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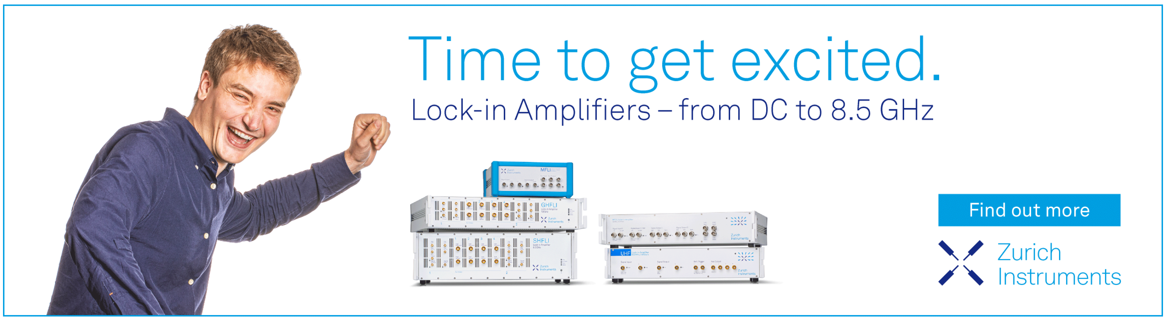

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ABSTRACT

Charged particle spectrometry is a critical diagnostic to study inertial-confinement-fusion plasmas and high energy density plasmas. The OMEGA Laser Facility has two fixed magnetic charged particle spectrometers (CPSs) to measure MeV-ions. *In situ* calibration of these spectrometers was carried out using ^{241}Am and ^{226}Ra alpha emitters. The alpha emission spectrum from the sources was measured independently using surface-barrier detectors (SBDs). The energy dispersion and broadening of the CPS systems were determined by comparing the CPS measured alpha spectrum to that of the SBD. The calibration method significantly constrains the energy dispersion, which was previously obtained through the measurement of charged particle fusion products. Overall, a small shift of 100 keV was observed between previous and the calibration done in this work.

I. BACKGROUND AND MOTIVATION

High-energy (~MeV) charged particles are generated during multiple stages of Inertial Confinement Fusion (ICF) implosions.[1,2] The charged particle generation mechanisms include primary-fusion reactions,[3] secondary-fusion reactions,[4] neutron elastic scattering,[5] and laser plasma interactions.[6] These processes generate charged particles with defined spectra, which can subsequently be modified by plasma stopping or electric fields. Precision charged particle spectroscopy has proven extremely valuable to measure plasma stopping power,[7–9] electric and magnetic fields,[10,11] and areal density in ICF implosions.[5,12]

The Charged Particle Spectrometer (CPS) 1 and 2 diagnostics[1,13] are used to measure charged-particle energy spectra from 0.1 to 30 MeV at the OMEGA Laser Facility.[14] CPSs 1 and 2 utilize a dipole magnet to disperse particles based on their gyro-radius. Solid-state CR39 detectors[15] provide both the detection and identification of charged particles based on the properties of the tracks left behind by the charged particles in the CR39 material.

As shown in Refs. 1, 2, 5–10, 13, and 16, CPSs 1 and 2 have made tremendous contributions to both programmatic and basic science ICF experiments. For example, CPSs 1 and 2 are used to measure "knock-on" deuterons generated from elastic scattering of 14.1 MeV DT neutrons,

$$n(14.1\ \text{MeV}) + \text{D} \rightarrow n' + \text{D}(< 12.1\ \text{MeV}). \tag{1}$$

Measurements of the knock-on deuterons provide information about the areal density, ρR, of the fuel assembly at stagnation.[5] In addition, CPSs 1 and 2 have been extensively used to understand charged particle stopping in High Energy Density Plasmas (HEDPs) by measuring the energy loss of the charged-particle fusion products generated from the D+D and D+^{3}He fusion reactions,[7]

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}(1.01\ \mathrm{MeV}) + p(3.01\ \mathrm{MeV}), \quad (2)$$

$$\mathrm{D} + \mathrm{D} \rightarrow n(2.45\ \mathrm{MeV}) + {}^3\mathrm{He}(0.82\ \mathrm{MeV}), \quad (3)$$

$$\mathrm{D} + {}^3\mathrm{He} \rightarrow \alpha(3.71\ \mathrm{MeV}) + p(14.7\ \mathrm{MeV}). \quad (4)$$

In addition, D+D, D+^{3}He, and, more recently, T+^{3}He[17] reactions are also commonly used in charged-particle radiography. CPSs 1 and 2 provide important measurements of the emitted particle energies, which can be up-shifted due to capsule charging during the implosion.[6,10,11]

Critical to the measurements described above is the absolute energy calibration of CPSs 1 and 2. Periodic calibration of both CPSs 1 and 2 is required to retain precision spectral measurements as the systems age. In addition, CPS 1 has recently been relocated on the OMEGA target chamber, requiring a completely new set of calibration data. In the past, calibration of CPSs 1 and 2 was performed by measuring charged particle lines generated from D+D and D+^{3}He fusion reactions. This calibration effort was expensive as it required dedicated experimental time on the facility to produce implosions generating these reactions.

This paper details an *in situ* calibration platform using alpha emitters to measure the energy dispersion and broadening of CPSs 1 and 2. The platform uses small ^{241}Am and ^{226}Ra sources, positioned at the target chamber center (TCC), to produce alpha lines from 4 to 8 MeV. This method is conducted offline and does not use the experimental time of the facility. The absolute energy dispersion and energy broadening of CPSs 1 and 2 are measured. Section II details the CPS systems. Section III highlights the calibration method and resulting data. It also compares previous calibrations to the new calibration acquired with the alpha emitters. Section IV presents an outlook and future work using the calibration platform.

II. CHARGED PARTICLE SPECTROMETER (CPS) SYSTEMS ON OMEGA

CPSs 1 and 2 are identical but placed at different locations on the OMEGA target chamber, as illustrated in Fig. 1(a). The CPS 1 (CPS 2) acceptance slit is located 255 (100) cm from TCC and is located at port H11 (H1), which is located at a polar angle of 100.81° (138.23°) and an azimuthal angle of 126° (50.25°) on the chamber. The width of the acceptance slit varies from 0.1 to 3 mm to accommodate a wide dynamic range of particle yields and is 20 mm long. Figure 1(b) displays a cross-sectional view of the CPS 2 system.

Particles enter through the rectangular slit into the 7.6 kG magnetic field region. The magnetic material consists of multiple pieces of Nd-Fe-B epoxied together. The magnet and yoke structure is 28 cm long, 17 cm wide, and 20 cm high, while the pole-gap height is 2 cm. Ions are subsequently deflected onto CR39 detectors, fielded along different rails denoted as B, C, and D. The B, C, and D rails follow different circular arcs to cover a wide range of particle trajectories deflected by the magnet. Individual pieces of CR39 are 4.8 cm wide by 3.0 cm high and placed at designed holders along a

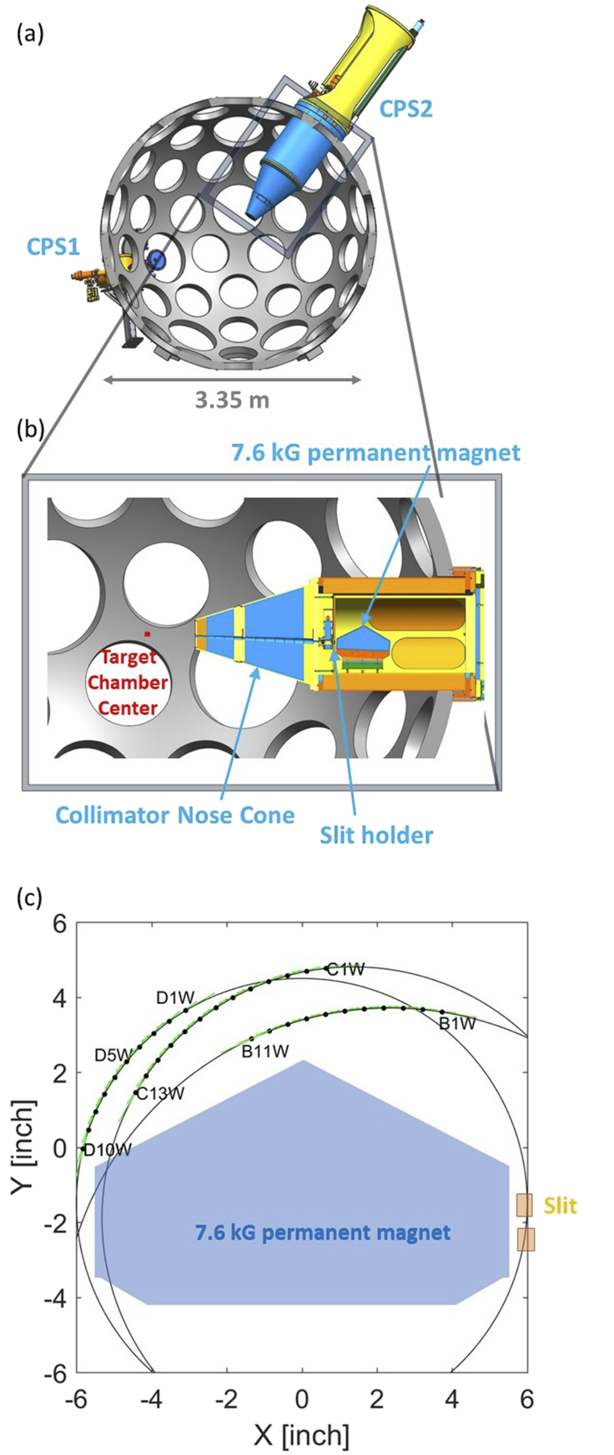

FIG. 1. (a) Locations of CPSs 1 and 2 on the OMEGA target chamber. (b) Slice of the CPS 2 re-entrant tube inside the OMEGA target chamber. (c) Schematic of the internal CPS layout. Charged particles enter through a slit (orange) into the 7.6 kG magnetic field region (blue). The particles are subsequently deflected onto the detector fingers. CR39 detectors can be fielded on B, C, and D rails indicated by the black dots. The CR39 is positioned tangent to the circular arc of each rail.

rail. Rail B has 11 holders, B1W-B11W, and similarly, rails C and D have 13 and 10 holders, respectively. The holder locations are indicated by the black dots, and CR39 is positioned tangent to the circular arc defining each rail as depicted by the green tangent lines in Fig. 1(c).

A. Energy calibration platform

In situ calibration of the CPS 1 and 2 spectrometers was done by using two button sources: 10 μCi ^{241}Am and 0.13 μCi ^{226}Ra. The sources are mounted on a holder, which is inserted into the OMEGA target chamber. The holder positions the active sources at TCC, emitting toward either the CPS 1 or 2 slit. For a 1 mm slit width, the expected count rate of alphas for the 10 μCi ^{241}Am source is 0.045 (CPS1) and 0.29 (CPS2) counts per second. Correspondingly, measuring 5000 alpha particles, which would determine the peak energy to 1.5%, takes 30 and 4.7 hours for CPSs 1 and 2, respectively. Calibration runs usually occur over a weekend or maintenance period of the facility and do not impact the experimental schedule.

B. Alpha source emission spectrum

Independent measurements of the alpha emission spectra from the two sources were acquired at vacuum using a silicon surface barrier diode (SBD) with a nominal depletion depth of 2000 μm. The energy resolution of the SBD is 17 keV.[18] The SBD is calibrated to the spectral grade ^{226}Ra source. The ^{226}Ra source has a 51 nm electroplated gold coating sealing the active material. The energy loss of each alpha peak is determined from SRIM tables using the known thickness of gold. The alpha peaks from ^{226}Ra are downshifted to 4.76, 5.46, 5.98, and 7.63 MeV. Each emission peak has a FWHM of 80 keV on average. The ^{241}Am source is not spectral grade because its activity levels require a thicker gold layer to seal the source. The ^{241}Am peak is heavily downshifted to 4.52 MeV and a FWHM of 0.535 MeV. The SBD measured energy spectrum for both the ^{241}Am and ^{226}Ra source is shown in Fig. 2.

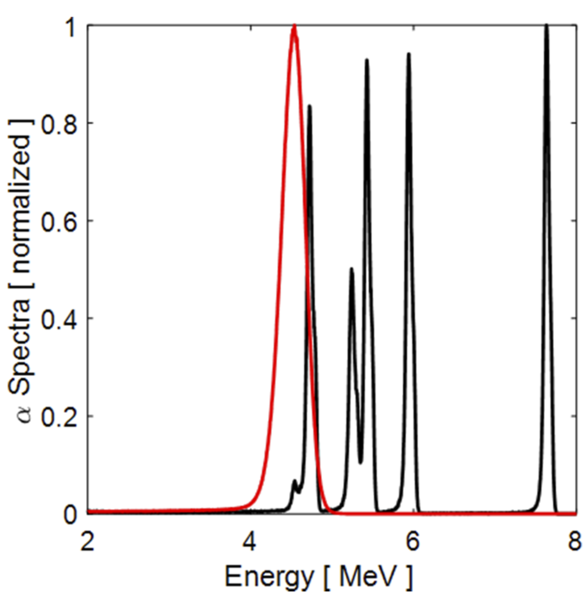

FIG. 2. ^{241}Am (red) and ^{226}Ra (black) alpha energy spectra measured with a silicon surface barrier detector for ^{241}Am (red) and ^{226}Ra (black).

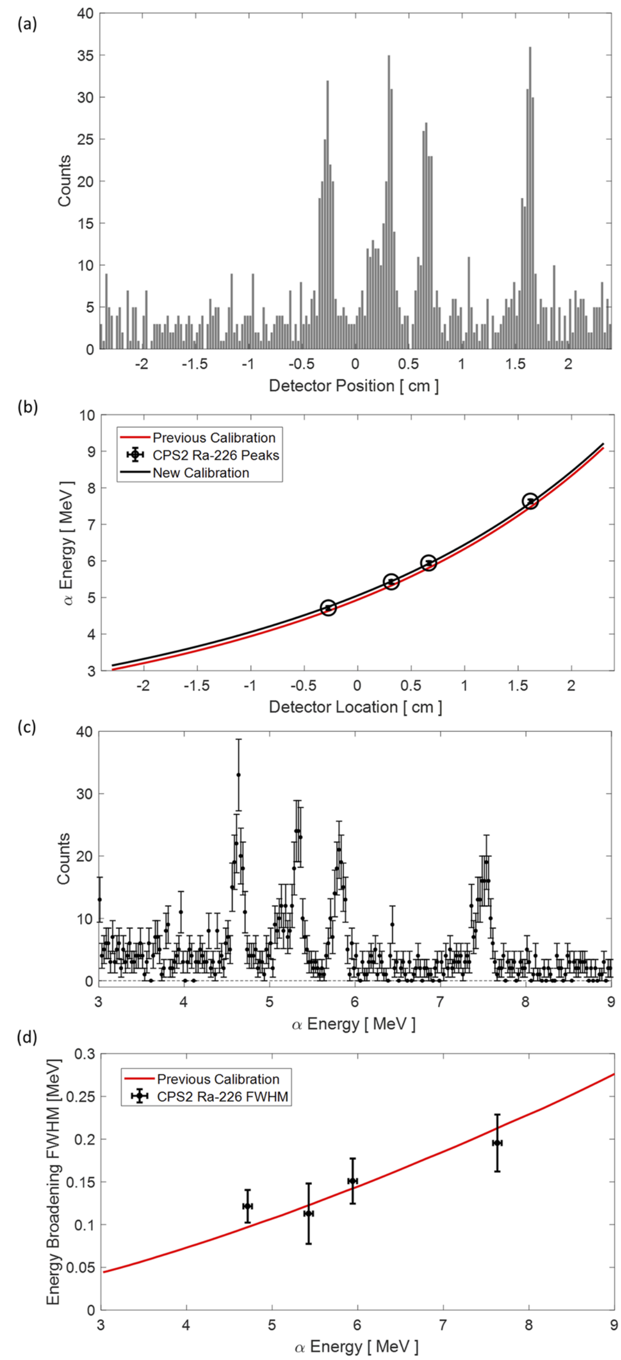

FIG. 3. (a) ^{226}Ra alpha spectrum measured by D6W on CPS2. (b) Energy calibration as a function of detector position. (c) ^{226}Ra alpha energy spectrum with a new calibration curve. (d) CPS2 instrument broadening.

III. CALIBRATION RESULTS

A. ^{226}Ra

The CPS2 system fielded with the D6W detector with a 1 mm slit was exposed to the ^{226}Ra source for 63 h. Figure 3(a) shows a histogram of the tracks identified as a function of position on CR39. The calibration of the energy dispersion is done by fitting the prominent four alpha-peak mean energies to their expected emitted energies from the source. The energy dispersion across CR39 is fitted with a parabolic function, which is expected from a dipole magnet. Figure 3(b) displays the previous calibration (red curve). In addition, the new calibration is shown by the black curve. The new calibration curve is found to be systematically up-shifted by 100 keV when compared to the previous calibration. Figure 3(c) shows the measured alpha spectrum using the new calibration to set the energy axis. Furthermore, the energy broadening of CPS2 was probed. Figure 3(d) shows the expected FWHM broadening of lines for the CPS2 system using a 1 mm slit. The FWHM of the four alpha peaks is shown in Fig. 3(d) to be in good agreement with the scaling predicted by previous calibrations.

B. ^{241}Am

The CPS 1 and 2 systems were also exposed to the same ^{241}Am source. The CPS 1 system was exposed for 64 h, while the CPS 2 system was exposed for 24 h. Figure 4 shows the alpha spectrum from the ^{241}Am source as measured by using an SBD, CPS 1, and CPS 2. Both CPSs 1 and 2 were calibrated with the ^{226}Ra source to set the energy dispersion. Figure 3 shows excellent agreement between the three independent measurements of the spectrum from the ^{241}Am source. The FWHM of the ^{241}Am was 0.535 MeV as measured by using the SBD. Both CPSs 1 and 2 were run with a 1 mm slit. Both CPSs 1 and 2 capture the spectral shape because the broadening due to the slit is negligible for this alpha line.

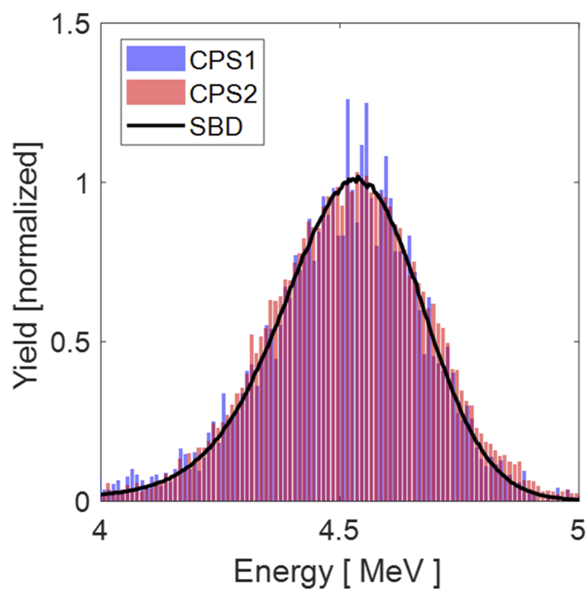

FIG. 4. Measurements of the ^{241}Am alpha spectra with an SBD (black), CPS 1 (blue), and CPS2 (red).

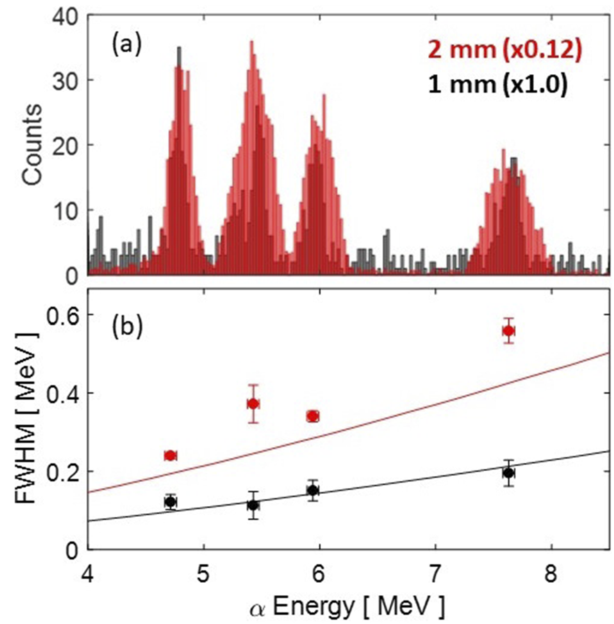

FIG. 5. (a) Measurements of ^{226}Ra lines with CPS 2 D6W using a 1 mm (black) and 2 mm (red) slit. The counts as measured by using the 2 mm slit were scaled by 0.12×. (b) Linewidths of the measured lines as a function of alpha energy. Also shown is the scaling predicted by previous calibrations in solid lines.

C. Impact of slit width on energy broadening

Two separate calibration runs were conducted to probe the energy broadening due to the finite width of the acceptance slit. CPS 2 was run with a 1 mm slit and a 2 mm slit. The measured ^{226}Ra alpha energy spectra are shown in Fig. 5(a). The FWHMs of the alpha lines are shown in Fig. 5(b), and for reference, the alpha FWHM measured with the SBD is 80 keV. The broadening of the spectral lines was predicted to be linearly proportional to the slit width; however, the 2 mm slit produced spectra ≈2.5× that of the 1 mm slit. The excess broadening is speculated to be a result of dipole-fringe fields becoming increasingly important as the acceptance trajectories the particles cover more of the magnetic area.

IV. CONCLUSIONS/OUTLOOK

Charged particle spectroscopy is critical for both ICF and HEDP experiments at OMEGA. An off-line *in situ* absolute calibration platform has been established for CPSs 1 and 2 on the OMEGA Laser Facility, which uses a variety of alpha emitters. The calibration method provides information about the energy, energy dispersion, and energy broadening of the spectrometer. Modifications to the previous calibration for the energy dispersion of the CPS 1 and 2 detectors were necessary, while the instrument broadening was well captured by previous calibrations for 1 mm slits. As the slit width increased to 2 mm, the broadening was not captured possibly due to the field topology of the dipole magnet. Periodic calibration of the two systems will be required to observe shifts or changes to the energy dispersion and broadening.

In this work, the D6W detector was calibrated, which measures the knock-on deuteron spectrum from cryogenic DT implosions at OMEGA to determine ρR.[5] Future energy calibrations will be conducted by ranging down the energy of the alpha particles with aluminum filters to 1–4 MeV. This energy range is relevant to charged particle stopping power experiments and proton radiography. Future work will also involve repeat calibration runs to quantify repeatability.

This method also has prospects to calibrate other diagnostics *in situ*. Recently, a new magnetic spectrometer, MagSPEC, has been designed and fielded on both the National Ignition Facility (NIF) and OMEGA designed to measure low-yield charged particles, such as the $^3He + ^3He \rightarrow p$ reactions [24]. In addition, *in situ* calibration of Thompson parabola diagnostics at OMEGA[19] is planned. Furthermore, the calibration method can be adapted to NIF. Currently at the NIF, charged particle spectrometers are calibrated offline in a separate diagnostics laboratory.[20] While this method measures the magnet dispersion, it is unable to probe alignment and geometry effects on the particle energy dispersion. This will be critical for diagnostics, such as the time-resolved Magnetic Recoil Spectrometer (MRS-t).[21,22]

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

P. J. Adrian: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Writing – original draft (equal). **J. Armstrong**: Software (equal). **A. Birkel**: Methodology (supporting). **C. Chang**: Investigation (equal). **S. Dannhoff**: Formal analysis (supporting). **T. Evans**: Formal analysis (supporting). **M. Gatu Johnson**: Formal analysis (supporting); Funding acquisition (equal); Project administration (supporting). **T. M. Johnson**: Formal analysis (supporting). **N. Kabadi**: Validation (supporting). **J. Kunimune**: Methodology (supporting). **C. K. Li**: Funding acquisition (equal). **B. Reichelt**: Validation (supporting). **S. P. Regan**: Funding acquisition (equal). **J. Pearcy**: Methodology (supporting). **R. D. Petrasso**: Conceptualization (equal); Funding acquisition (equal). **G. Pien**: Project administration (lead). **M. McCluskey**: Project administration (equal). **F. H. Séguin**: Formal analysis (equal). **G. D. Sutcliffe**: Formal analysis (supporting). **J. A. Frenje**: Conceptualization (equal); Formal analysis (equal); Funding acquisition (lead); Investigation (equal); Methodology (equal); Supervision (lead); Writing – review & editing (equal).

DATA AVAILABILITY

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

REFERENCES

[1] F. H. Séguin *et al.*, Rev. Sci. Instrum. **74**, 975 (2003).
[2] J. A. Frenje, Plasma Phys. Controlled Fusion **62**, 023001 (2020).
[3] L. Ballabio, J. Källne, and G. Gorini, Nucl. Fusion **38**, 1723 (1998).
[4] H. G. Rinderknecht *et al.*, Phys. Plasmas **22**, 082709 (2015).
[5] J. A. Frenje *et al.*, Phys. Plasmas **11**, 2798 (2004).
[6] D. G. Hicks *et al.*, Phys. Plasmas **8**, 606 (2001).
[7] J. Frenje *et al.*, Phys. Rev. Lett. **122**, 015002 (2019).
[8] J. Frenje *et al.*, Phys. Rev. Lett. **115**, 205001 (2015).
[9] A. Zylstra *et al.*, Phys. Rev. Lett. **114**, 215002 (2015).
[10] J. R. Rygg *et al.*, Rev. Sci. Instrum. **86**, 116104 (2015).
[11] J. R. Rygg *et al.*, Science **319**, 1223 (2008).
[12] A. B. Zylstra *et al.*, Phys. Plasmas **22**, 056301 (2015).
[13] D. G. Hicks *et al.*, Rev. Sci. Instrum. **68**, 589 (1997).
[14] T. R. Boehly *et al.*, Opt. Commun. **133**, 495 (1997).
[15] R. M. Cassou and E. V. Benton, Nucl. Track Detect. **2**, 173 (1978).
[16] H. G. Rinderknecht *et al.*, Phys. Rev. Lett. **114**, 025001 (2015).
[17] G. Sutcliffe *et al.*, Rev. Sci. Instrum. **92**, 063524 (2021).
[18] S. C. McDuffee *et al.*, Rev. Sci. Instrum. **79**, 043302 (2008).
[19] J. A. Cobble *et al.*, Rev. Sci. Instrum. **82**, 113504 (2011).
[20] D. Mariscal *et al.*, Rev. Sci. Instrum. **89**, 10I145 (2018).
[21] J. H. Kunimune *et al.*, Rev. Sci. Instrum. **92**, 033514 (2021).
[22] J. A. Frenje *et al.*, Rev. Sci. Instrum. **87**, 11D806 (2016).