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Measurements of fuel and ablator $\rho R$ in Symmetry-Capsule implosions with the Magnetic Recoil neutron Spectrometer (MRS) on the National Ignition Facility

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The Magnetic Recoil neutron Spectrometer (MRS) on the National Ignition Facility (NIF) measures the neutron spectrum in the energy range of 4–20 MeV. This paper describes MRS measurements of DT-fuel and CH-ablator $\rho R$ in DT gas-filled symmetry-capsule implosions at the NIF. DT-fuel $\rho R$’s of 80–140 mg/cm$^2$ and CH-ablator $\rho R$’s of 400–680 mg/cm$^2$ are inferred from MRS data. The measurements were facilitated by an improved correction of neutron-induced background in the low-energy part of the MRS spectrum. This work demonstrates the accurate utilization of the complete MRS-measured neutron spectrum for diagnosing NIF DT implosions. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4886418]

I. INTRODUCTION

The Magnetic Recoil neutron Spectrometer (MRS) on the National Ignition Facility (NIF) was designed to measure the neutron spectrum from Inertial Confinement Fusion (ICF) in the energy range of 4–20 MeV.1–5 This energy range covers the essential details in the spectrum. The primary neutron yield ($Y_{PT}$) is determined by integrating the spectrum from 13 to 15 MeV, and the ion temperature ($T_{\text{ion}}$) is determined from the width of the primary peak. An areal density ($\rho R$) is inferred from the ratio of down-scattered neutron yield in the range 10–12 MeV to the primary neutron yield. Signatures of tertiary neutrons from in-flight reactions are visible in the 15–20 MeV range for DT neutron yields approaching $10^{16}$. The shape of the neutron spectrum below 10 MeV also contains essential information on the relative importance of fuel and ablator $\rho R$ and $\rho R$ asymmetries. Full exploitation of the MRS data in this energy range requires detailed understanding of the background in the MRS measurement.

This paper describes how the background in the low-energy part of the MRS spectrum is characterized through measurements and MCNPX (Monte Carlo N-Particle extended) neutron-scattering simulations. We show how the complete MRS spectrum can be used to determine DT-fuel and CH-ablator $\rho R$ in DT gas-filled Symmetry Capsule (Sym-Cap) implosions with correct treatment of the background. The fidelity in the background determination is established through a self-consistency check, where results from fits to different regions of the MRS spectrum are compared. To further establish the fidelity of the analysis, the determined DT-fuel and CH-ablator $\rho R$’s are also compared to and cross-validated against the CH-ablator $\rho R$ data measured with the Gamma Reaction History (GRH) diagnostic,6 and to the expected fuel $\rho R$ based on simulations.7

II. NEUTRON BACKGROUND

The primary components of the NIF MRS are a deuterated polyethylene foil positioned 26 cm from Target Chamber Center (TCC), in which neutrons elastically scatter to produce recoil deuterons, a 20-cm$^2$ magnet aperture at 596 cm from TCC which selects forward-scattered recoil deuterons, an Ne-Fe-B magnet (located behind the aperture) in which recoil deuterons are momentum analyzed, and an array of nine $4.8 \times 6.8 \text{ cm}^2$ CR-39 track detectors to record the spectrum of the momentum-separated deuterons (Fig. 1(a)), from which the neutron spectrum is inferred. The detector array is encased in polyethylene shielding to reduce the direct and ambient neutron background. Except for the aperture which is open to the chamber vacuum, most of the MRS is also shielded by the steel chamber wall and a 50 cm thick layer of gunite. The combined shielding reduces the background about two orders of magnitude.

CR-39 detectors are insensitive to x-rays, photons, and electromagnetic background, but they are somewhat sensitive to background neutrons interacting with the detector material.8 In addition, intrinsic background due to defects in the CR-39 must be considered. Low MRS signal in the

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The measured background varies across the piece. (c) MCNPX-simulated neutron fluence as a function of x-position. As shown, the neutron fluence is predicted to be non-uniform across the piece, with a shape qualitatively similar to the measured background.

III. RESULTS FROM SYMCAP EXPERIMENTS

Having a detailed understanding of the characteristics of the background at the different detectors, an accurate determination of the low-energy part of the MRS spectrum can now be made to look at the detailed shape of this part of the spectrum. This was done in a series of five DT-gas filled SymCap implosions,\textsuperscript{11, 12} which are indirectly driven implosions with a thick CH-plastic payload to emulate the DT ice in a cryogenically layered implosion. Due to the significantly higher CH \( \rho R \) than the DT fuel \( \rho R \) in these implosions, the number of downscattered neutrons from CH becomes comparable to the number of downscattered neutrons from the DT fuel, making this type of implosion an ideal candidate for attempting to separate CH-ablator and DT-fuel \( \rho R \) contributions to the neutron spectrum. Because of lower convergence, these implosions are also expected to be less affected by low-mode \( \rho R \) asymmetries than cryogenically layered DT implosions. In this analysis, we neglect any potential low-mode \( \rho R \) asymmetries (though it should be noted that for two of the shots, N130625 and N130814, an intentional 8\% up-down asymmetry in the laser drive was imposed to seed implosion asymmetry).

Fig. 2(a) shows the reduced MRS spectrum for shot N130625 (\( Y_\text{DT} = 7.0 \times 10^{14} \)). A modeled neutron spectrum (Fig. 2(b)), with a primary-neutron (Gaussian\textsuperscript{13}) component, CH- and DT downscattered neutron components, and that the background was distinctly non-uniform across CR-39 detectors #1–5. Fig. 1(b) shows the measured background distribution along x for CR-39 detector #2.

To understand this observation, a detailed MCNPX\textsuperscript{10} model of the NIF target bay including the MRS housing and shielding was used to assess the expected distribution of neutron-induced background across the individual CR-39 detectors. The result for CR-39 detector #2 is shown in Fig. 1(c). The simulations show a variation in neutron fluence along the x-direction that is in qualitative agreement with the observation. The level of variation depends on what neutron energy range is considered in the simulation. For all neutrons, the variation is \( \sim 13\% \) (see Fig. 1(c)), for neutrons with energy above 2.4 MeV, \( \sim 21\% \), and for neutrons with energy above 10 MeV, \( \sim 34\% \). To allow for a comparison of simulated and measured results, the processes by which neutrons interact with CR-39 must be considered. For neutron energies below \( \sim 10 \) MeV, elastic \( n,p \) scattering is the dominant interaction process. Neutrons below 2.4 MeV are not expected to contribute in CCT for detector #2 because recoil protons with energy less than 2.4 MeV are effectively ranged out in the 75 \( \mu \)m of CR-39 between layers. Neutrons above \( \sim 10 \) MeV are expected to also generate reactions, the signature of which may be different in CCT than elastic \( n,p \) reactions. The MCNPX modeling also indicates that the background variation is larger for CR-39 detectors closer to the MRS aperture. The most likely explanation for this result is that the variation of the neutron-fluence background, due to scatter on the inside of the MRS shielding, is larger for the low-energy detectors than for the high-energy detectors (due to larger solid-angle variation).
a TT-neutron component, is folded with the MRS response function and adjusted until a best-fit to the measured spectrum is found. On the basis of the TT and DT reactivities, the magnitude of the TT component is fixed relative to the DT yield (the TT spectral shape is fixed in this analysis according to the work in Ref. 14.) (The validity of this approach is confirmed by the $Y_{DD}/Y_{DT}$ ratios measured on the five SymCaps studied, which are in agreement with the values expected based on reactivities.) The DT-fuel component used to give DT fuel $\rho R$ was calculated on the basis of $nD$, $D(2n)$,$^{15}$ nT,$^{16}$ and $T(2n)$ cross-sections, scaled for simulated emission profile effects, and the CH-ablator component used to give CH-ablator $\rho R$ was calculated using MCNPX for an implosion with 440 mg/cm$^2$ CH-ablator $\rho R$, $T_{ion} = 2.9$ keV, and SymCap-like geometry, to account for multi-scatter and profile effects. From the spectrum shown in Fig. 2(a), a DT-fuel $\rho R$ of $140 \pm 24$mg/cm$^2$ and a CH-ablator $\rho R$ of $399 \pm 77$mg/cm$^2$ were determined. The best fit is describing the spectrum well ($\chi^2_{red} = 1.1$).

CH-ablator and DT-fuel $\rho R$ values determined from the MRS spectrum for the five shots studied are shown in Fig. 3. To confirm the validity of the background correction, fits to the full MRS spectrum were compared to fits constrained to either the low ($E_d = 3.5–7$ MeV) or high ($E_d = 7–11$ MeV) energy part of the spectrum. As can be seen from Fig. 2, there are limited features to distinguish the two components in these narrower parts of the spectrum (in particular in the range $E_d = 3.5–7$ MeV). This is why the error bars from the fits to the narrow part of the spectrum are larger than the error associated with the fit to the total spectrum. These results were also compared to fits to synthetic data (full spectrum fits as well as fits limited to the $E_d = 7–11$ MeV and $E_d = 3.5–7$ MeV ranges). Synthetic data were generated by folding a model neutron spectrum such as in Fig. 2(b), with seeded $Y_{DT} = 8 \times 10^{14}$, $T_{ion} = 2.7$ keV, $\rho R_{DT} = 115$ mg/cm$^2$ (average MRS result from the five shots), and $\rho R_{CH} = 440$ mg/cm$^2$ (average GRH result from the five shots), through the MRS response function, and then imposing a random Poisson fluctuation around the value in each bin. The results from the fits to the different parts of the spectrum correspond well to the spread in values inferred from fits to the synthetic data. Given the uncertainties involved, the fits from the three parts of the spectrum are in good agreement. The shot-by-shot comparison of MRS and GRH-inferred CH-ablator $\rho R$’s for these shots is shown in Fig. 4. Within error bars, the overall agreement is good, cross-validating results from both diagnostics. The MRS-inferred fuel $\rho R$’s are also in good agreement with expectations based on simulations.

IV. CONCLUSIONS

We report on MRS measurements of CH-ablator and DT-fuel $\rho R$ from DT gas-filled SymCap implosions at the NIF. DT fuel and CH ablator $\rho R$’s in the range of $80–140$ mg/cm$^2$ and $400–680$ mg/cm$^2$ are obtained, respectively. The
analysis is facilitated by an improved background determination in the low-energy part of the MRS spectrum ($E_n < 10$ MeV). To confirm the validity of the background correction, results from fits to the $E_d = 3.5$–$7$ MeV and the $E_d = 7$–$11$ MeV spectral ranges are compared to results from fits to the full spectrum. The good agreement between the CH-ablator $\rho R$ values derived from MRS spectra and those based on GRH measurements as well as the equally good agreement between the MRS-derived DT-fuel $\rho R$ values and those based on calculations establishes the fidelity of the MRS (and GRH) results. This work demonstrates the accurate utilization of the complete MRS-measured neutron spectrum for diagnosing both SymCap and layered implosions at the NIF.

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