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High-resolution measurements of the DT neutron spectrum using new CD foils in the Magnetic Recoil neutron Spectrometer (MRS) on the National Ignition Facility

M. Gatu Johnson,[1,a)] J. A. Frenje,[1] R. M. Bionta,[2] D. T. Casey,[2] M. J. Eckart,[2] M. P. Farrell,[3] G. P. Grim,[2] E. P. Hartouni,[2] R. Hatarik,[2] M. Hoppe,[3] J. D. Kilkenny,[3] C. K. Li,[1] R. D. Petrasso,[1] H. G. Reynolds,[3] D. B. Sayre,[2] M. E. Schoff,[3] F. H. Séguin,[1] K. Skulina,[2] and C. B. Yeamans[2]
[1]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[3]*General Atomics, San Diego, California 92186, USA*

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The Magnetic Recoil neutron Spectrometer (MRS) on the National Ignition Facility measures the DT neutron spectrum from cryogenically layered inertial confinement fusion implosions. Yield, areal density, apparent ion temperature, and directional fluid flow are inferred from the MRS data. This paper describes recent advances in MRS measurements of the primary peak using new, thinner, reduced-area deuterated plastic (CD) conversion foils. The new foils allow operation of MRS at yields 2 orders of magnitude higher than previously possible, at a resolution down to ~200 keV FWHM. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4959946]

I. INTRODUCTION

Neutron spectrometers on the National Ignition Facility[1] (NIF) are fielded in five locations distributed around the target chamber to diagnose fuel assembly, stagnation, and thermonuclear burn in cryogenically layered DT Inertial Confinement Fusion (ICF) implosions.[2] From the measured neutron spectra, the key implosion parameters of yield (Y_{DT}), apparent ion temperature (T_{ion}), and areal density (ρR) are inferred.[3] The ρR is inferred from the measured down-scatter ratio (*dsr*), i.e., the ratio of neutrons in the energy ranges 10-12 MeV and 13-15 MeV. Directional velocity of the burning fuel is determined from the mean energy of the primary DT neutron peak.[4] Comparing results between different lines-of-sight (LOS) provides information about implosion symmetry,[5] believed to be one of the primary remaining challenges on the road to achieving thermonuclear ignition in the laboratory. Recently, understanding manifestations in the shape of the primary DT neutron spectrum of burn dynamics and flows in the implosions has emerged as an important path toward a clearer picture of the assembled fuel at peak compression.[6] This path imposes stringent requirements on the precision of primary DT-neutron peak measurements, which requires high-resolution spectrometers. At the same time, yields for the best-performing NIF implosions have recently climbed to nearly 10^{16},[7] with the expectation of further increases by more than an order of magnitude as implosion performance improves further; this additionally imposes the requirement on the spectrometers of being capable of operating at high yields.

One of the NIF neutron spectrometers, the Magnetic Recoil neutron Spectrometer (MRS),[8–12] uniquely measures the neutron spectrum from NIF DT implosions using the recoil technique combined with a magnet. In the MRS, a fraction of the neutrons generated in a NIF experiment scatter elastically in a deuterated plastic conversion foil 26 cm from target chamber center (TCC). Forward-scattered recoil deuterons are selected by an aperture in front of a permanent Nd–Fe–B magnet behind the target chamber wall. These recoil deuterons are momentum separated and focused by a magnet and detected by an array of CR-39 nuclear track detectors positioned at the focal plane of the spectrometer. Depending on the energy of the recoil deuterons, they are detected at different locations along the focal plane covering a deuteron energy range of ~3 to 18 MeV. The neutron energy spectrum in the range of 4-20 MeV is inferred from the measured recoil deuteron energy spectrum. While the overall geometry of the MRS is fixed, efficiency and resolution of the system can be controlled by the choice of conversion foil.

The original foils developed for the NIF MRS were manufactured by GA using a hot-press method.[13] These foils, ranging in thickness from 50 to 260 μm, cannot be made thinner than ~50 μm due to limitations in the fabrication technique. An upper limit for allowable yield in the MRS system with a given foil is set by the requirement that deuteron tracks on the CR-39 do not overlap,[14] in which case the tracks cannot be accurately counted. To allow operation of MRS at high yields, thinner foils manufactured using a glow-discharge-polymer (GDP) coating method were developed by GA.[15] The two types of foils are compared in Fig. 1. While the hot-press foils are stand-alone, the GDP-coated foils are deposited onto a Ta

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[a)]Author to whom correspondence should be addressed. Electronic mail: gatu@psfc.mit.edu.

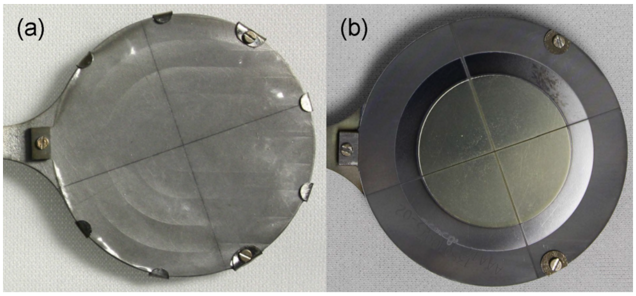

FIG. 1. Comparison of (a) a 58 μm thick, 13 cm^2 hot-press-made MRS foil and (b) a 35 μm thick, 4 cm^2 glow-discharge-polymer (GDP) coated MRS foil. The hot-press foil is a stand-alone plastic, while the GDP-coated foil is deposited on a 13 cm^2, 250 μm thick Ta backer. Both foils are mounted on the same type of Ta-W alloy foil holder for fielding 26 cm from TCC. Note that the thin hot-press coated foil shown in (a) requires clamping tabs around the foil to prevent the plastic from curling when exposed on a NIF shot.

plate and can be made as small and thin as desired. Three size/thickness combinations were selected to optimally cover a wide range of yields. Performance parameters for standard hot-press and GDP-coated foils are summarized in Table I. The allowable upper yield limit depends not only on total signal count but also on etch conditions for the CR-39 detectors; if the material is etched longer, the tracks become larger, leading to overlap at lower absolute signal levels. MRS CR-39 data are routinely etched for 6 h at 80 °C in 6-normal NaOH. These etch conditions are assumed when determining the optimal yield range quoted in Table I. Longer etch time allows for improved signal-to-background separation. The shortest etch time demonstrated to work for MRS data is 2 h at the same etch conditions; this etch time was assumed when deriving the upper yield limits quoted in Table I. In addition to allowing operation at higher yields, the GDP-coated foils also provide substantially improved resolution. The resolution of MRS is set by a combination of three factors: deuteron ranging in the foil, geometry of the system, and ion-optical broadening from transport through the magnet.[10] While some improvement in resolution between the hot-press and GDP-coated foils is due to the reduced foil thickness, improved ion-optical properties due to smaller foil area contribute as well.

II. PERFORMANCE OF NEW FOILS

In Fig. 2, MRS data measured with the thinnest hot-press foil are compared with data measured with the thick-

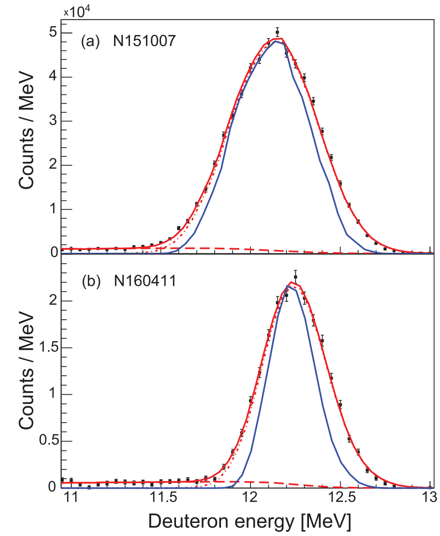

FIG. 2. (a) MRS data for NIF shot N151007 with MRS operated using a 58.5 μm, 13 cm^2 hot-press foil, contrasted to (b) MRS data from shot N160411 with MRS operated using a 36.8 μm, 4 cm^2 GDP-coated foil. The yields for these two cryogenically layered DT implosions were 1.6×10^{15} (N151007) and 3.5×10^{15} (N160411). Also shown are best fits to the data (solid red curves) using primary (dashed-dotted red curves) and downscatter (dashed red curves) components, and the MRS response for mono-energetic 14 MeV neutrons for the two cases (solid blue curves). $T_{ion} = 3.9\pm0.7$ keV is inferred from the data in (a) and $T_{ion} = 3.7\pm0.2$ keV from the data in (b).

est GDP-coated foil for cryogenically layered DT implosions with comparable T_{ion}. The data are analyzed using a forward-fit technique with the same model neutron spectrum used in analysis of NIF nTOF neutron spectrometer data,[16] folded with the MRS instrument response function to convert it to the deuteron energy scale. The free fitting parameters are the mean peak energy, T_{ion}, Y_{DT} and a scattering amplitude; the best fits are shown in solid red in Fig. 2. Also shown in Fig. 2 is the simulated MRS response for mono-energetic 14 MeV neutrons for the two cases (solid blue). The systematic uncertainty in the T_{ion} measurement, σ_{Tion}, can be shown[17] to depend on the spectrometer resolution (ΔE_{MRS}) and its uncertainty ($\sigma_{\Delta EMRS}$):

$$\sigma_{T_{ion}} = 2\times\left(\frac{\sigma_{\Delta E_{MRS}}}{\Delta E_{MRS}}\right)\frac{1}{177^2}\Delta E_{MRS}^2. \quad (1)$$

Parameters impacting ΔE_{MRS} and the resulting σ_{Tion} are summarized in Table II for the two foils used to record the data in Fig. 2. Given the quadratic dependence on resolution, the systematic uncertainty in the MRS T_{ion} measurement is much

TABLE I. MRS performance properties for foils manufactured using the hot-press and GDP-coating methods.

Foil type	Foil thickness (μm)	Foil area (cm^2)	Resolution at $E_n = 14$ MeV FWHM (keV)	Efficiency at $E_n = 14$ MeV	S/B in peak	S/B per % dsr at the upper yield limit[a]	Optimal yield range	Upper yield limit[b]
GDP	10	1.0	170	2.04×10^{-13}	2	0.005	$Y_{DT} > 6\times10^{16}$	1×10^{18}
GDP	23	2.2	256	1.08×10^{-12}	11	0.05	$1\times10^{16}-6\times10^{16}$	2×10^{17}
GDP	35	4.0	340	3.05×10^{-12}	27	0.28	$3\times10^{15}-1\times10^{16}$	9×10^{16}
Hot press	58	13	550	1.81×10^{-11}	45	2.4	$8\times10^{14}-3\times10^{15}$	2×10^{16}
Hot press	135	13	1090	4.39×10^{-11}	180	31	$2\times10^{14}-8\times10^{14}$	1×10^{16}
Hot press	260	13	2140	8.40×10^{-11}	218	70	$Y_{DT} < 2\times10^{14}$	1×10^{16}

[a]Depending on yield, standard counting or coincidence counting analysis may give a better S/B value;[11] the best value is quoted in each case.
[b]The upper allowable yield limit depends on CR-39 etch conditions (see text for details).

TABLE II. Parameters impacting the MRS spectral resolution ΔE_{MRS} and its uncertainty $\sigma_{\Delta EMRS}$, and the resulting inferred systematic uncertainty in the T_{ion} measurement (σ_{Tion}). Where two values are given, the value in italics is for the 36.8 μm, GDP-coated foil, while the value in regular print is for the 58.5 μm, hot-press foil. With ΔE_{MRS} and $\sigma_{\Delta EMRS}$ known, σ_{Tion} is calculated using (Eq. (1)).

MRS parameter	Nominal value	Parameter uncertainty	Impact on $\sigma_{\Delta EMRS}$ (%)
Foil dist. to TCC (cm)	26	±0.3	±*0.05*/0.14
Foil radius (cm)	*1.15*/2.02	±*0.01*/0.024	±*0.04*/0.15
Foil thickness (μm)	*36.8*/58.5	±*0.3*/2.0	±*0.81*/3.3
Aperture area (cm^2)	20	±0.2	±*0.02*/0.03
Magnet dist. (cm)	596	±0.2	±0.00
d-density (10^{22} cm^{-3})	*6.2*/7.7	±0.1	±*1.63*/1.17
Foil offset (cm)	0	±0.1	±*0.68*/0.54
$\sigma_{\Delta EMRS}/\Delta E_{MRS}$ (%)		*1.94*/3.53	
ΔE_{MRS} (keV)		*338*/549	
σ_{Tion} (keV)		*0.142*/0.679	

reduced for the new, GDP-coated foils. Note that because the GDP-coated foils are transparent, their thickness can be absolutely characterized using interferometry to an accuracy of ±0.3 μm, while the thickness of the hot-press foils can only be measured to an accuracy of ±2 μm.

In Fig. 3, the MRS-inferred T_{ion} is compared to T_{ion} measured by the other NIF spectrometers[16,18] for cryogenically layered DT implosions where the GDP-coated foils were used. As shown by the data, the MRS results compare well to the other measurements. (Note that some variation in inferred apparent T_{ion} between LOS can be expected due to asymmetric flows in the implosions.[19])

Absolute neutron yields are measured with MRS[20] and with Neutron Activation Detectors (NAD).[21] The MRS and NAD-measured yields for all DT shots to date with the MRS fielded with a GDP-coated foil are contrasted in Fig. 4. The first GDP-coated foil was fielded on a total of 11 shots, and a reduced inferred MRS yield is observed relative to NAD yield as a function of time (~1% reduction per shot). Re-characterization of the foil at GA post-exposure has confirmed that this apparent drop in yield is due to material loss from the GDP-coated foil. This material loss is an unwanted and unexpected characteristic of the new foils. The cause is not yet clear; ablation due to scattered laser light or due to x-ray heating of the Ta foil holder are both possible causes. No similar effect has been observed for the hot-press foils, which are not in complete thermal contact with the Ta foil holder. The two materials are also chemically different; the C:D isotope composition is ~1:1.4 for the GDP-coated foils, and 1:2 for the hot-press foils. Foil material loss will also impact T_{ion} measurements. For the foil used to make the measurements in Fig. 4(a), Geant4 simulations show that a ~12% total material loss not corrected for in the analysis would lead to ~0.4 keV reduction in inferred T_{ion}. Note, however, that material loss will not impact the MRS *dsr* measurements, since a reduced deuterium content in the foil will impact the yield in the 10-12 MeV and 13-15 MeV ranges equally.

In a first attempt to solve the material loss problem, one GDP-coated foil was covered with a flash coating of Cr before exposure (Fig. 4(c)). Unfortunately the Cr was found to impose additional stress on the material, causing the CD coating to delaminate from the Ta backer. Each GDP-coated foil has since been fielded on a limited number of shots to minimize material

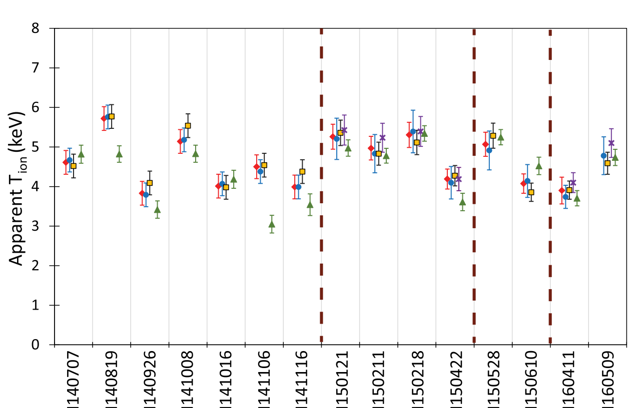

FIG. 3. MRS-inferred apparent T_{ion} (green triangles) compared to T_{ion} inferred from Spec-A (red diamonds), Spec-E (blue circles), Spec-SP (yellow squares), and NITOF (purple crosses) for cryogenically layered DT implosions on which a GDP-coated foil was used in the MRS. Four different GDP-coated foils have been used to date, separated by the vertical dashed lines in the figure.

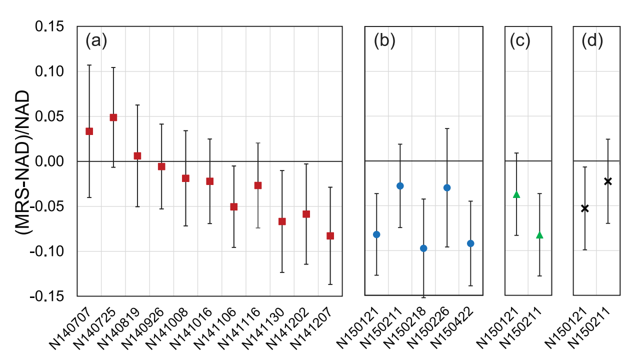

FIG. 4. MRS-inferred absolute neutron yield compared to the yield inferred using a suite of neutron activation (NAD) detectors for NIF DT implosions with MRS fielded using a GDP-coated foil. Four different 4 cm^2 GDP-coated foils, (a) 44.9 μm, (b) 35.6 μm, (c) 37.0 μm with a flash coating of Cr, and (d) 36.8 μm, have been fielded in the MRS system to date. For the first foil which was fielded on a total of 11 shots, a reduction in the MRS-inferred yield relative to NAD is seen over time (a), which has been attributed to material loss from the GDP-coated foil after repeated exposure to shots in the NIF target chamber.

loss impact on data. We plan as a next step to try fielding hot-press foils covered with a Ta mask to reduce effective foil area. In parallel, we will also continue to investigate what is causing the material loss, and attempt to come up with a mitigation technique which will allow continued fielding of the higher-precision GDP-coated foils in the MRS system.

III. CONCLUSIONS

The MRS on the NIF has been upgraded with smaller, thinner deuterated conversion foils manufactured by GA using the GDP-coating method. The foils allow operation of MRS at yields 2 orders of magnitude higher than previously possible. In addition, the new foils provide up to 3 times better resolution and are better characterized, leading to a substantial reduction in the systematic uncertainty in primary DT neutron peak measurements. MRS-inferred Y_{DT} and T_{ion} using the new foils compare well with measurements using other NIF neutron detectors.

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