the response function needed.

V. Conclusions

A method for deriving ion temperatures from current-mode neutron time-of-flight detectors has been developed which allows analysis of data even when the statistics create large fluctuations around a Gaussian signal. The results from this method compare well, though not perfectly, with results from a single-hit neutron array.

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Figures

Figure 1: Convolution of a Gaussian with $\sigma=1$ with exponentials of different decay times demonstrating the effect of the exponential component on the width and shape of the signal.

Figure 2: The neutron time-of-flight signal from a current-mode detector located 8.36 m from an ICF target which produced 1.3×10^{13} DT neutrons. Two decay constants are seen in the data, and a good fit is obtained using the function given in Eq. 4.

Figure 3: Ion temperatures measured for DT targets using a detector at 8.36 m ("10-m detector") and at 18.33 m ("20-m detector"). Somewhat different temperatures are obtained using different digitizers, labeled "Scope 61" or "Scope 62," demonstrating the necessity of characterizing the entire system.

Figure 4: Fit of the integral of a time-of-flight signal using the function in Eq. 5 & 6, along with the original data and the curve obtained using the parameters of the fit in Eq. 4 for a target yielding 2.5×10^8 DD neutrons. For this shot, the "10-m" detector was moved to 5.87 m from the target.

Figure 5: A comparison of ion temperatures obtained from a current-mode detector located 5.87 m from target chamber center to those obtained from a 1020-element single-hit neutron array. An average difference of about 0.3 keV indicates that further characterization of the detectors is still needed.

Figure 1
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