Neutron spectrometry—An essential tool for diagnosing implosions at the National Ignition Facility (invited)


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Neutron spectrometry—An essential tool for diagnosing implosions at the National Ignition Facility (invited)b)


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DT neutron yield (Yn), ion temperature (Ti), and down-scatter ratio (dsr) determined from measured neutron spectra are essential metrics for diagnosing the performance of inertial confinement fusion (ICF) implosions at the National Ignition Facility (NIF). A suite of neutron-time-of-flight (nTOF) spectrometers and a magnetic recoil spectrometer (MRS) have been implemented in different locations around the NIF target chamber, providing good implosion coverage and the complementarity required for reliable measurements of Yn, Ti, and dsr. From the measured dsr value, an areal density (ρR) is determined through the relationship ρR (g/cm²) = (20.4 ± 0.6) × dsr^10-12 MeV. The proportionality constant is determined considering implosion geometry, neutron attenuation, and energy range used for the dsr measurement. To ensure high accuracy in the measurements, a series of commissioning experiments using exploding pushers have been used for in situ calibration of the as-built spectrometers, which are now performing to the required accuracy. Recent data obtained with the MRS and nTOFs indicate that the implosion performance of cryogenically layered DT implosions, characterized by the experimental ignition threshold factor (ITF), is a function of dsr (or fuel ρR) and Yn, has improved almost two orders of magnitude since the first shot in September, 2010. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4728095]

I. INTRODUCTION

Hot-spot ignition planned at the National Ignition Facility (NIF) (Ref. 1) requires the formation of a round, high temperature hot spot surrounded by high fuel areal density (ρR). Experimental information about yield (Yn), ion temperature (Ti), ρR, and ρR asymmetries are critical for diagnosing implosion performance and understanding how the fuel assembles. To obtain this information, a suite of neutron spectrometers has been implemented and extensively used on the NIF for measurements of the neutron spectrum in the energy range from 1.5 to about 20 MeV. This range covers all essential details of the neutron spectrum, allowing for the simultaneous determination of ρR, Ti, Yn, and possible non-thermal features in the implosion. From the primary neutron spectrum, Ti and Yn are determined, and from the ratio between down-scattered and primary neutrons, the down-scattered ratio (dsr) is determined, which is to the first order proportional to the fuel ρR. The neutron spectrometers are part of a neutron diagnostic suite,2 which also includes the neutron activation diagnostic (NAD) system3 for absolute yield and relative spatial yield variation measurements, and a neutron imaging system (NIS) (Ref. 4) for measurements of the spatial distribution of the primary and down-scattered neutron source.

The neutron spectrometers, which include several neutron time-of-flight (nTOF) detectors5-7 and a magnetic recoil neutron spectrometer (MRS)8-11 are fielded at different locations surrounding the NIF target chamber, providing good implosion coverage and the complementarity required for reliable measurements of Yn, Ti, and dsr. From the measured dsr value, an areal density (ρR) is determined through the relationship ρR (g/cm²) = (20.4 ± 0.6) × dsr^10-12 MeV. The proportionality constant is determined considering implosion geometry, neutron attenuation, and energy range used for the dsr measurement. To ensure high accuracy in the measurements, a series of commissioning experiments using exploding pushers have been used for in situ calibration of the as-built spectrometers, which are now performing to the required accuracy. Recent data obtained with the MRS and nTOFs indicate that the implosion performance of cryogenically layered DT implosions, characterized by the experimental ignition threshold factor (ITF), is a function of dsr (or fuel ρR) and Yn, has improved almost two orders of magnitude since the first shot in September, 2010. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4728095]
locations around the implosion for directional measurements of the neutron spectrum (Fig. 1). This ensures good coverage of the implosion, allowing for determination of ρR asymmetries and possible non-thermal effects. The diametrically different detection principles of the MRS and nTOF spectrometers add to the reliability of the measurements.

To achieve the required accuracy for the measurement of the absolute neutron spectrum, a set of commissioning experiments was conducted on the NIF for an in situ calibration and characterization of the different spectrometers. With the spectrometers fully commissioned, they are now used routinely in support of the National Ignition Campaign (NIC).

This paper is structured as follows. Section II describes the inertial confinement fusion (ICF) neutron spectrum. Aspects of the $dsr$ measurement and how it relates to the total and Deuterium-Tritium (DT) fuel $\rho R$ are also discussed in this section. Section III discusses the neutron spectrometer commissioning experiments, and Sec. IV presents spectrometry data from cryogenically layered DT implosions.

II. THE ICF NEUTRON SPECTRUM

The ICF neutron spectrum has been described elsewhere, and is therefore only discussed briefly in this paper. The $\text{D(T,n)}\alpha$ reaction produces primary neutrons with a kinetic energy of 14.03 MeV (zero temperature). As the DT reactions occur in a hot plasma, the primary neutron spectrum is Doppler broadened and energy upshifted due to a finite $T_i$. For a single-temperature plasma, $T_i$ is determined from the Doppler width ($\Delta E_n^{\text{FWHM}}$) of the primary neutron spectrum, which is well represented by a Gaussian distribution [$T_i$ is to the first order equal to ($\Delta E_n^{\text{FWHM}}/177$) keV]. Temperature profiles or non-thermal reactions result in deviations from the single-Gaussian non-thermal effects could, for instance, be caused by bulk flows in the fuel at velocities as high as the speed of sound. Scattering in the cold, dense fuel and ablator that surrounds the hot spot gives rise to a low-energy (down-scattered) component in the neutron spectrum. The physical quantity measured by the neutron spectrometers is the down-scattered ratio, which is defined as $dsr(E) = Y(E)/Y_{\text{13-15 MeV}}$, while hydrodynamic codes simulate compression performance given in $\rho R$. Figure 2(a) shows neutron spectra simulated using the neutron transport code MCNPX (Ref. 15) for implosions with $\rho R$ varying from 0.1 to 2.0 g/cm$^2$. As shown, both shape and magnitude of the down-scattered neutron spectrum change significantly with increasing $\rho R$. As discussed in Refs. 9, 12, and 16, the magnitude of the down-scattered neutron spectrum relative to the neutron yield, or $dsr$, is to the first order proportional to $\rho R$. The conversion factor ($C$) between the fuel $\rho R$ and down-scatter ratio, $dsr(E) = Y(E)/Y_{\text{tot}}$ (where $Y_{\text{tot}}$ is the total number of DT neutrons produced in the implosion), has been derived analytically to be

$$\rho R_{\text{DSR}} \approx \frac{5m_p}{\sigma_n(E) + \sigma_t(E)} dsr(E) = C \times dsr(E),$$

where $m_p$ is the proton mass and $\sigma(E)$ is the energy dependent cross sections for elastic $n,D$ and $n,T$ scattering and $(n,2n)$ breakup reactions in D and T. These nuclear processes contribute to the measured low energy neutron spectrum and need to be included when integrating the cross sections over the appropriate energy interval. Eq. (1) is only valid for a point source (PS) and a 50:50 DT plasma. As the derivation of Eq. (1) only considers single scattering for a low $\rho R$ case, it needs to be modified to take into account (i) multiple scattering, (ii) attenuation of primary and down-scattered neutrons, (iii) the effect of ablator $\rho R$, and (iv) the effect of implosion geometry (size and shape of the primary and scattering sources). As $\rho R$ increases, multiple scattering and attenuation become more significant at neutron energies below ~8 MeV, resulting in a change in the spectral shape. This is shown in Fig. 2(b), which illustrates the single-scattering and multiple-scattering components for $\rho R = 0.2$ and $\rho R = 2.0$ g/cm$^2$ implosions. In addition, because multiple scattering and attenuation are significant in high-$\rho R$ implosions at the
NIF, the measured primary yield \( Y_{n,13-15\text{MeV}} \) does not well represent the total yield used in Eq. (1).

At bang time, some of the ablator mass needs to be preserved to control hydrodynamic instabilities in the implosion.\(^{16}\) This remaining mass will contribute to the down-scattered neutron signal, but on a level much lower than the down-scattered neutron signal from the DT fuel. This is due to the smaller cross sections for the ablator material per mg/cm\(^2\). If we assume a CH ablator (which is currently used on the NIF) and a relative \( R \) contribution from CH of \( X = \rho R_{CH}/\rho R_{DT} \), then the fractional CH contribution to the observed \( dsr_{10-12\text{MeV}} \) can be written as

\[
dsr_{\text{CH}} \approx \frac{50\sigma_{\text{CH}}(E)}{130\sigma_{\text{DT}}(E)} X \times dsr_{\text{DT}} \approx 0.12 X \times dsr_{\text{DT,10-12MeV}}.
\]

(2)

X has been estimated from simulations using the 2D hydro code LASNEX\(^{17}\) to be \( \sim 0.1 \), which means that \( \sim 1\% \) of the observed \( dsr_{10-12\text{MeV}} \) will be due to the CH ablator. This, however, means that the CH-ablator \( R \) is not well probed by down-scattered neutrons and needs to be measured in other ways, such as with knock-on protons,\(^{18}\) gamma-ray spectroscopy,\(^{19}\) or with x-ray methods.\(^{20}\)

In realistic implosion geometries, the average neutron path length through the dense fuel is generally longer than the path length in the point-source case. This leads to higher measured \( dsr \) values for a given \( R \), and a reduced conversion factor. LASNEX simulations of numerous NIF implosions were used to derive the following conversion factors for the total and fuel \( R \):

\[
\rho R_{\text{tot}}(\text{g/cm}^2) = (20.4 \pm 0.6) \times dsr_{10-12\text{MeV}},
\]

(3)

\[
\rho R_{\text{fuel}}(\text{g/cm}^2) = (18.8 \pm 0.5) \times dsr_{10-12\text{MeV}}.
\]

(4)

In these simulations, \( X \) was determined to be \( 0.08 \pm 0.04 \).

The part of the implosion sampled by a spectrometer depends primarily on the \( dsr \) energy range used, composition of the fuel and ablator material, energy dependence of the differential cross section for the different nuclear processes, and implosion geometry. When only considering \( n,D \) and \( n,T \) elastic scattering (and not the \( n,2n \) processes), the sampled angular interval for a given scattered neutron energy range can be determined from the (non-relativistic) relationship

\[
E_n = \frac{1}{(A+1)^2} E_n (\cos \theta + (A^2 - \sin^2 \theta)^{1/2})^2.
\]

(5)

Here, \( E_n \) is the energy of the down-scattered neutron, \( \theta \) is the neutron scattering angle in the lab system, and \( A \) the mass number of the scattered nucleus. Using Eq. (5), the sampled angular ranges for \( E_n = 10-12 \text{ MeV} \) and \( E_n = 6-12 \text{ MeV} \) can be illustrated for a neutron point source as in Fig. 3. For a more realistic implosion geometry, the fraction of the implosion sampled is increased relative to the point source case.

Currently, \( E_n = 10-12 \text{ MeV} \) is used for \( dsr \) measurements, but broader or different energy ranges have been used and will be routinely used in the near future. Ultimately, the plan is to use the whole neutron spectrum down to thermal energies\(^{21}\) to extract as much information as possible about the implosion.

III. COMMISSIONING EXPERIMENTS

The different neutron spectrometers were installed and commissioned on the NIF in stages. The nTOFs were installed in 2009 and 2010, the MRS in late 2010, and the neutron imager time-of-flight (NITOF) in 2011. These spectrometers were commissioned over a time period of about 6–12 months, during which the systems were calibrated in situ in a coordinated fashion. In this section, the commissioning experiments are discussed in some detail. Common to all is that a series of exploding pusher implosions\(^{22}\) was used to calibrate or verify the performance of the spectrometers before they were used to diagnose cryogenically layered DT implosions.

A. MRS

As the principle of the magnetic recoil neutron spectrometer (MRS) has been described in detail elsewhere,\(^{8-11}\) it is only discussed briefly in this paper. The system consists of four main components: a \( 13 \text{ cm}^2 \) deuterated polyethylene foil (CD\(_2\)) positioned 26 cm from target chamber center (TCC), a focusing magnet, made of Nd-Fe-B, positioned just outside the NIF chamber, an array of nine CR-39 detectors positioned at the magnet focal plane, and 6000 lbs of polyethylene shielding fully enclosing the spectrometer. The principle of the MRS is as follows. A small fraction of the emitted neutrons hit the CD\(_2\) foil and produce elastically scattered deuterons. Forward-scattered deuterons are selected by an adjustable-sized magnet aperture positioned in front of the magnet. Selected deuterons are momentum analyzed and focused onto the CR-39 detector array. The position of the detected deuteron depends on its energy. The CR-39 detectors are processed in etch and scan labs, and then analyzed to reconstruct the recoil deuteron spectrum, from which the neutron spectrum is inferred (currently using a forward-fitting technique).

The efficiency of the MRS can be accurately calculated from first principles, allowing the MRS to provide a solid, independent \( Y_n \) measurement.\(^{23}\) Spectral broadening due to geometry, CD\(_2\) foil thickness, and magnet properties

\[
\text{FIG. 3. Implosion region sampled when using (a) the } E_n = 10-12 \text{ MeV and (b) the } E_n = 6-12 \text{ MeV range for the } dsr \text{ measurement. The implosion fraction sampled is } 17\% \text{ and } 53\% \text{ for } 10-12 \text{ MeV and } 6-12 \text{ MeV, respectively. For the determination of an average } R \text{ that better represents the implosion performance, the } 6-12 \text{ MeV energy range is preferable. These schematic drawings only consider single } n,D \text{ elastic scattering (green), } n,T \text{ elastic scattering (red), a point source, and a dense DT shell.}
determines the spectrometer resolution. In standard fashion, the efficiency can be increased at the expense of resolution by using a thicker CD2 foil. To date, the MRS has been operated with six different foils, manufactured by General Atomics, ranging from ~50 to 250 μm in thickness. In addition, the MRS can be operated without a conversion foil for measurements of charged particles (e.g., 14.7 MeV protons from D3He reactions) emitted directly from the implosion.

An accurate reconstruction of the neutron spectrum from the measured recoil-deuteron spectrum requires detailed knowledge about the instrument response function (IRF), which is calculated ab initio based on the MRS geometry and measured magnetic field map. The calculated IRF requires verification through in situ measurements to establish the as-built properties of the system. The MRS has been operated, without the CD2 conversion foil, on D3He Exploding Pusher shots N100823 (black circles) and N110722 (magenta crosses), Fig. 4(a). Solid calibration data were also obtained on a series of DT gas-filled exploding pushers (Fig. 4(b)). On DT shot N101030, the MRS was fielded in medium-resolution mode (~140 μm foil thickness, ΔE_MRS ≈ 1100 MeV full width half maximum (FWHM)), on DT shot N101212, it was fielded in medium-resolution mode with a 75 μm Ta ranging filter behind the foil to get a calibration point at ~8.5 MeV deuteron energy, and on DT shot N101217 it was fielded in high-resolution mode (~50 μm foil thickness, ΔE_MRS ≈ 510 MeV FWHM). It was found that this set of data could be described by simulations to an accuracy of ±50 keV neutron energy equivalent if the magnetic field strength, as given by the manufacturer, Dexter Magnetic Technologies Inc., is increased by 4.95%.

The MRS was designed to minimize scattering materials between TCC and the CD2 foil to avoid any background interference in the low-energy down-scattered neutron region, which could compromise the dsr measurement. It was also designed to reduce the ambient neutron background to the required level. Data from two DT exploding pushers (N101030 and N110217), in which the ρR is negligibly small, were used as a “null” test to ensure the quality of the MRS dsr measurement. The inferred dsr_{10,12MeV} for N101030 and N110217 is (0.1 ± 0.1)% and (−0.2% ± 0.5)%, respectively, indicating that the background interference in the dsr measurement is insignificant.

B. nTOF

The suite of nTOF spectrometers includes a total of 12 instruments for diagnosing Deuterium-Deuterium (DD) and DT implosions. In this paper, we focus on the nTOFs used for measurements of Y_n, T_i, and dsr in DT implosions. At this point, these include two liquid scintillators (Spec-A and Spec-E) at about 20 m from TCC, a set of chemical vapor deposition (CVD) diamonds at 20 m (IgHi), and a plastic scintillator at 27.3 m (NITOF). All nTOFs consist either of a fast CVD diamond or a scintillator detector coupled to a photodiode (PD) or photomultiplier tube (PMT), biased to high voltage. Each nTOF is operated in current mode with the signal collected on one or more oscilloscopes. With a fixed and well-known distance to TCC and known IRF (discussed later), the neutron spectrum can be inferred from the time-of-flight signal.

Common to all these nTOF detectors is that an accurate absolute yield calibration could not be applied. Instead, they were cross-calibrated to the yield measured with the MRS and Zr and Cu neutron activation (NAD) on DT exploding pushers. The yield calibration is continuously checked as new data are collected.

1. nTOF 20 m-SPEC detectors

The nominally identical Spec detectors, positioned 20 m from TCC in the neutron alcove (A) and on the equator (E), are the workhorse nTOF detectors designed to measure the neutron spectrum in the range 1.5–15 MeV and to provide accurate dsr and T_i measurements. They are oxygen-quenched xylene-based liquid scintillators with a relatively narrow response (5 ns), coupled to two PMTs, PMT140 and PMT240, with different gain. The less-sensitive PMT140 (gain 10^3) is used to record the high-intensity neutron spectra from DT implosions, while the more-sensitive PMT240 (gain 10^5) is gated to only measure the spectrum below ~4 MeV, avoiding saturation from the 14-MeV neutrons. The PMT140 is primarily used for the primary-neutron and 10–12 MeV dsr measurements. PMT240 is used to record the DD spectrum in a DT background and n,D and n,T elastic back-scatter edges (discussed in detail in Ref. 24).

To determine the IRFs for the Spec-A and Spec-E detectors, including cables, scintillators, and PMTs, an impulse response was first measured using an x-ray burst of...
FIG. 5. (a) Neutron-time-of-flight (nTOF) Spec-A traces for a low-\(\rho R\) exploding pusher (N111121, red) and a high-\(\rho R\) DT layered shot (N111112, black). (b) Spec-E traces for the same shots. See text for details.

FIG. 6. Example of neutron imager time-of-flight (NITOF) data from DT Exploding Pusher shot N111121 (red) and DT layered shot N111215 (green, time shifted −20 ns to match N111121). The black curve represents the best-fit to the exploding pusher data using the IRF. The N111121 13–15 MeV intensity is renormalized to N111215. The intensity difference in the 6–12 MeV equivalent region (indicated in the figure) is due to down-scattered neutrons.

3. NITOF

The neutron imager time-of-flight (NITOF) detector is an NE-111 plastic-scintillator based detector fielded on the equator in the same LOS as the neutron imaging system at 27.3 m from TCC. The IRF (width 2.17 ns FWHM) is independently constructed from x-ray response measurements on the OMEGA laser facility (first decay constant), combined with scintillator decay property measurements using neutrons from an AmBe source at Los Alamos National Laboratory (LANL) (two longer decay constants).

DT exploding pusher data are accurately described by adjusting the width and amplitude of the IRF, as shown for N111121 in Figure 6, where data from layered shot N111215 are also shown for comparison. Unlike the other nTOF detectors, the NITOF low-energy baseline level is not determined from DT exploding pusher measurements. The background subtraction for the \(d\sigma/dT\) measurement is done using data taken from equivalent out-of-beam detectors fielded on the same shot. The main background of scattered neutrons comes from the neutron imaging system itself. With its independent IRF calibration and unique scheme for \(d\sigma/dT\) determination, NITOF adds important complementary \(d\sigma/dT\) and \(T\) data (absolute accuracy 0.5% and 0.5 keV, respectively).

IV. DIAGNOSING CRYOGENICALLY LAYERED DT IMPLOSIONS

The suite of neutron spectrometers has been used to diagnose about 30 cryogenically layered implosions from the first duffed pre-tuning Tritium-Hydrogen-Deuterium (THD) implosions in 2010 and early 2011\(^{25,26}\) through to the more recent 50:50 DT implosions in Uranium Hohlraums.

These measurements have been essential for diagnosing the implosion performance, characterized by the experimental ignition threshold factor (ITFx),\(^{16,27,28}\) and for guiding NIC towards the first demonstration of ignition in a laboratory. The IFTx has improved from \(1.5 \times 10^{-3}\) on N100929 to \(0.1\) on N120321.

Figure 7(a) shows the primary neutron yield measured with the MRS compared to the weighted average yield measured with the NADs (including Cu and Zr NAD data) for
all layered shots. The plot shows consistent agreement over a large yield range.

As the IRFs for Spec-A, Spec-E, IgHi, NITOF, and MRS are independently determined, \( T_i \) results from these detectors are contrasted to the weighted average value shown in Fig. 7(b). The agreement between the Spec-A, Spec-E, and NITOF measurements is remarkable, given the different methods for determining the IRF. The error bars for MRS \( T_i \) data are large because the primary neutron yields have been \(<10\)^15, which requires the MRS to be operated in medium-resolution mode.

Figure 7(c) shows the \( dsr \) (10–12 MeV) data measured with the MRS, Spec-A, Spec-E, and NITOF as a function of the weighted average \( dsr \) value. As shown by the data, the SPEC-E \( dsr \) data are systematically lower than the \( dsr \) measured by the other spectrometers, which is most likely due to \( \rho R \) asymmetries, but further investigations are required before any final conclusions can be drawn. The issue is currently being addressed by analyzing all the \( dsr \) data over a wider energy range, which corresponds to a larger coverage of the implosion (Fig. 3). This provides a better average \( \rho R \) measurement. Using Eq. (3), the \( dsr \) values shown in the figure correspond to \( \rho R \) values in the range 0.5–1.3 g/cm².

The individual measurements of \( Y_n \), \( T_i \), and \( dsr \) are weighted together, taking into account their errors, to get an average value that better represents the overall implosion performance. This average value is robust due to the large implosion coverage and the varying detection principles of the different instruments.

V. SUMMARY

A suite of neutron spectrometers, including an MRS and several nTOF detectors, has been implemented and extensively used on the NIF for measurements of the neutron spectrum in the energy range from 1.5 to about 20 MeV. The as-built performance of these spectrometers has been accurately calibrated using a series of DT and D\(^3\)He exploding pusher commissioning experiments. The spectrometers, which perform well and meet the required accuracies for the \( Y_n \), \( T_i \), and \( dsr \) measurements, have been essential for diagnosing the implosion performance of DT layered implosions and for guiding NIC towards the first demonstration of ignition in the laboratory.

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20S. P. Regan, private communication (2012).
24C. Forrest et al., “High resolution spectroscopy used to measure ICF neutron spectra on OMEGA,” Rev. Sci. Instrum. (these proceedings).