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An improved method of unfolding neutron TOF spectrum for low ion temperature inertial confinement fusion

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Abstract: The fuel ion temperature in inertial confinement fusion can be determined from the neutron energy spectrum. For the implosion experiment with low neutron yield, and thus low signal-to-noise ratio, a new technique to unfold the neutron energy spectrum from the observed neutron time-of-flight signal is presented in this paper. This method uses a low-pass filter to remove noise from the signal with a threshold value determined by power spectrum analysis. This technique has been applied to the analysis of the observed neutron time-of-flight signals in the indirect drive implosion experiment conducted on Shenguang III prototype laser facility, and fuel ion temperatures of about 1.0 keV are obtained.

Key words: time-of-flight detector, deconvolution, low-pass filter, power spectrum

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1 Introduction

The profile of the neutron energy distribution is a function of the fuel ion temperature, and thus the neutron energy spectrum obtained by a current-mode neutron time-of-flight (TOF) detector can be used to determine the fuel ion temperature from inertial confinement fusion targets (ICF) [1]. The real neutron energy spectrum must be unfolded by the detector response function because the measured neutron time-of-flight signal is a convolution of the real neutron signal and the detector response. To do so, three methods are usually applied, which are: derivative, convolution, and deconvolution [2, 3]. The derivative method assumes that the measured signal is a convolution of real neutron signal with the exponential decay part of a plastic scintillator, and the other components which do not obey exponential decay are neglected. The convolution method assumes that the real neutron spectrum and the detector response obey some distributions, and the best result is found by fitting the measured data based on least square principle with the distribution function. The deconvolution method is theoretically strict in that the real neutron spectrum can be given directly by deconvolving the measured signal and the detector response without making any assumption.

Usually, the detector response drops rapidly at high frequency range and the noise in the measured signal tends to be exaggerated. Consequently, it will be very difficult to unfold the real neutron signal directly from the measured signal with the deconvolution technique. To reduce the effect of noise, it is necessary to conduct the deconvolution in coupling to a filtering process. The most important work involved in the filtering process is to determine the threshold of the filter, which may have an important influence on the unfold result. However, little work has been reported on the method of determining filter threshold. In this paper, an unfolding method based on power spectrum analysis is presented. By analyzing the power spectra of the deconvolution result and measured signal, the optimized filter threshold is obtained and the fuel ion temperature can be determined from the measured neutron energy spectrum. The method is applied to the diagnostics of the ion temperature in an indirectly-driven implosion conducted on the Shenguang III prototype laser facility.

2 Method and detector system

For the implosion ions with a Maxwellian distribution, the energy spectrum of neutrons is nearly Gaussian with a full width at half maximum (FWHM) proportional to the square root of ion temperature [4]. The neutron flight velocity is related to neutron energy, so we can obtain the neutron energy spectrum by measuring the arrival time distribution of neutrons when an ultrafast quenched plastic scintillation detector is placed at a certain distance from pulsed neutron source. The

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width of neutron time-of-flight signal is related to the ion temperature ($T_{\rm i}$) by the equation [3]:

$$\Delta t_{\rm tof}=C\times d\sqrt{T_{\rm i}}, \qquad (1)$$

where $\Delta t_{\rm tof}$ is FWHM of the neutron TOF signal, d is the distance from the neutron source to the detector, and constant C is 0.778 or 0.122 for DD neutron or DT neutron, respectively.

The neutron time-of-flight detector consists of a 1% benzophenone quenched BC-422 plastic scintillator that is coupled to a high time resolution microchannel plate photomultiplier tube (MCP-PMT). The output signal of the detector is sent to a digital oscilloscope with a bandwidth of 8 GHz and a sampling rate of 20 GS/s. To balance the detection efficiency and the time response, a plastic scintillator that is 2 cm thick×4 cm diameter is applied to the indirectly driven implosion experiment on Shenguang III prototype. The time response of this detector system is calibrated by implosion neutrons from a DT-filled capsule [5]. When the detector is placed close to the target, the thermal broadening of fusion neutrons can be neglected. The measured response contains a neutron emission time width that is also included in the TOF signal, and this time width can be offset in the unfolding process. The time response of the detector system is about 1.11 ns FWHM for DT neutrons, as shown in Fig. 1(a).

3 Data and unfolding technique

The width of neutron TOF signal is related to the ion temperature and the distance between the detector and the neutron source, as shown in Eq. (1). To reduce the influence of detector response on the real neutron spectrum, the width of measured signal must be bigger than the time response of the detector system [6, 7]. The thermal broadening of fusion neutrons will become wider with the increasing of the distance between the detector and the neutron source; meanwhile, the neutrons interacting with detector will become fewer. The optimum location of detector is determined by balancing the thermal broadening of fusion neutrons and statistical sampling of detected neutrons. The DT neutron yields of the indirectly driven experiment on Shengang III prototype are 10^9–10^{10}, and the distance between the detector and the target is about 7 m. Fig. 1(b) shows a typical neutron TOF signal measured with about 10^{10} DT neutron yield.

The true TOF signal $f(t)$ is deduced from measured neutron signal $F(t)$ and the detector response $g(t)$ by the equation: $f(t)=F(t)\odot g(t)$. Supposing that Fourier transforms of $f(t)$, $F(t)$ and $g(t)$ are $f(\omega)$, $F(\omega)$ and $g(\omega)$, respectively, then we have $f(\omega)=F(\omega)/g(\omega)$. Since the detector response $g(\omega)$ drops off quickly at high frequency, any noise in the data $F(\omega)$ will be exaggerated. As a result, the useful neutron signal plays a major role at low frequency and the enlarged noise becomes significant at high frequency. So we can choose a low-pass filter to remove the interference of high-frequency noise. When the frequency threshold of the low-pass filter is set as ω_0, any noise whose frequencies are above ω_0 can be removed. The width of filtered result greatly depends on the threshold value. If the threshold is set higher than ω_0, some noises above ω_0 will be mixed in the filtered result. If the threshold is set lower than ω_0, a part of real neutron signal will be removed and the filtered result will become distorted (ω_0 here is assumed to be the optimum frequency).

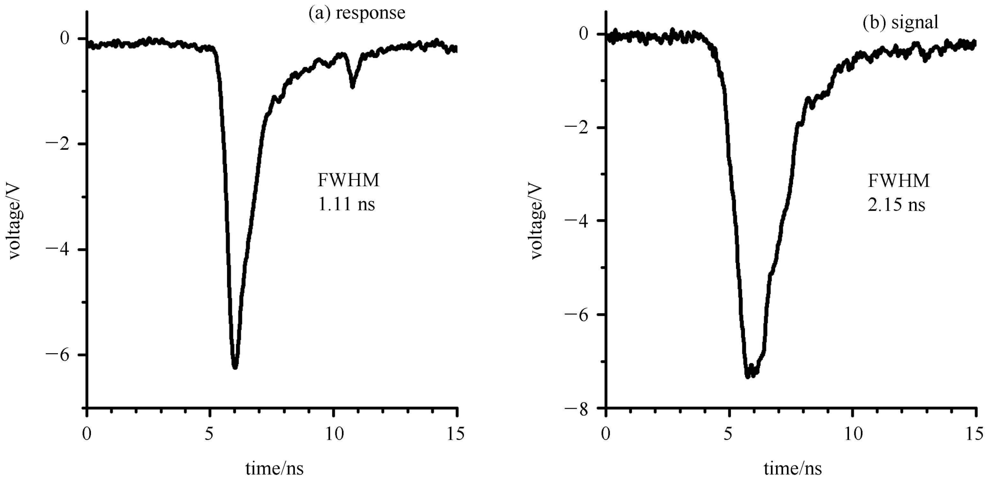

Fig. 1. (a) The time response of detector system calibrated by implosion DT neutrons. (b) The typical neutron TOF signal from indirectly driven experiment.

The proper threshold value of low-pass filter can be chosen by analyzing the power spectra of measured signal and the deconvolution result. The measured data $V[n]$ (n=0, $\cdots$, $N-1$) with a time interval Δt can be expanded into a discrete Fourier series, as follows:

$$\begin{aligned} F(m) &= \Delta t\sum_{n=0}^{N-1}\exp(-\mathrm{i}2\pi f_m t_n)V[n] \\ &= \Delta t\sum_{n=0}^{N-1}\exp(-\mathrm{i}2\pi mn/N)V[n], \end{aligned} \tag{2}$$

where $f_m=m/N\Delta t$, $m=0,\cdots,N-1$, and $t_n=n\Delta t$. The power spectrum of $V[n]$ related to the Fourier series can be expressed as:

$$P(m)=\frac{|F(m)|^2}{N\Delta t}. \tag{3}$$

The amplitude of power spectrum indicates the relative intensity of each frequency component included in the measured data. By analyzing the power spectrum of the deconvolution result, we can find the frequency range of the true neutron TOF signal and that of the enlarged noise, respectively.

The power spectra of measured neutron signal and deconvolution result are shown in Fig. 2(a) and Fig. 2(b), respectively. For the measured data, the neutron signal mainly distributes in the frequency range of 0–0.77 GHz and the amplitudes of high-frequency components are so low that they can be negligible, as shown in Fig. 2(a). After deconvolution, the enlarged noises become major components at high frequency. It can be seen that the frequencies of the true neutron TOF signal are also mainly below 0.77 GHz and those of enlarged noises are above 1.14 GHz from Fig. 2(b). So we can choose a proper threshold value of the low-pass filter between 0.77 GHz and 1.14 GHz. For any threshold value of this range, the enlarged noise can be filtered and the true neutron TOF signal has no distortion in the filtered result.

Since the frequencies of true neutron signal and enlarged noises are different, the filtered portion varies with chosen threshold value, resulting in different FWHM of the filtered result. The frequency ranges of true neutron signal and enlarged noise can be determined directly from the relation between the width of the filtered result and the threshold value. In order to obtain this relation, we have developed a deconvolution-filtering program that uses a series of threshold values to get the corresponding widths of the filtered results. The result produced by this program is shown in Fig. 3(a). When the threshold value is below 0.77 GHz, a part of true neutron TOF signal will be filtered and the width of the filtered result becomes larger. The true neutron TOF signal will be distorted worse when the threshold value becomes smaller. If the threshold value is above 1.14 GHz, some noise cannot be filtered, and the width of filtered result will become smaller as noise overlaps the true neutron signal. In the flat range of 0.77 GHz to 1.14 GHz, the threshold value has no significant influence on the width of the filtered result since the true neutron signal has no distortion and the effect of high-frequency noise is negligible. From Fig. 3(a), we can see that the relation between the width of filtered result and the threshold value accords with the result of power spectrum analysis. By choosing any value of this flat range, for example 0.89 GHz, the filtered deconvolution result is obtained, as shown in Fig. 3(b). The true neutron TOF signal has a FWHM of 1.10 ns and the ion temperature is 2.08 keV from Eq. (1).

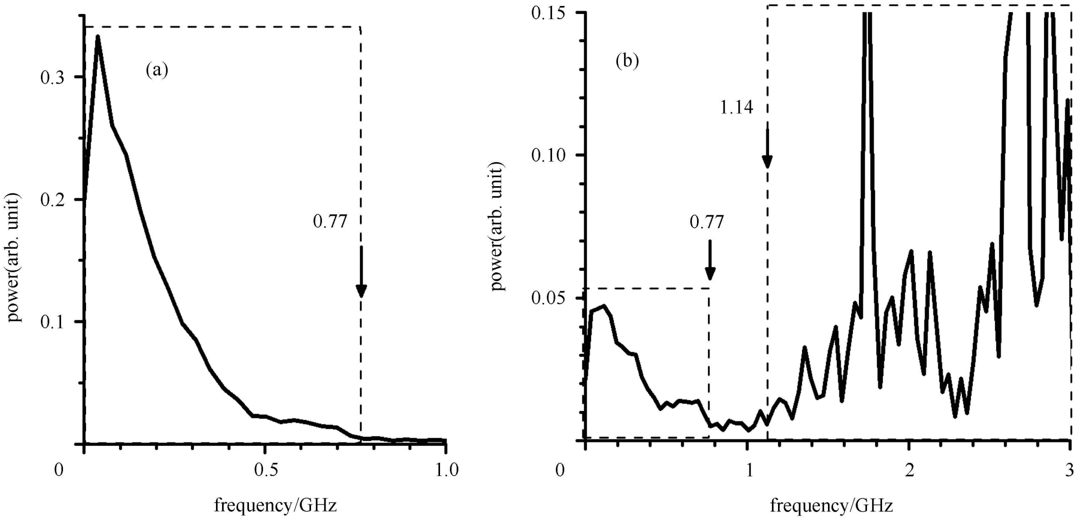

Fig. 2. The power spectra of (a) measured signal and (b) the deconvolution result.

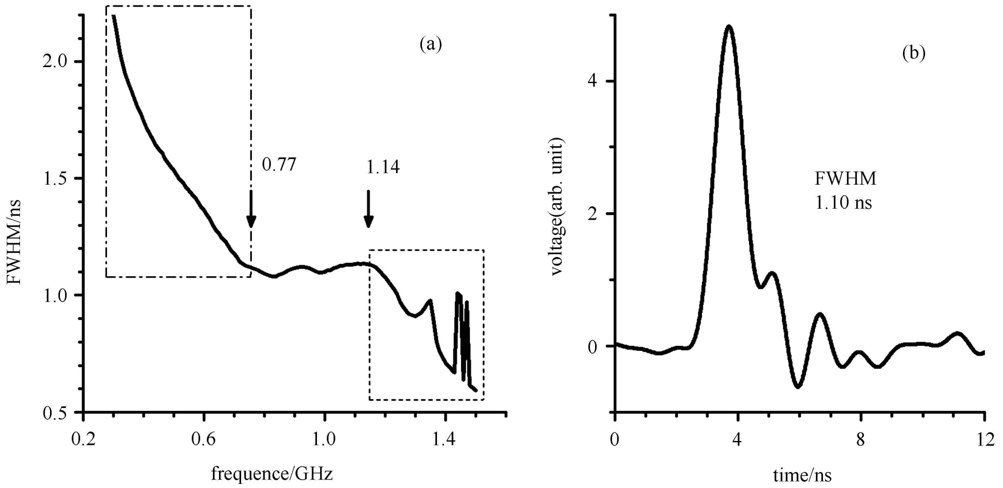

Fig. 3. (a) The relation between the FWHM of filtered deconvolution result and the threshold value of low-pass filter. (b) The filtered deconvolution result with a threshold value of 0.89 GHz.

4 Experimental results

All of the capsules used in the moderate-convergence implosion experiments are 2.04 μm thick glass spherical shells attached with 12.5 μm thick CH layers and filled with about 10 atm DT gases. The neutron yield of each shot is determined by copper activation measurement system and the ion temperature is measured by TOF detector using this unfolding method. The ion temperature error comes from the uncertainty of the FWHM of measured signal, the statistical fluctuation of detected neutrons, and the uncertainty of the FWHM of unfolded neutron TOF spectrum. The former two uncertainties are analyzed according to formula 12 in Ref. [8]. The third uncertainty can be estimated by filtering standard Gaussian curve. For some shot, suppose that f_0 is the chosen threshold value of filter and h_0 is the FWHM of unfolded result. Gaussian curves with different FWHMs are filtered with f_0, and a table is created containing the FWHM of the original curve and that of the filtered curve. Searching through this table, we obtain the filtered curve whose FWHM is the closest to h_0. The third uncertainty is then estimated by the FWHM difference between the original Gaussian curve and the corresponding filtered curve. Table 1 lists the data processing results, where the P, D and Y_n are the DT pressure, the thickness of CH layer, and neutron yield, respectively.

Table 1. The measurement result of ion temperature for moderate-convergence implosions.

shot no.	P/atm	D/μm	T_i/keV	error(%)	Y_n
102	7.2	12.5	2.85	10.7	1.07×10^{10}
103	8.3	12.6	2.3	15.1	1.06×10^{10}
104	6.3	12.8	2.35	18.5	6.8×10^{9}
106	6.6	12.4	2.08	8.6	8.9×10^{9}

For the low-convergence experiments, the capsules filled with 100 atm DT gas have a 2.94 μm thick glass spherical shell, and a CH layer whose thickness ranges from 10 μm to 30 μm. The relation between ion temperature and ablator thickness is studied in these experiments. Fig. 4 lists the measurement results compared with the calculation results in theory by simulation program. In Fig. 4, the solid curves represent the calculation results in different DT pressures and the asterisks represent the unfolded ion temperatures. The neutron yields range from 1×10^9 to 4×10^9, and the ion temperatures are between 1 keV and 1.5 keV, with uncertainties of 30%–50%. The uncertainties mainly come from the larger statistical fluctuation because of fewer detected neutrons and a bigger unfolded error.

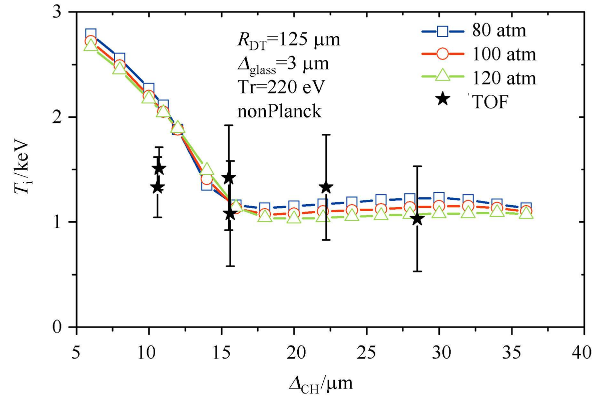

Fig. 4. (color online). The relation between the ion temperature (T_i) and ablator thickness (Δ_CH). The solid curves are the calculation results under different DT pressures by simulation program. In simulation, the radii of capsules are 125 μm and the thickness of glass spherical shells are 3 μm while the hohlraum radiation temperatures are 220 eV. The asterisks are unfolded ion temperatures of implosion experiments.

5 Conclusions

Although the unfolding method of neutron TOF spectrum with the deconvolution technique is theoretically strict, it is difficult to unfold the real neutron signal directly because of the interference of enlarged noise at high frequency. The thermal broadening of fusion neutrons is related to the ion temperature and the distance from the neutron source to the detector. Since this distance is restricted by the detection efficiency of the TOF detector, the thermal broadening of fusion neutrons will be small when the neuron yield is low. In a previous work [2], the unfolded ion temperatures are around 4 keV with uncertainties about 25% when the DT neutron yields are about 10^9 in the directly driven implosion experiments. When the detector response is smaller than the thermal broadening of fusion neutrons, the response does not have a great effect on the real neutron signal. In this instance, the neutron energy spectrum can be unfolded by a low-pass filter with an imprecise threshold value and the ion temperature is obtained with a greater uncertainty. Otherwise, it will become difficult to choose the threshold of the low-pass filter when the ion temperature reduces so low that the thermal broadening is smaller than the detector response. Even the ion temperature reduces to as low as 1 keV in the indirectly driven implosion experiments with 10^9 DT neutron yields. The ion temperature can also be obtained by the unfolding method based on the analysis of power spectrum in this paper. This method can also be used in the high ion temperature experiments, and the uncertainties of ion temperatures will become smaller than they were. This technique makes a great improvement on the range of ion temperature measurements under a similar order of magnitude of DT neutron yields.

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References

1 Murphy T J, Chrien R E, Klare K A. Rev. Sci. Instrum., 1997, **68**(1): 610–613

2 Chen J B, Zheng Z J, Peng H S et al. Rev. Sci. Instrum., 2001, **72**(9): 3534–3536

3 Murphy T J, Lerche R A, Bennett C et al. Rev. Sci. Instrum., 1995, **66**(1): 930–932

4 Russotto M A, Kremens R L. Rev. Sci. Instrum., 1990, **61**(10): 3125–3127

5 CHEN J B, ZHENG Z J, PENG H S et al. Nucl. Instrum. Methods A, 2002, **491**: 474–477

6 Remington B A, Lerche R A, Cable M D. Rev. Sci. Instrum., 1990, **61**(10): 3128–3130

7 Murphy T J, Lerche R A. Rev. Sci. Instrum., 1992, **63**(10): 4883–4885

8 Lerche R A, Remington B A. Rev. Sci. Instrum., 1990, **61**(10): 3131–3133