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Measurements of collective fuel velocities in deuterium-tritium exploding pusher and cryogenically layered deuterium-tritium implosions on the NIF

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For the first time, quantitative measurements of collective fuel velocities in Inertial Confinement Fusion implosions at the National Ignition Facility are reported. Velocities along the line-of-sight (LOS) of the Magnetic Recoil neutron Spectrometer (MRS), positioned close to the equator (73°–324°), were inferred from the measured mean energy of the deuterium-tritium (DT)-primary neutron peak. Substantial mean energy shifts up to 113 ± 16 keV were observed in DT gas-filled exploding-pusher implosions, driven in a polar-direct drive configuration, which corresponds to bulk fuel velocities up to 210 ± 30 km/s. In contrast, only marginal bulk fuel velocities along the MRS LOS were observed in cryogenically layered DT implosions. Integrated analysis of data from a large number of cryogenically layered implosions has recently identified a deficit in achieved hot-spot energy of ~3 kJ for these implosions [C. Cerjan *et al.*, Phys. Plasmas (2013)]. One hypothesis that could explain this missing energy is a collective, directional fuel velocity of ~190 km/s. As only marginal bulk fuel velocities are observed in the MRS data, this might indicate that turbulent or radial flows would be a likely explanation for the missing energy. However, a directional velocity close to perpendicular to the MRS LOS cannot be ruled out. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4802810]

I. INTRODUCTION

The primary goal of cryogenically layered deuterium-tritium (DT) implosions at the National Ignition Facility[1] (NIF) is to compress the fuel to high enough densities and temperatures (or pressures) for ignition and energy gain to occur.[2] This requires effective conversion of the laser energy to fuel shell kinetic energy and to hot-spot thermal energy. If the implosion is set into collective, directional motion, the fuel shell kinetic energy corresponding to this motion is energy lost in the implosion process, resulting in less efficient conversion of kinetic energy to hot-spot thermal energy. Such collective motion could result from laser-drive asymmetries, caused by capsule offset from target chamber center (TCC) or issues with the hohlraum configuration (such as diagnostic holes and the plastic tent holding the capsule at the center of the hohlraum). Recent experiments at the NIF indicate the presence of systematic low-mode areal-density (ρR) asymmetries,[3–5] most likely caused by drive asymmetry. Integrated analysis of x-ray and neutron data from a large number of cryogenically layered DT implosions on the NIF has also identified a deficit in achieved hot-spot internal energy of ~3 kJ,[6] possibly connected to these drive asymmetries. The reason for this energy deficit is not clear at this point, but if the missing hot spot energy instead took the form of kinetic energy manifested as collective fuel motion along the hohlraum axis (P1 motion), a collective, directional velocity of ~190 km/s is expected for these implosions.

The collective motion of the fuel can be probed by measuring the energy shift of the spectral mean relative to the nominal mean energy of a reaction product.[7,8] Neutrons from the D + T reaction are ideal for this type of measurement because they escape the plasma without losing or gaining energy due to shell ρR[9] or electric fields,[10] respectively. Neutron spectrum measurements of the collective fuel motion in tokamaks have been reported,[11–13] but in the context of Inertial Confinement Fusion (ICF), this is the first reported measurement using the Magnetic Recoil Spectrometer (MRS).[14–17] Results for a large number of indirect drive cryogenically layered DT implosions, and for six polar direct drive, DT exploding pusher implosions are presented.

Fig. 1 shows the laser drive geometry for cryogenically layered (a), and polar direct drive exploding pusher (b) implosions. The laser beams are configured in a polar geometry optimized for indirect drive (through x-ray generation in a hohlraum). To utilize direct drive in this configuration requires polar direct drive with repointed beams for optimal illumination uniformity. This setup makes the symmetry of exploding pusher implosions highly sensitive to drive non-uniformities.[18]

MRS measurements have the advantage of being sensitive to small energy shifts associated with collective fuel

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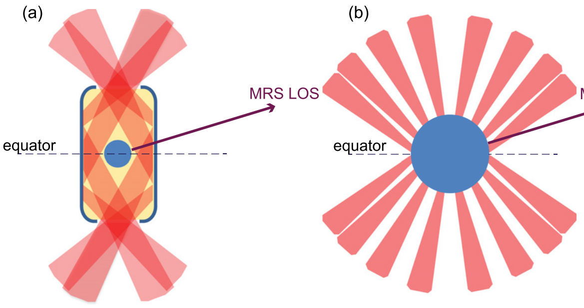

FIG. 1. Laser drive geometry for (a) indirectly driven cryogenically layered DT implosions and (b) polar direct drive exploding pusher implosions on the NIF. A total of 192 beams are available to illuminate the capsule in both configurations. Also indicated in the figure is the MRS LOS, 17° above the chamber equator.

motion, but are limited in that they can only address the presence of collective fuel motion along the MRS line-of-sight (LOS), 17° above the NIF chamber equator (Fig. 1). To extend the MRS measurement, 3D measurements of the full velocity vector can be made on the NIF using the Zirconium activation detectors distributed around the NIF target chamber. Preliminary measurements show good agreement with the MRS results for exploding pusher implosions.[19,20] However, activation measurements of the collective fuel motion in cryogenically layered DT implosions are complicated by the presence of large ρR asymmetries, and separating the two effects in the analysis is non-trivial.

The structure of the paper is as follows: Sec. II describes the underlying theory for neutron spectrum measurements of the fuel velocity. Section III discusses the MRS experimental setup and associated uncertainties, and Sec. IV provides the results. In Sec. V, implications of the results and future diagnostic improvements needed to conclusively diagnose the 3D fuel velocity on the NIF are discussed. Section VI concludes the paper.

II. THEORY

The mean energy of the neutron spectrum can be expressed relativistically as[21]

$$E_n = \frac{1}{2}\xi V_{CM}^2 + (\xi - m_n) + \frac{1}{2}\frac{(m_d + m_t)^2 - m_n^2 + m_\alpha^2}{(m_d + m_t)^2}K + V_{CM}\cos\theta \times \sqrt{\xi^2 - m_n^2}, \tag{1}$$

where

$$\xi = \frac{(m_d + m_t)^2 + m_n^2 - m_\alpha^2}{2(m_d + m_t)^2}. \tag{2}$$

This expression is derived by omitting terms of order ${T_{\text{ion}}}^2/M$, where T_{ion} is the ion temperature and M is the reduced mass. Here, V_{CM} is the center-of-mass (CM) velocity, K is the total kinetic energy of the reactants in the CM system, and θ is the angle between V_{CM} and the velocity of the fusion product in the CM system. Assuming that the energy released in the reaction, defined by the Q value, is much larger than the total kinetic energy of the reactants ($Q \gg K$),[22] which is generally true for the fusion plasmas studied here, the mean energy of the neutron spectrum is dominated by the second term in Eq. (1), while spectral broadening is dictated primarily by the $\cos\theta$ term. Using the Brysk formalism,[23] which assumes Maxwellian distributions for the fuel ions, the spectral broadening is routinely used to determine T_{ion}. Note, however, that reactions of fuel ions in radial motion lead to additional (non-temperature related) broadening of the neutron spectrum through the $\cos\theta$ term, such as observed in (Ref. 24). Tail depletion of the fast-ion distribution such as proposed in (Ref. 25) would, on the other hand, lead to decreased spectral broadening at the same T_{ion} relative to the Maxwellian case.

The mean energy of the neutron spectrum is modified by both T_{ion} and collective fuel motion. In the analysis presented in this paper, we use the interpolation formulas derived from Eq. (1) in Ref. 21 to determine the expected mean neutron energy caused by T_{ion}. Deviation from this expected mean energy is interpreted as the effect of collective motion of the fuel. While a finite T_{ion} leads to an increased mean energy, collective fuel motion will either "red shift" or "blue shift" the spectrum, depending on the velocity vector relative to the diagnostic LOS. With a single neutron spectrometer, such as the MRS, only the velocity component along the LOS can be determined. A relationship between the mean energy shift and fuel velocity can be derived from Eq. (1). Under the assumption that $Q \gg K$, the relative velocity and K can be eliminated, and the energy shift can be expressed in terms of the collective fuel velocity, i.e.,

$$\Delta E_n = V_{CM}\cos\theta \times \sqrt{\xi^2 - m_n^2} + \frac{1}{2}\xi V_{CM}^2. \tag{3}$$

For the DT reaction, Eq. (3) can be approximated by

$$\Delta E_n \approx 0.544 \cdot \cos\theta \cdot V_{CM} + 5.31 \times 10^{-6} V_{CM}^2. \tag{4}$$

Here, V_{CM} is given in km/s and ΔE_{n} is given in keV. For low V_{CM}, this expression reduces to $\Delta E_{\text{n}} \approx 0.54 \times V_{\text{CM}}$ in the LOS of the observing instrument (Refs. 11–13).

III. EXPERIMENT

Measurements of the mean energy shift of the primary DT neutron spectrum were achieved with the MRS, which is positioned on the target chamber wall, 596 cm from TCC, with a viewing angle 17° above the chamber equator. The primary components of the system are a conversion foil made of deuterated polyethylene (CD_2) positioned at 26 cm from TCC, an adjustable-sized aperture at 596 cm from TCC, a permanent Ne-Fe-B magnet just behind the aperture, and an array of CR-39 detectors positioned at the focal plane of the spectrometer. The data are retrieved from the CR-39 post-shot in a dedicated etch-and-scan process. For further details about the system, the reader is referred to Refs. 14–17.

The energy calibration of the MRS is in principle defined by neutron-deuteron elastic scattering kinematics, magnetic deflection, and system geometry. However, the alignment of the as-built system has to be verified *in situ* through measurements of the primary DT neutron spectrum. For our purposes, several cryogenically layered DT implosions were used to determine the MRS energy calibration.[17] Four factors contribute to the systematic uncertainty of the calibration: (i) positioning and alignment of each CR-39 in the detector array, (ii) positioning and alignment of the conversion foil, (iii) ambient temperature fluctuations affecting the field strength of the magnet, and (iv) alignment of the CR-39 scans.

Two factors dictate the positioning and alignment uncertainty of each CR-39 in the MRS detector array. First, an uncertainty is associated with the fact that the detector array is assembled, inserted and positioned by a hard stop into the MRS vessel prior to every shot. Second, there is an uncertainty in the positioning and alignment of each of the nine individual pieces of CR-39 positioned in dedicated holders on the detector array (the primary neutron spectrum falls entirely on one of these CR-39 for all shots studied here). It is estimated that the total alignment uncertainty in the dispersion direction is about ±50 μm, which is equivalent to an energy uncertainty of about ±5 keV.

The CR-39 scan alignment is estimated to be better than ±50 μm (for reference, this corresponds to ~1/16th of a standard microscope frame), which is equivalent to a peak energy uncertainty of ±5 keV.

As the CD_2 conversion foil is removed and reinserted into the NIF target chamber between most shots, there is an uncertainty associated with the positioning and alignment of the foil. On 14 of the shots studied in this paper, the actual position of the foil in the MRS LOS was measured to an accuracy of ±100 μm, while on the remaining shots, the foil was positioned 26 cm from TCC with accuracy better than the lateral foil alignment tolerance requirement of ±1 mm. According to Geant4 simulations (Ref. 16), a ±1 mm positioning accuracy corresponds to an energy uncertainty of ±15 keV, while a ±100 μm accuracy corresponds to an energy uncertainty of ±2 keV. Only foil displacement in the dispersion direction has an impact on the mean energy of the DT neutron spectrum.

The temperature in the NIF target bay is kept at 68.0 ± 0.25 °F at all times, which has a small impact on the energy calibration of the MRS. As the remanence temperature coefficient affecting the field strength of the Neodymium-Iron-Boron (Ne-Fe-B) magnet is –0.12%/K, the temperature variation causes a magnetic field strength variation of ±0.017%. From a constant Larmor radius argument,

$$\frac{E_1}{E_2} = \left(\frac{B_1}{B_2}\right)^2, \tag{5}$$

where E is the energy, B is the magnetic field strength, and the field strength variation of ±0.017% leads to a mean energy shift of ±4.5 keV.

The uncertainties associated with the different factors and the total uncertainty of ±17 keV (±9 keV with the ±100 μm foil position accuracy) are listed in Table I. An important point is that these systematic errors are random in nature; they vary from shot to shot and cannot be calibrated out.

TABLE I. Systematic uncertainty of the MRS energy calibration. The uncertainty associated with each factor is specified (see text for details).

Factor	Uncertainty	σ_{En} [keV]
CR-39 detector alignment	±50 μm	±5
CR-39 scan alignment	±50 μm	±5
CD_2 foil positioning and alignment	±1.0 mm (±100 μm)	±15 (±2)
Temperature variations affecting magnet	±0.25 °F	±4.5
Total		±17 (±9)

IV. RESULTS

Fig. 2 shows two MRS recoil deuteron energy spectra for cryogenically layered DT implosions N110620 (primary DT yield $Y_n = (4.1 \pm 0.1) \times 10^{14}$, ion temperature $T_{ion} = 4.3 \pm 0.3$ keV), and N111215 ($Y_n = (7.5 \pm 0.2) \times 10^{14}$, $T_{ion} = 3.5 \pm 0.1$ keV). Both spectra have been peak-area normalized to one. The mean neutron energy is determined through a χ^2 minimization fitting procedure: A modeled Gaussian neutron spectrum folded with the MRS response function is adjusted until the best match to the measured recoil deuteron spectrum is found. In particular, the mean energy, ion temperature, and magnitude are changed until the best fit is obtained. The $\pm 1\sigma$ precision on the mean energy from the fit is ±3 keV in both cases. Measured mean energies are corrected

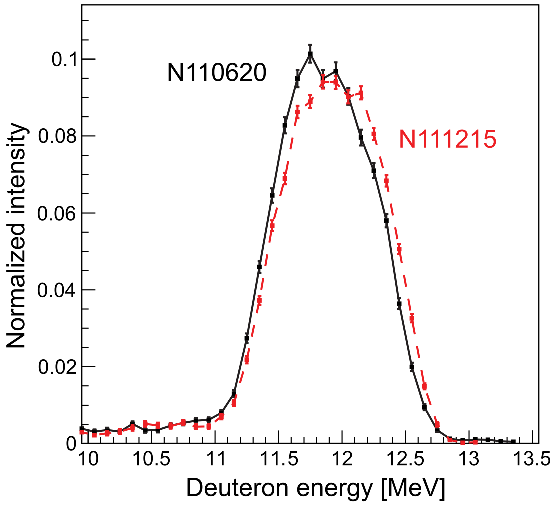

FIG. 2. MRS recoil deuteron spectra (peak area normalized to one) for cryogenically layered DT implosions N110620 (solid black) and N111215 (dashed red). Mean neutron energies are determined from the measured spectra through a χ^2 minimization fitting procedure (see text for details). The statistical precision in the determination of mean neutron energy for these two shots is ±3 keV, which is typical for the shots studied in this paper. The systematic mean energy uncertainty for N110620 (for which CD_2 foil position data to ±100 μm accuracy is available) is ±9 keV. For N111215, the foil position is only known to ±1 mm, and the systematic uncertainty is ±17 keV (Table I). After correcting for the expected shift due to T_{ion} and the measured CD_2-foil position shift for N110620, a measured mean energy difference of 67 ± 19 keV is determined.

for the expected shift due to $T_{\rm ion}$, as discussed in Sec. II. The expected energy-shift difference for the two shots associated with $T_{\rm ion}$ is 2.7 keV.[21] The observed difference in mean energy after correcting for the $T_{\rm ion}$ related shift is 67 ± 19 keV, which is substantially larger than the MRS energy calibration uncertainty (here, the result from N110620 has been corrected for a measured CD_2 foil-position shift of $370 \pm 100\,\mu$m, while no correction is applied for N111215, where the foil position is only known to ± 1 mm).

MRS measurements of the mean neutron energy have been made on 28 cryogenically layered DT implosions and one surrogate[26] DT implosion (Fig. 3(a)), and on six DT exploding pusher implosions (Fig. 3(b)). The mean energies are reported as shifts relative to the average value of the mean energy for the cryogenically layered DT implosions, which is used to define the MRS energy calibration. Note that two detector arrays are fielded in the MRS (black hollow symbols and red solid symbols in Fig. 3, respectively). The average mean energy shift determined from layered and surrogate data recorded on the first detector array (black, 20 shots) is +2 keV, while the average energy shift for cryogenically layered DT data on the second detector array (red, 9 shots) is −4 keV. From these observations, it is clear that any systematic difference in mean energy between the two detector arrays is negligible. Unlike for the layered implosions, the "red" array provides a higher average energy shift for the Exploding Pushers (Fig. 3(b)), further supporting the conclusion of no significant difference between the two detector arrays. Data from both detector arrays are consequently used to infer velocity with the same methods and error analysis, without any detector array-dependent corrections.

As can be seen in Fig. 3(a), the measured mean energy shifts for the cryogenically layered DT implosions are generally small. Comparing individual measurements, velocities of order 60 km/s are inferred along the MRS LOS for the extreme cases (N110620, N110914, N111215, and N120720). When looking at all shots, the calculated reduced χ^2 between the experimentally measured values and the "null velocity" hypothesis is 1.9. In contrast, mean energy shifts are substantial for a few of the polar direct drive DT exploding pushers (Fig. 3(b)). Determined collective fuel velocities along the MRS LOS range from -70 ± 30 km/s (for shot N120721) to 210 ± 30 km/s (for shot N120217). The calculated reduced χ^2 of 12.9 between the six data points and their average clearly indicates that the data are not consistent with the "null velocity" hypothesis.

V. DISCUSSION

MRS measurements of the mean energy of the DT neutron spectrum show substantial collective fuel velocities along the MRS LOS for a few DT exploding pusher implosions driven in polar direct drive configuration. This is not surprising given the high sensitivity to drive intensity asymmetries when using this configuration (Sec. I). Measured collective velocities are indeed found to correlate with out-of-spec laser intensities. The highest velocity shot N120217, for example, had eight dropped laser beams in the direction of the MRS, leading to a drive configuration literally pushing the implosion towards the MRS.

For cryogenically layered DT implosions, the MRS measurements indicate, on the other hand, that the collective fuel velocities along the MRS LOS are low. As discussed in Sec. I, recent integrated analysis of x-ray and neutron data indicate a residual kinetic energy of ~3 kJ (Ref. 6) during burn. This energy could go into radial or turbulent flow, or into collective fuel motion of the type discussed in this paper. If we assume that the energy goes into collective fuel motion, a 190 km/s velocity must be invoked. This corresponds to a mean neutron energy shift of ~100 keV, which can in principle be observed by a neutron spectrometer positioned in the line of motion. The absence of such substantial energy shifts in the MRS data might indicate that turbulent or radial flows would be a likely explanation for the missing energy. However, the MRS measurements would also be consistent with a

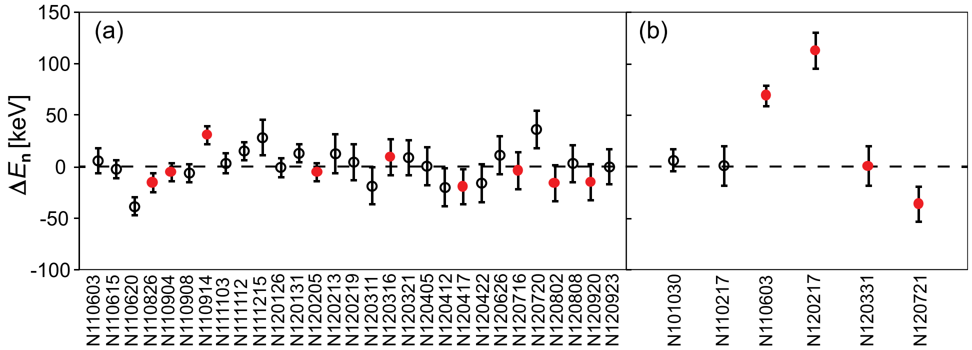

FIG. 3. MRS measurement of the mean neutron energy shift for (a) cryogenically layered DT implosions from June 2011 to September 2012 (and DT surrogate implosion N120923) and (b) polar direct drive DT exploding pusher implosions. All shifts are reported relative to the weighted average for the cryogenically layered implosions in panel (a) (which is taken as the MRS energy calibration) and after correcting for the expected shift due to $T_{\rm ion}$ (on shots where actual CD_2 foil position data are available, a correction for the foil position has also been applied). The solid red points represent data taken on one MRS detector array, hollow black points on the other. Velocity along the MRS LOS can be inferred from the energy shift according to $v_{\rm collective} \approx 1.84 \times \Delta E_n$. The observed velocities are small for the layered implosions. Calculated reduced χ^2 between the experimentally measured values in (a) and the "null velocity" hypothesis is 1.9. On the other hand, observed energy shifts are substantial for a few of the exploding pusher implosions in (b), indicating significant velocity along the MRS LOS. Here, reduced χ^2 between the experimentally measured values and the "null velocity" hypothesis is 12.9.

collective velocity in a direction close to perpendicular to the MRS LOS (e.g., along the hohlraum axis).

Evidence for residual kinetic energy along the hohlraum axis during burn has been obtained from recent shell and hot-spot symmetry measurements,[4] which indicate occasional P1 offsets of the hotspot along the hohlraum axis. Recent simulations suggest that these observations may be the result of laser-drive non-uniformities.[27–29] A downward collective motion of the implosion is consistent with these observations. It would also be consistent with the MRS data presented here, given that only ∼1/4th of a vertical velocity vector would manifest itself in the MRS LOS.

To fully constrain the problem of collective fuel motion, 3D information is required. Zirconium activation measurements are currently being conducted to infer the 3D velocity vector for exploding pusher explosions.[19,20] However, the possible presence of substantial ρR asymmetries in cryogenically layered implosions complicates the measurement for layered implosions. The reason for this that it is non-trivial to conclusively separate velocity from ρR effects in the activation data because both effects manifest themselves as percent level variations in measured yields.[30] A new technique using a single nTOF detector at 20 m from TCC is being developed for measurements of the difference between the deuterium-deuterium (DD) and DT mean energy from which an absolute collective fuel velocity can be determined.[31] There are three LOSs that could potentially be used for this measurement—a "South Pole" detector located at 161° polar and 56° azimuthal angle, and two near-equatorial detectors at (90°,174°) and (116°,316°). Between these three measurements, it is possible in principle to conclusively address any questions about collective fuel velocities.

VI. CONCLUSIONS

For the first time, quantitative measurements of the collective fuel velocity in ICF implosions using neutron spectrometry are reported. Results for both indirect-drive cryogenically layered implosions and polar direct drive exploding pushers on the NIF are presented. Substantial collective fuel velocities up to 210 ± 30 km/s along the MRS LOS are observed for polar direct drive DT exploding pusher implosions. These implosions are used for calibration of the nuclear diagnostics, and the velocities observed have complicated the calibration of the Zirconium activation diagnostic for ρR asymmetry measurements. The observed collective fuel velocities correlate with unintended laser drive asymmetries (beams with out-of-spec intensity).

The results presented here indicate that collective fuel velocity effects are small along the MRS LOS for cryogenically layered DT NIF implosions (reduced $\chi^2 = 1.9$ between measurements for 29 shots and the null-velocity hypothesis). However, a systematic collective fuel velocity cannot be conclusively ruled out based on a single LOS. If present, such an effect is crucial to diagnose, given its potential importance in the effort to achieve ignition on the NIF. Future collective velocity measurements that will fully diagnose the 3D velocity vector will help conclusively answer whether such an effect is responsible for degrading performance of cryogenically layered implosions on the NIF.

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