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1.B Analysis of Neutron Time-of-Flight Data

The fuel-ion temperature can be determined from the neutron-energy spectrum obtained with a neutron time-of-flight (TOF) detector.[1] For present target conditions, the energy spectra of neutrons produced in deuterium-tritium (DT) and pure deuterium (DD) fuel implosions are unaltered by the outer target layers and, therefore, contain valuable information about the temperature of the reactants in the core region. LLE has successfully deployed several neutron TOF spectrometers.[2] A method has been developed to unfold the neutron-energy spectrum from the observed signal and extract the fuel-ion temperature. This method is verified by modeling the TOF detector and the fuel with Monte Carlo techniques. The Monte Carlo model provides a method of statistical error analysis that yields information on the number of detected events required to extract a useful fuel-ion temperature from ICF neutron TOF data.

Method of Analysis

During an ICF implosion, fuel ions acquire a thermal energy distribution, which causes the neutron energy spectra to be Doppler broadened. The relationship between the fuel-ion temperature and the broadening of the neutron energy spectrum was derived by Brysk,[3] using the following assumptions: the ion thermal velocity distribution is Maxwellian; there is negligible nonthermal ion motion; and the fusion cross section has a form predicted by semiclassical Gamow theory.[4] These derivations showed that the neutron energy spectrum is Gaussian with the full-width at half-maximum (FWHM), ΔE, proportional to the square root of the ion temperature t_i:

$$\Delta E = 177 * \sqrt{t_i}, \quad (1)$$

$$\Delta E = 82.5 * \sqrt{t_i} \quad (2)$$

for DT fuel and DD fuel, respectively.

The detected signal consists of a convolution of the detector-response function, the neutron temporal-emission history, and the thermally broadened neutron spectrum. In our present target experiments, the neutron-emission pulse width is of the order of ~150 ps, which is significantly less than the instrument's 600- to 800-ps response time.

Analysis of the observed neutron TOF signal thus amounts to deconvolution of the detector-response function from the thermally broadened neutron-energy spectrum. Since applying deconvolution to a noisy signal can be numerically troublesome, we have developed a convolution-fitting program, CONGAUSS, which uses an averaged, measured, detector-response function and a neutron spectrum determined from a fuel model, to unfold the TOF spectrum. We currently model the fuel with a Gaussian neutron-energy spectrum based on Brysk's results.

For a range of temperatures, the model Gaussian neutron-energy spectra are convolved with the detector-response function to create a table containing the ion temperature represented by the Gaussian and the FWHM of the corresponding convolved function. A search is made through this table, looking for the convolved function that has the minimum $\chi^{(2)}$ with the observed data. The appropriate fuel-ion temperature is then extracted from the table.

Results of Analysis: Experimental

Two neutron TOF detectors are used for ICF experiments on OMEGA, one at 10 m for DT targets and the other at 1.8 m for DD targets. The detectors consist of a 1%-quenched Bicron BC-422 scintillator, 3.81 cm in diameter and 2.54 cm thick, optically coupled to ITT F4129f microchannel-plate photomultiplier tubes. These detectors have calculated neutron-detection efficiencies of about 6%. The electronic signal from the photomultiplier is recorded on a Textronix 7104 oscilloscope equipped with a 7A29 plug-in, which provides 1-GHz bandwidth. The oscillograph from this recording system is digitized using an inexpensive hand scanner and personal computer.

Figure 43.13 shows the averaged detector response to random cosmic rays for the 10-m neutron TOF detector. This signal represents an average over ten detected events. The response function has a FWHM of 0.8 ns and contains an electronic artifact in the pulse tail.

Figure 43.14 shows data from a DT target and the convolved function from which the energy spectrum FWHM was derived. On this experiment, approximately 400 events were detected in the 10-m TOF detector. The analysis, using CONGAUSS, yielded a fuel-ion temperature of 2.3 keV. The pulse height of the convolved function has been normalized to that of the data to do the $\chi^{(2)}$ calculation.

Results of Analysis: Monte-Carlo Modeling

To check the accuracy of our data reduction and to model the fundamental physics of the neutron-detection process, a Monte Carlo simulation was

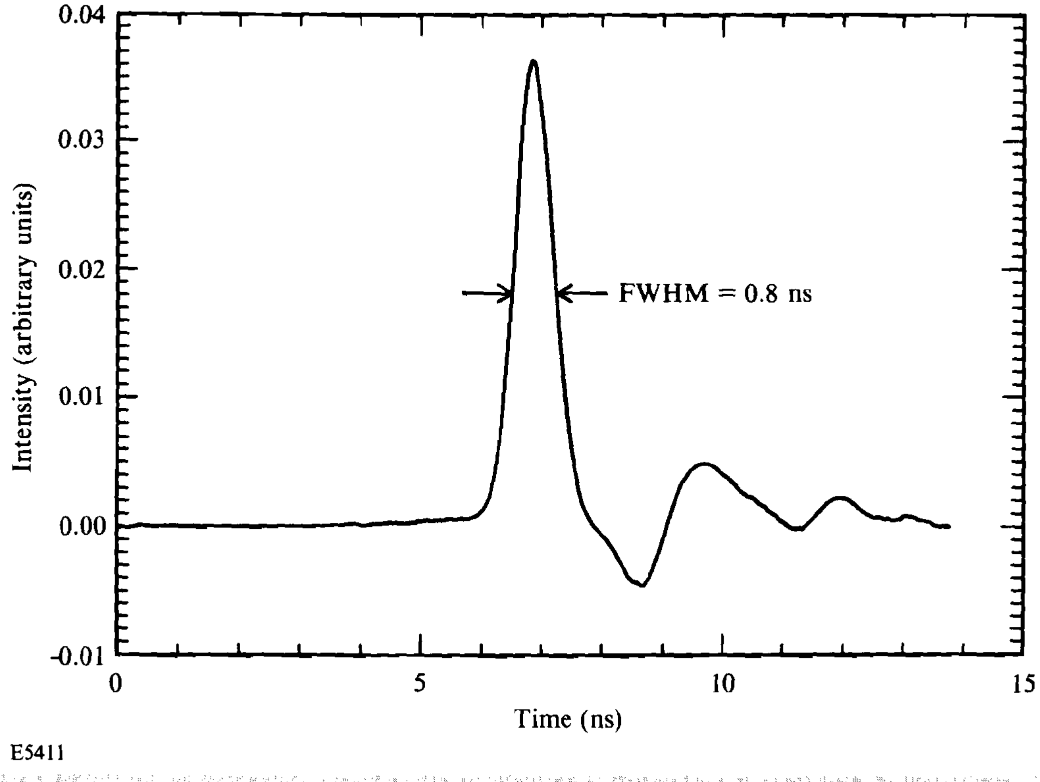

Fig. 43.13
Averaged detector-response function of the neutron time-of-flight detector located 10 m from the target.

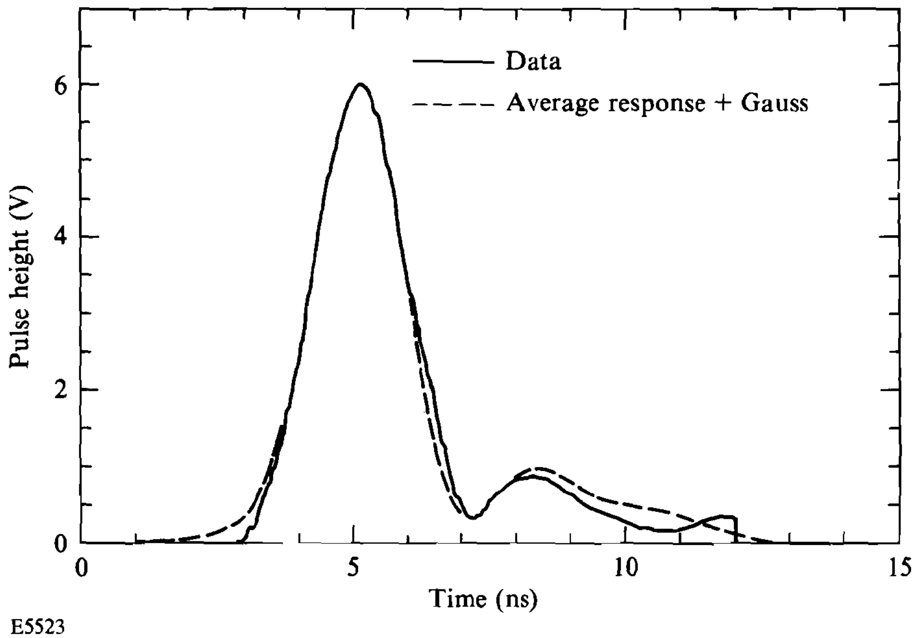

Fig. 43.14
Comparison of neutron TOF data and the convolution of the detector-response function and time-converted Gaussian energy spectrum from which an ion temperature of 2.3±0.8 keV is extracted. A $\chi^{(2)}$ of 0.054 was calculated for this fit. This was shot number 16176 for which there were 400 detector hits.

performed. The model for this simulation uses the measured, single-neutron electronic response of the detector to simulate the shape of each neutron event and theoretical probability functions to simulate the pulse height of the detector and neutron times-of-arrival. Neutrons interact by colliding with protons in the plastic (hydrogenous) scintillator. The proton recoil produces a light flash, which is detected by a photomultiplier. The model for the observed pulse-height distribution uses two assumptions: a uniform proton-recoil spectrum and a light output L from the proton-detection process with the following functional form[5]:

$$L \sim E^{1/3} ,$$

where E is the proton-recoil energy. The cumulative probability distribution for the pulse height H' is

$$P(H') = H'^{2/3} / H'_{max}{}^{2/3} ,$$

where H'_{max} is the pulse height at maximum recoil energy. Note that the pulse heights will vary from 0 to H'_{max}, which is typically around 0.1 V. These pulse-height variations cause uncertainty in the number of detected events. To simulate the time of arrival of each neutron we used a Gaussian energy distribution. However, the program is not restricted to this fuel model, thus allowing more complex fuel conditions to be modeled at a later time.

The input parameters to the simulation are the ion temperature and the number of detected events. The shape of each detected event is represented by the detector-response function, while the pulse height and time of arrival are obtained from respective cumulative probability distributions. The time- and height-adjusted response functions are then summed to obtain the resulting (current-mode) time-of-flight spectrum. Figure 43.15 shows a comparison of the neutron TOF data analyzed earlier and a Monte Carlo simulation with the same parameters. The simulation is in good agreement with the data. The Monte Carlo simulation routine was tested by extracting the ion temperature of the simulated detector signal using the reduction program CONGAUSS. The result is shown in Fig. 43.16. For a model input temperature of 2.3 keV, CONGAUSS extracts an ion temperature of 2.5 keV, which is within the statistical error of the simulation. Repeating the simulation several times with an ion temperature of 2.3 keV and 400 detected events, we consistently see uniformly shaped simulated pulses from which we can extract reasonable ion temperatures. However, when the number of detected events is significantly less, the simulations show wildly varying pulse shapes from which a fuel-ion temperature cannot be extracted without large errors. This suggests that there is a minimum number of detected events required to create a TOF spectrum that will yield a credible ion temperature. To investigate this point further, we have done a statistical error analysis using the Monte Carlo program.

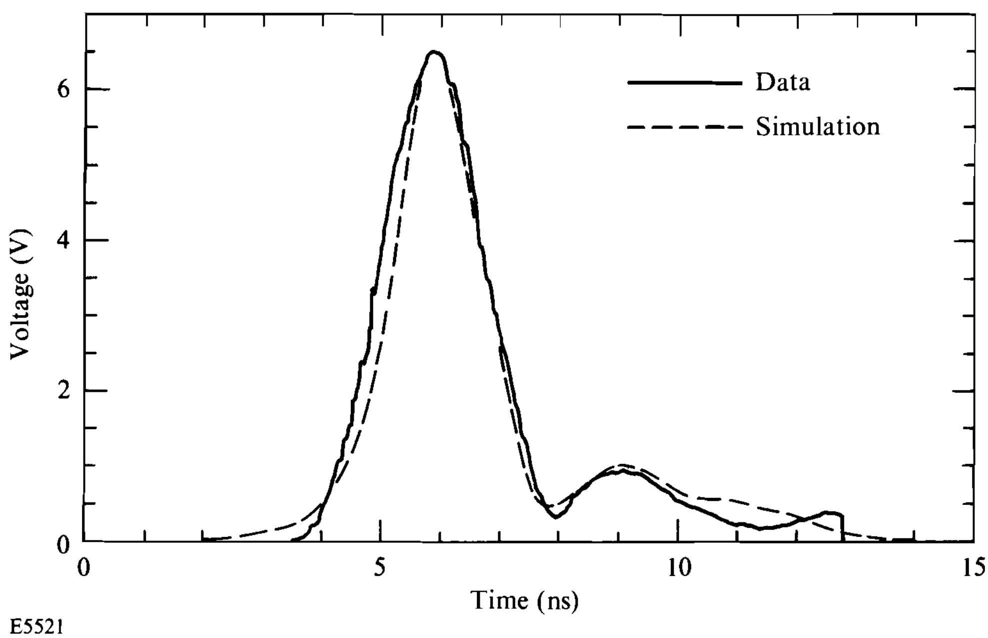

Fig. 43.15
Monte Carlo simulation of TOF data with a 2.3-keV ion temperature and 400 detected events. The data simulated is from shot number 16176; $\chi^{(2)}$ of the fit is 0.061.

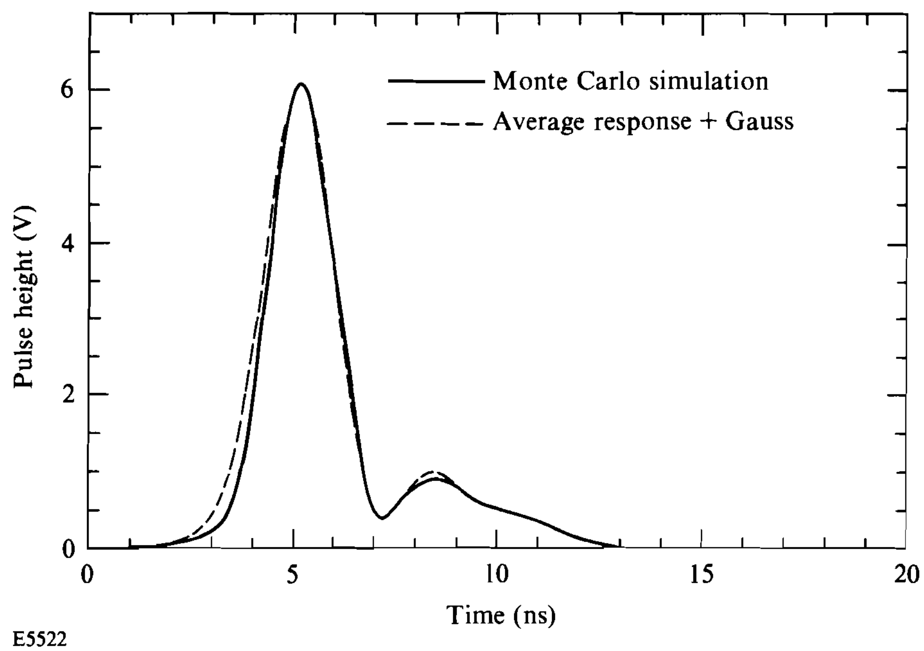

Fig. 43.16
Comparison of Monte Carlo simulation with the convolved function from CONGAUSS. The simulation temperature is 2.3 keV and the ion temperature extracted from CONGAUSS is 2.5±1.0 keV. 400 detected events were used in the simulation; the comparison gives a $\chi^{(2)}$ of 0.025.

For a given ion temperature the simulation was executed 200 times using various numbers of detected events at a single ion temperature. Each simulated pulse was used as input to CONGAUSS, which extracted the ion temperature of the TOF spectrum. In Fig. 43.17 the fractional error in the ion-temperature measurements generated from the Monte Carlo routine is compared with the theoretical,

$$2/\sqrt{2N},$$

fractional error.[6] The difference between the curves reflects the error incurred by not knowing the exact number of detected events. As expected, the fractional error in ion temperature declines with increasing numbers of detected events. However, the absolute error, and thus the fractional error, depends on the ion temperature as well. As the ion temperature increases for a fixed number of detected events, the spectral energy-density profile becomes broader, thereby creating a larger error. To obtain equal fractional errors for different ion temperatures, a larger number of detected events is thus required for the higher-ion-temperature implosion than the lower-ion-temperature implosion.

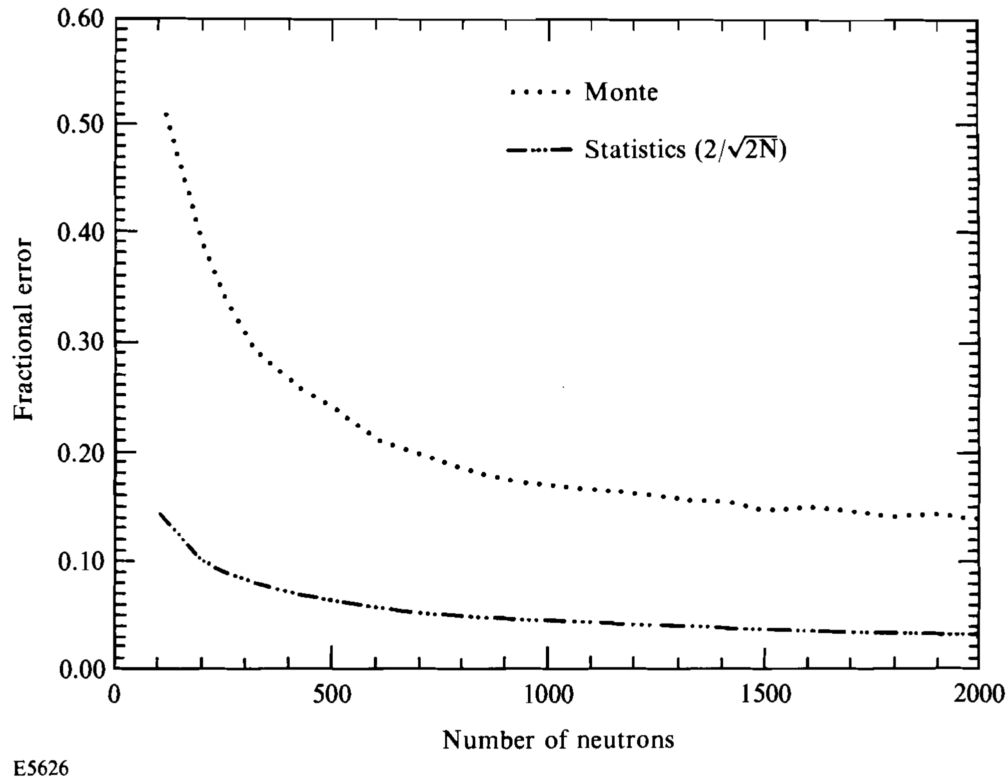

Fig. 43.17
Plot of fractional error in the fuel ion temperature versus the number of detected neutrons for theoretical statistics and the Monte Carlo calculations using an ion temperature of 2.31 keV.

In our present 1- to 3-keV temperature regime, systematic measurement errors are about 35%. From Fig. 43.17 our error analysis shows a similar error for about 250 detected events. Thus, we require significantly more than 250 detected events to extract a meaningful fuel-ion temperature corresponding to neutron yields > 4×10^9 for DT targets on the 10-m TOF detector.

Conclusion

We have developed a method to extract the fuel-ion temperature from ICF neutron time-of-flight data. A useful temperature can be extracted from the data only if a statistically significant number of neutrons are detected. In our present temperature regime, using a single, current-mode detector, accurate measurements of fusion neutron spectra can only be obtained on experiments producing greater than 250 detected events.