Ion Temperature Analysis of Implosions
of DT-Filled Capsules

DE91 002672

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Abstract

Fuel ion temperatures have been deduced for a series of implosions of DT-filled capsules by measuring the thermally broadened neutron time-of-flight signals at 10 m and at 20 m from the target. Typical temperatures were around 1 keV, and the corresponding thermal broadening was comparable to or less than the time response of the detectors. Under these conditions, error minimization is crucial, and we find that the location of the detector and the analysis technique are important. An optimum location exists, but is very sensitive to the yield of the implosion and to the detector response.

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The demonstration of a high gain implosion through inertial confinement fusion will ultimately depend upon our ability to compress fuel to a high density. This in turn hinges upon our ability to keep the fuel as cool as possible during the initial phases of the implosion, since cool fuel compresses more easily than hot fuel. It is therefore desirable to be able to measure the fuel temperature, T_i , with a high degree of reliability. In this report we probe the extent to which T_i can be determined with the neutron detectors currently in use at the NOVA laser-fusion facility at Lawrence Livermore National Laboratory. As an experimental data set, we will use a recent set of implosions of DT-filled capsules.

Fuel T_i is deduced from the temporal broadening of the pulse of neutrons arriving at a detector a known distance from the target. Each detector consists of a 2.4 cm thick by 4.6 cm diameter piece of Bicron BC418 fast ("quenched") plastic scintillator optically coupled to a microchannel plate (MCP) photo multiplier tube. The signal from each detector is connected to Tektronix 7912 transient digitizers, which digitize and record the input signal voltage as a function of time. One detector was placed 18.33 m from the target, and another was 8.36 m, henceforth to be referred to as the 20 m and the 10 m detector, respectively. The neutrons emitted during an implosion arrive in a single burst, hence signals from individual neutron interactions in the detector "pileup", and the detector is run in "current mode". Before such a signal can be interpreted, the charge

distribution and the impulse response from 14 MeV neutrons need to be calibrated.

The detector charge distributions were measured at our neutron generator laboratory, where deuterium is accelerated onto a tritium target, thus generating 14 MeV neutrons. After correcting for background due to scattering and for threshold effects, the mean charge deposited, $\langle q \rangle$, and standard deviation, σ_q , for each detector were determined. A unitless parameter combining $\langle q \rangle$ and σ_q will turn out to be useful,¹ namely,

$$\alpha = \sqrt{1 + (\sigma_q / \langle q \rangle)^2} \quad . \quad (1)$$

We find $\alpha = 1.34$ and 1.40 for the 20 m and 10 m detectors, respectively. The resulting uncertainty in T_i due to the $\pm 10\%$ uncertainty in α is negligible.

The impulse response was measured on a low yield DT-neutron shot by placing each detector 50 cm from the target, where thermal broadening was negligible. The resulting signal for the 20 m detector is shown in Fig. 1b, and has FWHM of 1.25 ns. For the 10 m detector, the impulse response (not shown) had FWHM of 1.39 ns.

The first step in the data analysis is to deconvolve (unfold) the impulse response from the measured signal, as illustrated for the 20 m detector in Fig. 1. The solid curve in Fig. 1a represents the observed "raw" voltage signal, as recorded on a shot with DT-neutron yield of 7×10^9 , and has FWHM of 3.26 ns. To arrive at the true neutron time-of-flight (TOF) distribution requires that the impulse

response, shown in Fig. 1b, be unfolded from the observed signal. We accomplish the unfold in an iterative fashion by guessing an initial "solution", folding it with the impulse response, then comparing with the measured signal. Based on the comparison, we improve our initial guess, and so on, until the solution, folded with the impulse response, is in good agreement with the observed signal. The unfolded solution thus arrived at is shown in Fig. 1c. The dotted curve in Fig. 1a represents the final comparison of solution folded with impulse response, based upon which we terminated the iteration.

The double peak structure in the unfolded TOF distribution results from the shoulder on the leading edge of the raw signal. Dividing its total charge by $\langle q \rangle$ for this detector indicates that about 170 neutrons interacted in the detector. Therefore, the structure in the unfolded distribution is only a statistical fluctuation. This conclusion is based on Monte Carlo simulations of observed signal shape as a function of shot yield and detector distance.² No such statistical fluctuation was seen in the signal from the 10 m detector, which was comprised of about 1500 neutron interactions.

The unfolded voltage signal, $V(t)$, is next transformed to a differential neutron multiplicity spectrum by writing

$$dN(t)/dt = V(t) / [\langle q \rangle (50 \Omega)] . \quad (2)$$

Defining $Y(t) = [dN(t)/dt]\delta t$, where δt is the bin width, then based on Eq. 7 in Ref. 1, the error for each "data point" is

$\delta Y(t) = \alpha \sqrt{Y(t)}$. The final TOF spectrum thus arrived at for the 20 m detector is shown in Fig. 2a, and that for the 10 m detector in Fig. 3a.

If we assume a Gaussian TOF distribution, as suggested by the data in Fig. 3a, then T_i is proportional to the square of the temporal broadening.^{1,3} For 14 MeV neutrons this leads to

$$T_i(\text{keV}) = (7.018 \times 10^5) \Delta t^2 / L^2, \quad (3)$$

where Δt is the FWHM in ns of the unfolded distribution and L is the distance in cm from the target to the detector.

To determine T_i , we fit a Gaussian thermal distribution to the data by χ^2 minimization. The region over which to fit, shown by the two dotted fiducial lines in Fig. 2a, is held fixed. The parameters varied are T_i , centroid (t_0), and overall amplitude (A_0), and the best fit is determined by mapping out the χ^2 vs T_i profile, as shown in Fig. 2b. The T_i corresponding to the overall minimum is equated with the best-fit T_i for the spectrum, and the uncertainty is related to the curvature. Approximating the profile as parabolic, then an increase of one above the minimum χ^2 corresponds to a change in T_i of one standard deviation.⁴ This is illustrated by the dashed and the dotted lines in Fig. 2b, and gives $T_i = 0.95 \pm 0.14$ keV.

For the same shot, a similar T_i analysis of the data from the 10 m detector is shown in Fig. 3, and results in $T_i = 0.90 \pm 0.05$ keV. The smaller relative error for this detector results from the sharper curvature of the χ^2 space

near its minimum, and reflects the higher statistical quality of the data. This is in agreement with the optimum detector location analysis given in Ref. 1, suggesting that on low yield shots, it is beneficial to locate the detector somewhat nearer the target to take advantage of the increased statistical quality of the data. Notice, though, that Δt of the unfolded distribution (0.96 ns) is less than that of the impulse response (1.39 ns).

The trade off for locating the detector closer to the target is a much greater dependence on detailed knowledge of the impulse response. We estimate an uncertainty of about 5% in the FWHM of the impulse response which, from Eq. 12 in Ref. 1, results in $\delta T_i/T_i = 20\%$ for the data shown in Fig. 3. When the width of the unfolded signal is less than the width of the impulse response, a small uncertainty in the impulse response can lead to a much larger uncertainty in the deduced T_i .

We have also done a temperature analysis for a higher yield shot where $Y_n = 2.8 \times 10^{10}$. In this case, the MCP of the 10 m detector saturated, but the 20 m detector did not. The number of neutrons interacting in the 20 m detector was about 500, and the overall statistical quality of the signal was better than that shown in Fig. 2. The resulting temperature was $T_i = 0.95 \pm 0.09$ keV. These results again are consistent with the findings in Ref. 1, which suggest that for yields above about 1×10^{10} , the exact location of the detector is not so crucial for a good T_i determination. There is high enough statistical quality at

20 m that a reasonable temperature analysis can still be conducted.

Scattering in the chamber wall and along the flight path could be a potential source of error in our measurements. Based on shots where both detectors gave useful data, we estimate that this effect is 5 - 10% or less. If the duration of neutron emission were not small, this width would tend to broaden the measured TOF signal. Based on calculations of the implosions with LASNEX,⁵ this broadening is predicted to be negligible. A more serious concern arises, though, if emission occurs from regions of fuel undergoing substantial motion. The resulting kinematic distortion of the neutron TOF spectrum would then not be handled properly in our analysis.

In summary we have examined to what extent fuel T_i can be determined from implosions of DT-filled capsules using our current detectors. On low yield shots, the limiting factor in trying to minimize $\delta T_i/T_i$ typically is the number of neutrons interacting in the detector. Moving the detector somewhat closer to the target can be beneficial, provided that the impulse response is understood in detail. Small uncertainties in impulse response can lead to much larger uncertainties in T_i . On higher yield shots, $\delta T_i/T_i$ is less sensitive to distance, and one is better off locating the detector somewhat farther from the target. We find that we can measure 1 keV temperatures to a precision of about $\pm 20\%$ or better on shots with DT-neutron yield $Y_n > 5 \times 10^9$ by locating detectors at 10 m and at 20 m.

We are pleased to acknowledge useful and stimulating discussions with S.M. Lane, the dedicated technical support of the staff at the NOVA laser-fusion facility at Lawrence Livermore National Laboratory, and funding by U.S. DOE Contract No. W-7405-ENG-48.

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Figure Captions

Figure 1: Deconvolution of the detector response from the observed voltage signal for the detector located at 20 m on a shot with a DT-neutron yield of $Y_n = 7 \times 10^9$. (a) The solid curve on the top trace is the observed ("raw") neutron TOF signal, and the dotted curve is the result of convolving the impulse response with the unfolded distribution. The degree of agreement with the observed signal is a measure of the quality of the unfold. (b) The DT-neutron impulse response for this detector as measured on a separate shot with the detector located at 50 cm from the target. (c) The unfolded ("true") neutron TOF distribution.

Figure 2: (a) Final neutron TOF spectrum for the 20 m detector corresponding to the unfold shown in Fig. 1c. The solid curve represents

the best fit temperature of $T_i = 0.95$ keV, and the dashed and dot-dashed curves map out the range defined by the error of $\delta T_i = \pm 0.14$ keV. The region included in the fits is marked by the two vertical dotted fiducial lines. (b) The χ^2 versus T_i profile from which the best fit T_i is determined. The uncertainty, δT_i , is represented by the curvature in the neighborhood of the minimum, as illustrated by the dashed and dotted lines, namely, $\Delta\chi^2 = +1$ corresponds to $\Delta T_i = \pm \sigma_{T_i}$.

Figure 3: Same as Fig. 2 except for the detector at 10 m from the target. The deduced temperature is $T_i = 0.90 \pm 0.05$ keV.

Fig. 1

(a)

dN/dt (Neutrons/ns)

(b)

Fig. 2

(24.6 cm / 7.2 cm) - 3 = 2.0 cm

Fig. 3

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