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

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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.

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.$^{1,2,3,4,5}$ This energy range covers the essential details in the spectrum. The primary neutron yield ($Y_{\text{pr}}$) 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 $10^{10}$. 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 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 (SymCap) 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 4.8×6.8 cm$^2$ CR-39 track detectors to record the spectrum of the momentum-separated deuterons (Fig. 1a), 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 guinite. 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 presence of high levels of neutron and intrinsic background in the CR-39 data is analyzed using the Coincidence-Counting Technique (CCT).$^9$ With this method, the CR-39 is etched and scanned in stages, and only tracks that appear in the same location (within a search-radius of order 50 µm) in two layers of the plastic separated by 50-200 µm are accepted as signal. Intrinsic background is completely eliminated for layer separation of 100 µm or more,$^9$ this is the case for all NIF MRS detectors except #1 (50 µm) and #2 (75 µm). For these detectors, ~60 (total) randomly distributed intrinsic coincidences are expected to remain after CCT. CCT also significantly reduces the neutron-induced background. The level of reduction depends on energy and angle of incidence of

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the background neutrons as well as on layer separation. Two
orders of magnitude reduction has been previously observed.\(^7\) In
addition, the number of background neutrons picked up by CCT
scales linearly with yield. In contrast, signal neutrons are
retained in the analysis as they traverse the CR-39 in straight
trajectories practically perpendicular to the two layers.

Each piece of CR-39 is divided into a signal region
reachable by the signal deuterons and a background region where
no signal is expected (the different regions for CR-39 detector #2
are shown in Fig. 1(a)). After having applied the CCT to the data,
the remaining average number of coincidences per cm\(^2\) in the
background region is characterized and used to correct for the
background across the signal region. Using this type of
correction, however, does not eliminate all background as the
background does vary across the piece of CR-39. To allow for
accurate correction for neutron-induced background, the
background was experimentally established on a NULL shot
(N130628, \(Y_{DT}=1.6\times10^{15}\)) where MRS was fielded without a
conversion foil. The background correction as determined on
N130628 is now routinely applied to the MRS spectrum. From
the measurement, it was found 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.

![Schematic drawing of the NIF MRS (not to scale), showing the Cd3 conversion foil, magnet and nine CR-39 detectors. A zoom-in on detector #2 defines the x (dispersion direction) and y (non-dispersion direction) coordinate system. The central shaded area is the signal region, and the outer blue area is the background region.](image)

To understand this observation, a detailed MCNPX\(^{10}\)-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 ~13% (see Fig. 1(c)),
for neutrons with energy above 2.4 MeV, the variation is ~21% and
for neutrons with energy above 10 MeV, the variation is
~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 ~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 ~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).

### 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\(^{11,12}\).

Members of this group used a single null shot (N130628) to
emulate the DT ice in a cryogenically-layered
implosion. Due to the significantly higher CH \(pR\) than the DT
fuel \(pR\) 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 \(pR\) contributions to the neutron spectrum.
Because of lower convergence, these implosions are also
expected to be less affected by low-mode \(pR\) asymmetries than
cryogenically-layered DT implosions. In this analysis, we neglect
any potential low-mode \(pR\) 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).

![Reduced MRS spectrum for shot N130625 (black points).](image)

![Modeled neutron spectrum that provides the best fit to the measured spectrum.](image)

Fig. 2(a) shows the reduced MRS spectrum for shot N130625 (~10\(^{15}\)). A modeled neutron spectrum (Fig.\(\text{Draft}\).
2(b), with a primary-neutron (Gaussian\textsuperscript{15}) component, CH- and DT downscattered neutron components and 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 reactivity, 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 \textit{YoniYor} 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 pR was calculated on the basis of \textit{n,DT} \textit{D(n,2n)}\textsuperscript{15}, \textit{n,T}\textsuperscript{16} and \textit{T(n,2n)} cross-sections, scaled for simulated emission profile effects\textsuperscript{17}, and the CH-ablator component used to give CH-ablator pR was calculated using MCNPX for an implosion with 440 mg/cm\textsuperscript{2} CH-ablator pR, \textit{T}(\textit{n,2n})=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 pR of 140±24 mg/cm\textsuperscript{2} and a CH-ablator pR of 399±77 mg/cm\textsuperscript{2} were determined. The best fit is describing the spectrum well ($\chi^2_{\text{red}}=1.1$).

![FIG. 3. (Color online) (a,c,e) CH-ablator pR and (b,d,f) DT-fuel pR determined from MRS spectra obtained on five DT gas-filled SymCap implosions. Values are determined from fits to the full spectrum (black points; a-b), to the \textit{E}=7-11 MeV range (blue crosses; c-d) and to the \textit{E}=3.5-7 MeV range (red circles; e-f). Also shown are histograms of CH-ablator and DT-fuel pR's determined from 1000 fits to synthetic MRS data with seeded pR\textsubscript{TR}=115 mg/cm\textsuperscript{2} and pR\textsubscript{C}=440 mg/cm\textsuperscript{2}. The black histograms (a-b) were determined from fits to the full spectrum, the dashed blue histograms (c-d) from the \textit{E}=7-11 MeV range, and the dashed red histograms (e-f) from the \textit{E}=3.5-7 MeV range.](image)

CH-ablator and DT-fuel pR 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 (\textit{E}=3.5-7 MeV) or high (\textit{E}=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 \textit{E}=3.5-7 MeV). This is the reason 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 with seeded pR\textsubscript{TR}=115 mg/cm\textsuperscript{2} and pR\textsubscript{C}=440 mg/cm\textsuperscript{2} (full spectrum fits as well as fits limited to the \textit{E}=7-11 MeV and \textit{E}=3.5-7 MeV ranges). 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 pR'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 pR’s are also in good agreement with expectations based on simulations.

![FIG. 4. (Color online). Comparison of CH-ablator pR inferred from the GRH and MRS analysis.](image)

IV. CONCLUSIONS

We report on MRS measurements of CH-ablator and DT-fuel pR from DT gas-filled SymCap implosions at the NIF. DT fuel and CH ablator pR’s in the range of 80-140 mg/cm\textsuperscript{2} and 400-680 mg/cm\textsuperscript{2} are obtained, respectively. The analysis is facilitated by an improved background determination in the low-energy part of the MRS spectrum (\textit{E}<10 MeV). To confirm the validity of the background correction, results from fits to the \textit{E}=3.5-7 MeV and to \textit{E}=7-11 MeV spectral ranges are compared to results from fits to the full spectrum. The good agreement between the CH-ablator pR values derived from MRS spectra and those based on GRH measurements as well as the equally good agreement between the MRS-derived DT-fuel pR 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.

V. ACKNOWLEDGEMENTS

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