

**A technique for extending by 103 the dynamic range of compact proton spectrometers for diagnosing ICF implosions on the National Ignition Facility and OMEGAa)**

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# A technique for extending by $\sim 10^3$ the dynamic range of compact proton spectrometers for diagnosing ICF implosions on the National Ignition Facility and OMEGA<sup>a)</sup>

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Wedge Range Filter (WRF) proton spectrometers are routinely used on OMEGA and the NIF for diagnosing  $\rho R$  and  $\rho R$  asymmetries in direct- and indirect-drive implosions of  $D^3He$ -,  $D_2$ -, and  $DT$ -gas-filled capsules. By measuring the optical opacity distribution in CR-39 due to proton tracks in high-yield applications, as opposed to counting individual tracks, WRF dynamic range can be extended by  $10^2$  for obtaining the spectral shape, and by  $10^3$  for mean energy ( $\rho R$ ) measurement, corresponding to proton fluences of  $10^8$  and  $10^9$   $cm^{-2}$ , respectively. Using this new technique,  $\rho R$  asymmetries can be measured during both shock and compression burn (proton yield  $\sim 10^8$  and  $\sim 10^{12}$ , respectively) in 2-shock National Ignition Facility implosions with the standard WRF accuracy of  $\pm \sim 10$   $mg/cm^2$ .  
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## I. INTRODUCTION

Wedge Range Filter (WRF) proton spectrometers<sup>1,2</sup> are routinely used at OMEGA<sup>3</sup> and at the National Ignition Facility (NIF)<sup>4</sup> for diagnosing shell and fuel areal density ( $\rho R$ ) in direct and indirect drive implosions of capsules filled with  $D^3He$ ,<sup>5,6</sup>  $D_2$ ,<sup>7,8</sup> or  $DT$ <sup>9</sup> gas. WRFs are often fielded at multiple locations in the target chamber, where they record spectra of fusion protons leaving an implosion in a number of different directions; this makes them ideal for studies of yield and  $\rho R$  asymmetries. At the NIF, WRFs are fielded at the equator and at the pole to diagnose low-mode  $\rho R$  asymmetries at shock-bang time (convergence  $\sim 4$ ) in indirect-drive implosions of  $D^3He$  gas-filled surrogates.<sup>10</sup> This is accomplished by measuring the energy downshift of the  $D^3He$  protons born at 14.7 MeV and emitted in the different directions, which can then be translated into the total  $\rho R$  in the same directions by making use of plasma stopping power calculations.

The WRF spectrometry technique is based on the recording of characteristics of individual proton tracks<sup>11</sup> generated in a CR-39<sup>12</sup> nuclear track detector (size, eccentricity, and optical contrast), making use of the fact that these characteristics are related to proton energy. However, when the proton fluence on CR-39 is raised to  $10^6$   $cm^{-2}$  and higher, proton tracks overlap even for short CR-39 etch times and information about individual tracks is eventually lost (see Fig. 1(c)). This prevents even the simple counting of tracks for determining proton fluence, let alone the characterization of individual tracks normally needed for WRF analysis.

Monte-Carlo simulations can be used to estimate the true proton yield by predicting the severity of track overlap for arbitrary proton diameter distributions<sup>13</sup> when the fluence is not too high, but this raises the upper limit on fluence by only a small factor and does not help when most tracks overlap. A compact, CR-39-based detector based on track counting has been developed for measuring proton yield when the fluence is very high<sup>14</sup> (by scattering a small number of protons into a large area where they can be counted), but it does not allow for spectral measurement.

In high-yield applications, WRF spectrometers are usually fielded far enough from the target to avoid excessive proton fluence, but in many experiments the total proton yield is not well-known beforehand or the fielding distance is constrained. At the NIF, for example, WRFs are fielded on Diagnostic Insertion Manipulators (DIM)<sup>15</sup> at a fixed distance of typically 50 cm from the implosion. When high proton yield leads to on-detector fluences greater than  $10^6$   $cm^{-2}$ , track overlap causes proton spectra found with standard analysis to be shifted and distorted, leading to large uncertainties in the  $\rho R$  measurement.

It has been shown<sup>16</sup> that when track overlap occurs, CR-39 can in some respects be treated like film and scanned for optical opacity as a function of position, though the relationship between local optical opacity and particle fluence is nonlinear. Opacity measurements contain no information about individual protons, and therefore seem unlikely to be useful for spectral studies, but this paper shows that there is a way to use them to obtain proton spectra from CR-39 exposed in WRF spectrometers when the fluence is high enough. The method greatly extends the WRF dynamic range, enabling accurate  $\rho R$  measurements for experiments at the NIF and OMEGA even when very high proton fluence ( $10^6$ – $10^9$   $cm^{-2}$ ) cannot be avoided.

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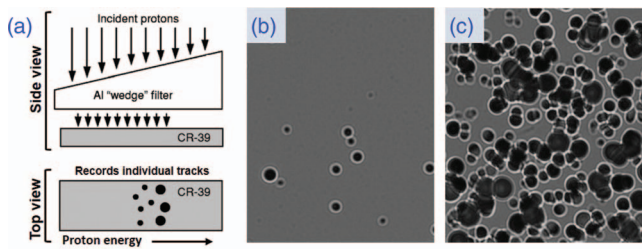


FIG. 1. (a) Schematic diagram of the WRF proton spectrometer and the formation of individual tracks in the CR-39.<sup>1</sup> (b) Proton tracks sparsely distributed within a microscope frame and (c) Proton tracks densely distributed within a microscope frame. Images (b) and (c) cover an area approximately  $10^{-4}$  cm<sup>2</sup> and are from CR-39 samples etched to 2 h, with track densities  $1 \times 10^5$  and  $1 \times 10^7$  cm<sup>-2</sup>, respectively.

## II. NORMAL WRF ANALYSIS AND LIMITATIONS

The WRF proton spectrometer consists of a thin wedge made of aluminum or zirconia positioned in front of a CR-39 nuclear track detector,<sup>1,2</sup> all arranged in a compact housing. Incident protons pass through a wedge-shaped ranging filter before striking the CR-39 nuclear track detector. Etching the CR39 with NaOH results in a conical pit at the location of each track, which refracts light and appears dark against the clear CR-39 background when viewed under an optical microscope. An automated microscope scanning system<sup>1</sup> is used to record the location, size, and other characteristics of every track on the CR-39. Protons of a given energy incident on the filter at different positions where the thickness is different will exit the filter with different energies, resulting in tracks of correspondingly different size in the CR39<sup>17</sup> as a function of location along the wedge (see Fig. 1(a)). The two-dimensional distribution of number of tracks vs. size and position is then converted into a histogram of number of protons per MeV. The WRF spectrometer covers an energy range of about 4–20 MeV, and measures the proton spectrum with absolute energy uncertainty of  $\pm 60$  keV at  $E_p = 14.5$  MeV.<sup>18</sup>

To demonstrate the decline in the quality of normal WRF data analysis as track overlap becomes more severe, several pieces of CR-39 from WRF spectrometers exposed to  $10^7$  14.7-MeV protons per cm<sup>2</sup> during an experiment at OMEGA were etched in stages to a total of 4 hours, in increments of one hour, and scanned at each stage. Figure 2(a) includes images representing the number of tracks per unit area at each etch time, showing how the number of individually counted tracks decreased as longer etch times increased the track sizes and resulted in more overlap. Figure 2(b) shows area-normalized spectra calculated from the scans in the normal way at the different etch times, illustrating how the spectra become increasingly distorted at higher etch times and eventually shift to slightly lower average energy. Figure 2(b) also includes the normally processed spectrum from another WRF spectrometer that was exposed during the same OMEGA shot, but 10 times farther away from the implosion (for a proton fluence 100 times lower). This spectrum is labeled as “Reference.” It can be expected to match the spectrum of the close-in WRF because, in previous experiments, spectra measured at different angles around these low-convergence, low- $\rho R$  implosions were identical within the measurement uncertainties.

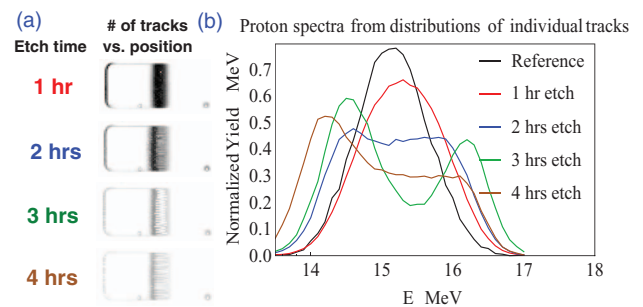


FIG. 2. (a) Scans of high-fluence CR-39 data ( $1 \times 10^7$  tracks/cm<sup>2</sup>) etched for 1, 2, 3, and 4 hours (OMEGA shot 67 017). The gray scale is the same in all four images; a darker pixel indicates a larger number of recorded tracks per unit area. Note the decreasing number of individually recorded tracks as the etch time increases due to track overlap. (b) Area-normalized proton spectra reconstructed from the data etched for 1, 2, 3, and 4 hours. Also shown is a reference proton spectrum obtained with another WRF spectrometer that was fielded much farther away from the same implosion, where the proton fluence was 100 times smaller. At higher etch times, the (high-fluence) spectra become very distorted due to overlap of individual proton tracks.

## III. OPACITY ANALYSIS

When proton tracks overlap seriously even at the shortest usable etch time (about 0.5 hours), individual track information is lost. However, nonlinear relationships connecting opacity, proton fluence, proton energy, etch time, and response of a given type of WRF-exposed CR-39 can be experimentally calibrated and modeled<sup>19</sup> at least up to a fluence of  $10^8$  cm<sup>-2</sup>. The possibility of reconstructing a proton spectrum using opacity as a function of position on the CR-39 was investigated using the same CR-39 samples described in Sec. II. This approach utilizes measured opacity and calibrated wedge-filter thickness as functions of position on the CR-39, together with knowledge of track size as a function of proton energy and etch time. The opacity is recorded with the same automated microscope system<sup>1</sup> used for normal track counting, but the software is modified to record average optical opacity as a function of position rather than the locations and properties of individual tracks. For this application, each opacity measurement is averaged over a  $100 \mu\text{m} \times 100 \mu\text{m}$  area on the CR-39.

The recorded opacity values are scaled to compensate for the nonlinear fluence-opacity relationship.<sup>19</sup> Then, if the etch time is relatively short, an approximate one-to-one mapping between filter thickness and proton energy is applied and the result is a proton spectrum.

Figure 3 shows the result this approach. In contrast to the standard track scans, the sequence of opacity scans (Fig. 3(a)) shows stronger signal (higher opacity) at higher etch times. This is due to an increasing area covered by the refracting tracks. The area-normalized proton spectra from opacity scans also agree with the reference proton spectrum within the uncertainty. For a proton fluence of  $10^7$  tracks/cm<sup>2</sup>, the new WRF analysis using the opacity technique recovers the expected spectral shape, with mean energy and spectral width in excellent agreement with expected values up to an etch time of 3 hours (see Fig. 4).

We inferred the expected behavior for CR-39 with a higher incident proton fluence than in the present study by

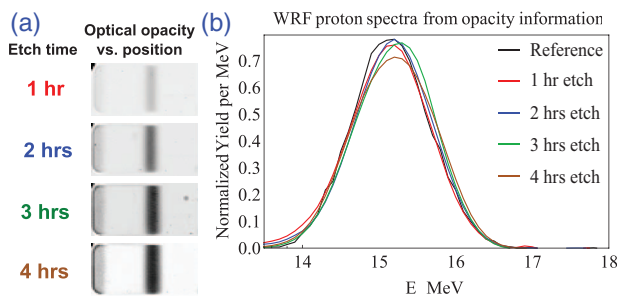


FIG. 3. (a) Scans of high-fluence CR-39 data ( $1 \times 10^7$  tracks/cm<sup>2</sup>) etched for 1, 2, 3, and 4 hours (shot 67017). The grey scale is the same in all four images; a darker pixel indicates higher opacity. In the opacity scan images, the monoenergetic D<sup>3</sup>He proton line is clear even at high etch times, which is in stark contrast to the data in Fig. 2. (b) Area-normalized proton spectra reconstructed from the data etched for 1, 2, 3, and 4 hours along with a reference proton spectrum obtained with another WRF spectrometer fielded farther away from the same implosion to observe a normal proton fluence. Note that even at higher etch times, the spectra are nominally Gaussian with mean and linewidth comparable to the reference proton spectrum.

etching the CR-39 above the optimal etch time and observe deviation from expected spectral shape, as total track area increases with etch time (see Fig. 4). Recovering the spectral shape requires the peak fluence to be in a region where opacity is not saturated. Recovering the mean energy only in the case where the spectral shape is known can be done by fitting only to the lower-fluence wings of the proton spectrum and thus applicable to even higher incident fluence. Overall, it is estimated that with appropriate etch times (long for low fluence, short for the highest fluence), the opacity method should work for proton fluences in the range from  $\sim 10^4$  cm<sup>-2</sup> to at least  $10^8$  cm<sup>-2</sup> (for spectral shape) and  $10^9$  cm<sup>-2</sup> (for mean energy). This corresponds to an increase in dynamic range by

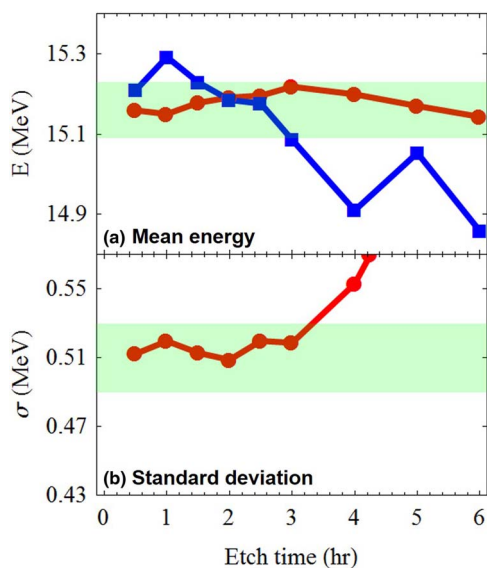


FIG. 4. (a) Proton mean energy, and (b) standard deviation of the proton spectrum, as a function of etch time when the standard track analysis (Blue) and opacity analysis (Red) were applied to the data. These quantities were determined from the proton spectra shown in Figs. 2 and 3 at a proton fluence of  $10^7$  tracks cm<sup>-2</sup>. The green region denotes  $\pm 1\sigma$  uncertainty of the expected values based on a reference proton spectrum obtained with another WRF spectrometer fielded farther away from the same implosion to observe a normal proton fluence.

a factor of  $10^2$  (for spectral shape) and  $10^3$  (for mean energy) relative to the normal WRF analysis, where the working range is typically from  $\sim 10^2$  cm<sup>-2</sup> to  $\sim 2 \times 10^6$  cm<sup>-2</sup>.

#### IV. APPLICATION AND CONCLUSION

A new analysis method has been developed that extends the dynamic range of the WRF spectrometer by three orders of magnitude. This method uses the local optical opacity of CR-39 to reconstruct the proton spectrum, with mean energy (and hence,  $\rho R$ ) uncertainty comparable to standard WRF analysis at high proton fluence ( $\sim 10^6$ – $10^9$  cm<sup>-2</sup>). This makes possible the measurement of  $\rho R$  values at both shock and compression times (where yields are  $\sim 10^8$  and  $\sim 10^{12}$ , respectively) in D<sup>3</sup>He gas-filled two-shock, near-vacuum hohlraum implosions at the NIF that produce  $\rho R$  up to  $\sim 200$  mg/cm<sup>2</sup>. Multiple WRF proton spectrometers fielded at the pole and equator will be used to assess  $\rho R$  asymmetries during shock and compression burns. The shock phase typically generates protons with energy  $\sim 13$  MeV ( $\rho R \sim 50$  mg/cm<sup>2</sup>), and the compression phase generates protons with an energy of  $\sim 10$  MeV ( $\rho R \sim 150$  mg/cm<sup>2</sup>). As the WRFs are fielded on the pole and equator at a fixed distance of approximately 50 cm from the implosions, the shock and compression proton fluences are  $3 \times 10^3$  and  $3 \times 10^7$  tracks/cm<sup>2</sup>, respectively, spanning a large dynamic range previously inaccessible using standard individual track analysis.

#### ACKNOWLEDGMENTS

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<sup>19</sup>The details of this relationship are beyond the scope of this paper, but will be described in a future publication. Here is a partial description: For a given etch time, assume  $O$  is optical opacity (0.0 for no reduction in light intensity; 1.0 for complete blocking of all light) and  $O_{\max}$  is the asymptotic maximum opacity approached when tracks are completely overlapped. Then it can be shown by numerical simulation and by experiment that the incident particle fluence is, to very good approximation, proportional to  $-O_{\max} \log_e(1.0 - O/O_{\max})$  for our data and in the fluence range considered here. Results may be different for other scan methods and more extreme fluences.