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ABSTRACT

Millimeter-sized CD foils fielded close (order mm) to inertial confinement fusion (ICF) implosions have been proposed as a game-changer for improving energy resolution and allowing time-resolution in neutron spectrum measurements using the magnetic recoil technique. This paper presents results from initial experiments testing this concept for direct drive ICF at the OMEGA Laser Facility. While the foils are shown to produce reasonable signals, inferred spectral broadening is seen to be high (~5 keV) and signal levels are low (by ~20%) compared to expectation. Before this type of foil is used for precision experiments, the foil mount must be improved, oxygen uptake in the foils must be better characterized, and impact of uncontrolled foil motion prior to detection must be investigated.

I. INTRODUCTION

Reactions between deuterium (D) and tritium (T) fuel ions produce neutrons of nominally 14-MeV energy. High-precision measurements of the primary DT neutron energy spectrum peak have emerged as crucial in determining (and subsequently mitigating) asymmetries in both direct[1] and indirect[2,3] drive inertial confinement fusion (ICF) implosions. The broadening (second moment) of the DT peak is used to infer an apparent ion temperature (T_{ion}) of the reacting fuel ($\Delta E \sim 177\sqrt{T_{\mathrm{ion}}}$),[4] including contributions from thermal plasma temperature and broadening due to non-thermal motion of the reacting ions;[5,6] comparison of high-precision measurements of this quantity in different directions around an ICF implosion provides an important asymmetry measurement.[7–10] Shifts in the mean energy of the DT peak (first moment) provide a measurement of collective fuel flow in the line-of-sight (LOS) of the observing instrument;[11] combining such measurements in several LOSs, a net flow vector can be inferred.[12,13] Theoretical efforts[14] and simulations[15] suggest that further information about implosion dynamics could also be obtained from higher moments of the spectrum peak, including skew and kurtosis, hitherto unavailable experimentally due to insufficient measurement resolution. All current ICF neutron spectrometers provide a single, time-integrated measurement of the neutron spectrum from each implosion;

an important proposed development is time-resolved measurements, which would allow these parameters to also be tracked as they evolve.[16]

One important technique for measuring the DT neutron spectrum is magnetic recoil spectrometry (MRS).[17] This concept, implemented in the existing time-integrating MRS instruments[18] at the OMEGA[19] and NIF[20] laser facilities, uses a cm-scale deuterated polyethylene (CD) conversion foil 10 cm/26 cm from the implosion at OMEGA/NIF to convert neutrons to deuterons, a fraction of which are then momentum-separated in a magnet to end up in a different physical location on a detector, allowing reconstruction of a recoil deuteron energy spectrum from which the neutron spectrum can be inferred [Fig. 1(a)]. A proposed extension of this technique is to use smaller CD conversion foils (mm-scale) much closer to the implosion (5 mm), which would improve the energy resolution, allowing for dramatically reduced uncertainties in DT peak measurements and, with improved detector technology, time-resolved measurements of the ICF neutron energy spectrum.[16,21,22] This works because the resolution of this type of detector system is a combination of broadening due to elastic scattering kinematics, deuteron ranging in the foil, and the ion-optical properties of the magnet, with total broadening $\Delta E_{\mathrm{MRS}} \approx \sqrt{(\Delta E_{\mathrm{kin}}{}^2 + \Delta E_{\mathrm{foil}}{}^2 + \Delta E_{\mathrm{mag}}{}^2)}$; reductions in ΔE_{kin} (smaller foil opening angle) and ΔE_{foil} (thinner foil) will be accompanied by lower detection efficiency, but ΔE_{mag} can be significantly reduced at maintained efficiency by fielding a smaller foil closer, maintaining the foil solid angle (ΔE_{mag} is close to linearly proportional to the foil radius).[22]

The smaller foil technique was previously tested for indirect drive ICF at the NIF.[21] Capability of using such a foil for direct drive at OMEGA would allow reduction in T_{ion} uncertainty by at least a factor of 4.[22] In this paper, results from initial tests of this foil concept in direct drive OMEGA implosions are presented. While a recoil deuteron spectrum is measured and shown to be in reasonable agreement with expectation, the results demonstrate that significant work would be required to reduce uncertainties in the system to the point of the predicted theoretical gains.

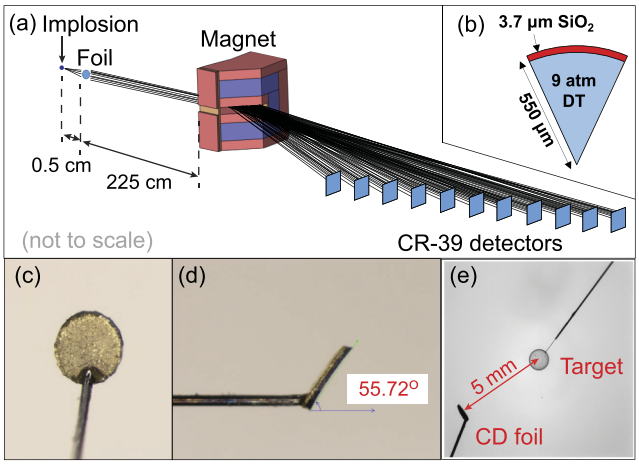

FIG. 1. (a) Schematic of the OMEGA MRS magnet and detector used to measure the recoil deuterons from 1-mm CD foils fielded 5 mm from the implosion. (b) Cartoon depiction of a typical thin glass-shell target used for these experiments. (c) Front view and (d) side view of a mounted GDP-coated foil, held at a precise angle with a SiC stalk. (e) Target viewing system image from OMEGA shot 91 955, showing the foil and ICF target aligned in the target chamber prior to the shot.

II. TESTING 1-MM CD FOILS WITH THE OMEGA MRS

Tests of the performance of 1-mm diameter CD foils fielded 5 mm from direct drive ICF implosions were done at the OMEGA laser, using the existing MRS to measure the recoil deuterons, on a series of shock-driven, thin-glass-shell target implosions. The diagnostic setup is illustrated in Fig. 1(a), with a typical ICF target shown in Fig. 1(b). The implosions produced on average 1.3×10^{14} DT neutrons with a T_{ion} of 11.5 keV. The three foils used were manufactured at General Atomics (GA) using a glow-discharge polymer (GDP) coating technique, with 40 μm of CD material coated onto a tantalum backer [Fig. 1(c); average backer thickness was 45 μm]. The average foil roughness was rather high at 1.6 μm rms, but this had been previously shown to not significantly impact results of indirect drive experiments at the NIF.[21] The foils were mounted on 140-μm diameter SiC stalks and held in place in the OMEGA target chamber using a target positioner at polar and azimuthal angles of 143° and 342°, respectively; the foils were carefully mounted at a pre-defined angle to ensure the surface normal was fielded parallel to the MRS LOS [Fig. 1(d)]. An advantage of fielding the foil so close to the target chamber center (TCC) is that it is visible in the target viewing system used for precision target positioning; this allows for very precise alignment of the foil [Fig. 1(e)].

Recoil deuteron spectra were measured using MRS on all three test shots. As an example, the spectrum measured on OMEGA shot 91 960 is shown in Fig. 2. An interesting feature of these data is that not only recoil deuterons from the CD foil are observed but also recoil deuterons from neutrons elastically scattering off of fuel D in the target [Fig. 2(a)]. Fuel D recoils are routinely measured using charged particle spectrometers to infer fuel areal density (ρR).[23] This 4π measurement gives a characteristic spectrum with a high-energy peak at 12.5 MeV followed by a dip and then rise toward lower energies (due to the shape of the n, d elastic scattering differential cross section); the signature seen in the MRS data in Fig. 2(a) is consistent with such a spectrum ranged through the 46-μm Ta backer and the 40-μm CD foil used on this shot (the peak energy is inferred to be 9.9 MeV, compared to 10.1 MeV expected for nominally 12.5 MeV deuterons ranging through the Ta/CD assembly). A fuel ρR of 2.5 ± 0.5 mg/cm^2 (uniform model) is inferred from the fuel D data in Fig. 2(a) using the method described in Ref. 23. Note that the interference of such a signal in DT neutron peak measurement in future experiments could be easily avoided by using a thicker Ta foil backer.

The primary data from these experiments are of course the recoil deuterons from the CD foil, indicated with a blue dashed box in Fig. 2(a) and shown enlarged in Fig. 2(b). The data are well described by the Geant4-simulated[24] MRS response function for this setup configuration [red curve in Fig. 2(b)]. From fits like this for each shot, an apparent T_{ion} and a DT neutron yield are inferred. The resulting numbers are shown compared to measurements using

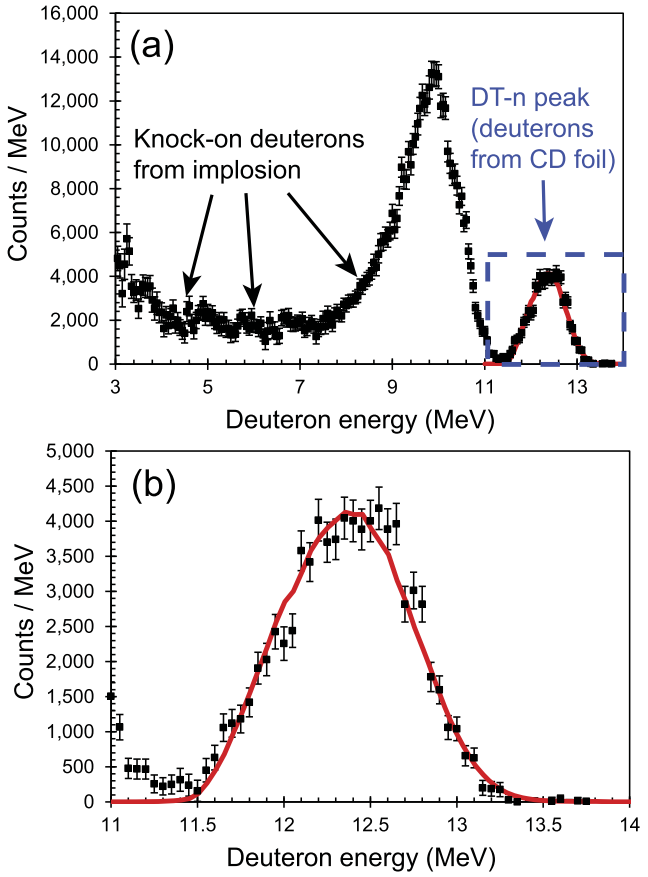

FIG. 2. Recoil deuteron spectrum measured using MRS on shot 91 960. (a) Full spectrum, including knock-on deuterons from DT neutrons elastically scattering on deuterons in the implosion fuel ranged through the foil assembly, and the DT neutron peak detected through recoil deuterons from the CD foil (blue dashed box). (b) Zoomed-in image showing only the blue-box region from (a), with the best fit to the data using the Geant4-simulated MRS instrument response function (red solid curve).

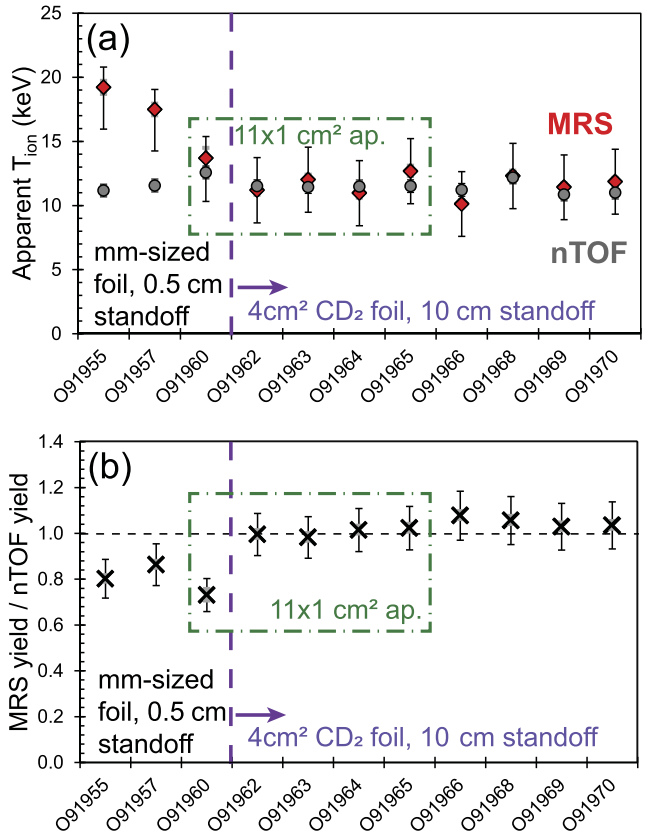

FIG. 3. Comparison of MRS-measured and nTOF-measured (a) apparent T_{ion} and (b) DT neutron yield. Total error bars are shown in black and statistical only in bold gray. The three left-most points in both panels represent implosions where the OMEGA MRS was fielded with a 1-mm diameter GDP foil 5 mm from TCC; on remaining shots, MRS was fielded in the standard configuration described in Ref. 22. MRS was run with an 11 × 1 cm^2 magnet aperture on shots within the green, broken line boxes and with an 11 × 2 cm^2 aperture on all other shots.

the nTOF neutron spectrometer 12mnTOFN[25] and also to MRS data using a standard, 4 cm^2, hot-press made, 57-μm thick CD_2 foil 10 cm from TCC[22] in Fig. 3.

The first important thing to note from Fig. 3 is the remarkable agreement within uncertainty between MRS and nTOF when MRS is fielded in the standard configuration. This confirms an overall good understanding of the MRS setup and expected agreement between MRS and nTOF measurements on this series of shots. Looking at the three implosions with MRS fielded with the 1-mm, GDP-coated CD foils, MRS measures a T_{ion} that is on average 5 keV higher than the nTOF value and a yield that is on average 20% lower, consistent with underestimated instrument broadening and overestimated efficiency of this configuration. Because of the good agreement between the two detectors seen with MRS fielded in the standard configuration, it can be concluded that these observed differences arise as a result of the new foils.

III. UNCERTAINTY CALCULATION AND REQUIRED IMPROVEMENTS

The MRS error bars plotted in Fig. 3 consider all known factors impacting yield and T_{ion} uncertainties. Uncertainties for the standard, 4 cm^2 foil configuration are described in detail in Ref. 22. Table I details the estimated systematic yield uncertainty, and Table II details the systematic T_{ion} uncertainty for the 1-mm foil configuration. For the three implosions testing 1-mm CD foils, 12 200, 13 500, and 4000 foil-born recoil deuterons were detected, respectively; at these signal levels, statistical uncertainties are also not negligible, with statistical T_{ion} uncertainties of 0.5 keV–0.8 keV and statistical yield uncertainties of 1%–3% (considered in Fig. 3 error bars).

The total yield uncertainty in Table I is calculated as described in Ref. 26. Two different MRS magnet apertures were tested on these experiments, 11 × 2 cm^2 and 11 × 1 cm^2, respectively. Here, the smaller dimension is the non-dispersion direction, which means the

TABLE I. Parameters impacting the systematic MRS yield uncertainty σ_{YDT} when running the spectrometer with a mm-sized CD foil 5 mm from the implosion. Note that two different aperture sizes were used for this experiment, 11 × 2 cm^2 and 11 × 1 cm^2; where the two configurations lead to different numbers, the 11 × 1 cm^2 numbers are given in italics.

MRS parameter	Nominal value	Parameter uncertainty	%Unc
Foil dist. R_f (cm)	0.5	±0.01	±2.0
Foil area A_f (cm)	7.9×10^{-3}	$\pm 0.2 \times 10^{-3}$	±2.0
Foil thickness t_f (μm)	40	±1.0	±2.5
Foil D density n_d (cm^{-3})	6.5×10^{22}	$\pm 3.2 \times 10^{21}$	±5.0
Aperture area A_a (cm^2)	21.3/*10.7*	±0.2	±0.9/*1.8*
Magnet dist. R_a (cm)	225	±0.2	±0.1
n, d scatt cx (mb/sr)	501	±12	±2.4
Transmission T (frac)	0.83/*1*	±0.04/*0*	±5.0/*0.0*
Total			±9.1/*7.8*

TABLE II. Parameters impacting the MRS spectral resolution ΔE_{MRS} and its systematic uncertainty $\sigma_{\Delta EMRS}$, and the resulting inferred systematic uncertainty in the T_{ion} measurement (σ_{Tion}) calculated using Eq. (1), when running with a mm-sized CD foil 5 mm from the implosion. Note that the aperture size does not significantly impact resolution; hence, the numbers apply for both the 11 × 2 cm^2 and 11 × 1 cm^2 aperture configurations.

MRS parameter	Nominal value	Parameter uncertainty	$\sigma_{\Delta EMRS}/\Delta E_{MRS}$ (%)
Foil dist. (cm)	0.5	±0.01	±1.1
Foil radius (μm)	500	±5	±0.5
Foil thickness (μm)	40	±1.0	±1.8
Foil density (g/cm^3)	1.1	±0.055	±3.5
Aperture area (cm^2)	10.7	±0.2	±0.2
Magnet dist. (cm)	225	±0.2	±0.0
CR-39 alignment (μm)	n/a	±100	±0.5
Total $\sigma_{\Delta EMRS}/\Delta E_{MRS}$			±4.1
ΔE_{MRS} = 0.75 MeV → σ_{Tion} = ±1.5 keV			
Additional factors	$\sigma_{\Delta EMRS}/\Delta E_{MRS}$		σ_{Tion}
Glue impact	2.2%		0.8 keV
Oxygen uptake impact	2.5%		0.9 keV

aperture size impacts efficiency but not resolution in the measurement. When the larger 11 × 2 cm^2 aperture is fielded, part of the signal distribution falls outside the detector in the non-dispersion direction, which has to be considered in the analysis; this adds additional uncertainty in the yield calculation as reflected in the transmission entry in Table I. Studying Table I, it is clear that when transmission uncertainty is eliminated by fielding the smaller magnet aperture, the yield uncertainty is dominated by the foil D number density uncertainty. This number is quoted by GA to be ±5%, considering observed sample variations in stoichiometry and fresh density of GDP-coated CD. Reducing the uncertainty in the D content in future experiments would require precise monitoring of exposure conditions and experiments to carefully track how D composition in the sample changes with exposure conditions and time, combined with combustion analysis of witness samples. The ultimate limit on the accuracy of the D content at shot time is likely to be 1.5%–2% using these methods.

The systematic T_{ion} uncertainty depends on the total resolution ΔE_{MRS} in the measurement and the uncertainty in this resolution $\sigma_{\Delta EMRS}/\Delta E_{MRS}$ as

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

The estimated ΔE_{MRS} for the existing OMEGA MRS fielded with the 1-mm foil is 0.75 MeV. This could be dramatically improved by fielding the foil with a different detector,[22] meaning that the absolute T_{ion} uncertainty numbers derived here are not representative for what would be achievable with mm-size CD foils in an optimized setup. It is still interesting, however, to study what factors dominate the uncertainty and also to consider why the estimated uncertainty is not enough to bring the MRS data points in Fig. 3 into agreement with nTOF measurements. Table II detailing the systematic T_{ion} uncertainty is divided into two main sections. The top section represents errors that will impact both positive and negative error bars; the factors listed here will always impact uncertainty but can be reduced with improved characterization. Similar to the yield case, the foil density uncertainty is also found to be the dominant factor here. Better characterized foil density is clearly a lever to improving precision when using these foils.

The additional factors listed in the bottom section of Table II only serve to inflate T_{ion} as measured in the experiments described here and have consequently been added only to the negative error bars in Fig. 3(a).

Since these experiments were intended to test foil performance only, the mounting method was not optimized. As can be seen in Fig. 1(c), the glue spot holding the foil to the stalk covers ~9.6% of the foil area. Recoil deuterons born in this section of the foil will lose energy on their way through the glue before reaching the MRS detector, artificially broadening the peak. This effect is not considered in the response function fit in Fig. 2. However, the impact of this has been estimated through MCNP simulations[27] (Fig. 4), considering the MRS setup geometry but not magnet transport. From these simulations, the glue and stalk are estimated to inflate inferred T_{ion} by 0.8 keV for the present geometry. However, this number comes with a large uncertainty; neither the glue spot area nor the thickness is well characterized, and the glue is also proprietary and its element composition is not well known. The problem with the glue impact on the signal can be easily solved in future optimized experiments, e.g., by using a mounting tab or attaching the stalk to the back (TCC side) of the foil. It appears unlikely, however, that the full observed difference in MRS and nTOF-inferred T_{ion} as seen in Fig. 3 can be explained by glue spot impact.

In addition to the initial D number density and stoichiometry uncertainty, GDP-coated foils have also been found to be susceptible to oxygen uptake over time.[28,29] Current best-estimates suggest that oxygen uptake should plateau at a level of 6 at. % and that oxygen is additive, forming OH or OD bonds without replacing D. However, data on this are limited, mostly available for CH (which may not directly apply to CD), and there is also evidence

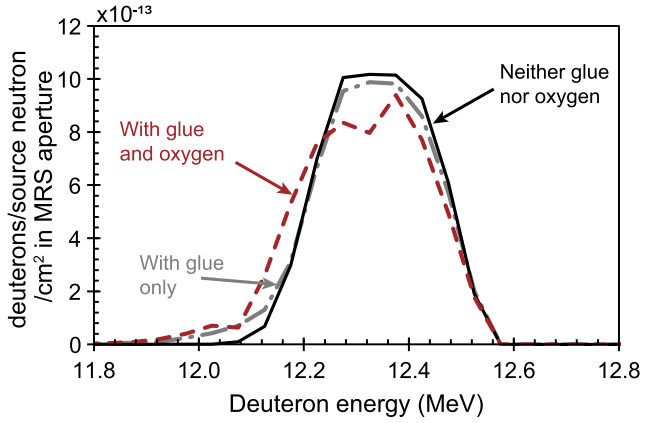

FIG. 4. MCNP-simulated recoil deuteron spectra from the mm-sized foil setup, considering the foil and MRS setup geometry up until and including the magnet aperture only (not including transport through the magnetic field), with the black solid line from a simulation considering neither glue nor oxygen uptake, the gray broken line including impact of the glue and stalk mount, and the red dashed line considering impact of the glue, stalk mount, and 6 at. % oxygen uptake in the foil material prior to the shot.

that there may be a gradient with material depth. An MCNP simulation of the impact of 6 at. % additive oxygen uptake (Fig. 4) suggests that this will inflate T_{ion} in our experiments by 0.9 keV. If the oxygen content is known, this can be considered in the analysis, but additional work to quantify this is essential before these foils are employed for precision neutron spectrum measurements. Note that D content tracking experiments and witness sample combustion analysis as outlined above will also answer the oxygen content question.

Similar to the glue effect, the oxygen uptake is also unlikely to fully explain the T_{ion} differences seen in Fig. 3. In addition, neither the glue nor the oxygen uptake is expected to impact the inferred yield. The MRS efficiency scales with the foil standoff distance r as r^{-2}. If the foil was further away than intended from the implosion when the neutrons reached it, this could explain the low inferred yield; to bring the yield down to 80% of expected, the foil would have to be at ~5.6 mm from TCC. The target viewing system images [Fig. 1(e)] clearly show that the foil was not that far removed before the implosion. While the UV laser beams do not hit the foil, unconverted laser light will; hence, a VisRad[30] simulation was done to address the question of any impact of foil material ablation due to unconverted light before neutron emission. The total unconverted light in the OMEGA target chamber is <0.5% of the UV energy, and the infrared/green unconverted light will focus 10.7 cm/6.1 cm downstream from TCC.[31] As a worst case scenario, if the full 0.5% unconverted light was infrared, this would lead to an intensity on the mm-sized foil of maximum 0.013 TW/cm^2. This laser intensity gives a total mass ablation[32] of 0.24 μg for a 1 ns laser pulse duration, which is <1% of the original foil mass; foil material ablation can thus not explain the yield discrepancy. Directional LOS flows of up to 100 km/s are commonly observed at OMEGA;[13] this could mean that the neutron-emitting fuel might have moved on the order of 100 μm, increasing the standoff distance and reducing efficiency. While this is a factor that should be considered when planning high-precision experiments with this setup, this would also not be sufficient to explain the results. However, the yield and T_{ion} differences observed in Fig. 3 could be self-consistently explained if the foil was on average 5.6 mm from the implosion and also tilted, increasing effective foil broadening ΔE_{foil} to inflate inferred T_{ion}. If a force from the implosion, e.g., due to x-ray emission (which would arrive prior to neutrons), was applied to the foil, it would be likely to impact the non-mounted end first, leading to a tilt. This process would also be expected to involve randomness, explaining the observed T_{ion}/yield match variations in Fig. 3 with some shots matching yield better (tilted, close foil) and some T_{ion} better (straight, further out foil). Such an effect appears likely to explain the observations, and the impact and mitigation of such uncontrolled foil motion must be investigated before using this configuration for high-precision measurements.

IV. SUMMARY AND CONCLUSIONS

In this paper, the concept of using mm-sized CD foils fielded 5 mm from the implosion for high-precision DT neutron spectrum measurements in direct drive ICF experiments has been tested. While there is a potential large payoff in the use of these foils, the results presented suggest that additional work is required to make them work for these measurements. First, the foil mounting technique would have to be improved; this would be straightforward. Second, the foils would have to be better characterized, specifically in terms of the D content and oxygen uptake. Finally, it is currently believed that the unexpectedly high T_{ion} and low yield observed in the 1-mm CD foil tests can be explained by foil motion; such uncontrolled foil motion will also have to be understood and mitigated.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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