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Massachusetts Institute of Technology

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A compact proton spectrometer for measurement of the absolute DD proton spectrum from which yield and ρR are determined in thin-shell inertial-confinement-fusion implosions

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A compact proton spectrometer for measurement of the absolute DD proton spectrum from which yield and ρR are determined in thin-shell inertial-confinement-fusion implosions

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(Dated: 5 June 2014)

A compact, step range filter (SRF) proton spectrometer has been developed for measurement of the absolute DD proton spectrum, from which yield yield and areal density (ρR) are inferred for deuterium-filled thin-shell inertial confinement fusion implosions. This spectrometer, which is based on tantalum step-range filters, is sensitive to protons in the energy range 1-9 MeV and can be used to measure proton spectra at mean energies of ∼1-3 MeV. It has been developed and implemented using a linear accelerator and applied to experiments at the OMEGA laser facility and the National Ignition Facility (NIF). Modeling of the proton slowing in the filters is necessary to construct the spectrum, and the yield and energy uncertainties are ±10% in yield and ±120 keV, respectively. This spectrometer can be used for *in situ* calibration of DD-neutron yield diagnostics at the NIF.

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I. INTRODUCTION

Charged-particle spectroscopy is a powerful tool for diagosing fusion yield (Y), areal density (ρR), and ion temperature (T_i) in inertial confinement fusion (ICF) implosions.[1–4] Several diagnostic techniques have been used, including magnet-based spectrometers[1,5,6] and ranging filters,[7] with detection substrates consisting of image plates[8] or the solid-state nuclear track detector CR-39.[7]

Though the existing suite of charged-particle spectrometers is able to detect protons over a wide range of energies, from ∼0.1 to ∼30 MeV, and at a variety of incident particle fluences,[9] there are limitations to their usage that render them unavailable for certain applications. In particular, the charged particle spectrometers (CPS)[5,7] operated at the OMEGA laser facility[10] are positioned at fixed locations and are limited to proton yields above 10^8. The wedge range filter (WRF) proton spectrometers[7,11] are compact and portable, and can be fielded simultaneously at multiple positions around implosions at OMEGA and the National Ignition Facility (NIF),[12] but their energy range for proton detection is limited to 4-20 MeV. The operating parameters of existing proton spectrometers used at OMEGA and NIF, in comparison to the step range filter (SRF) proton spectrometer presented in this work, are summarized in Table I.

The SRF combines the ease-of-use advantages of the WRFs with the ability to measure proton spectra at energies as low as 1 MeV. Using steps of thin tantalum foils in front of a piece of CR-39, protons in the range of 1-9 MeV can be detected. For low-energy (∼1-3 MeV) protons produced via the DD reaction,

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}(1.01\ \mathrm{MeV}) + \mathrm{p}(3.02\ \mathrm{MeV}), \tag{1}$$

the SRF can be used to measure the energy downshift of the proton spectrum, from which the total ρR is inferred. This detector is intended to diagnose thin-shell, deuterium-filled (D_2 or D^3He) implosions with a ρR less than 30 mg/cm^2, at which point the protons are ranged out. In addition to having utility in physics studies of shock-driven implosions,[13] these proton detectors can be used for an *in situ* calibration of DD-neutron detectors on OMEGA or NIF,[14] using a technique described by Waugh *et al.*[15]

This paper is organized as follows: Section II discusses the SRF detector design and principles of spectral measurement; Section III presents initial data obtained using a linear accelerator[16] and on the OMEGA and NIF laser facilities; Section IV discusses analysis uncertainties; and

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Spectrometer	Facility	Location (Positions)	Energy Range	Yield Range
Charged-Particle Spectrometers (CPS)	OMEGA	Fixed (2)	0.1-30 MeV	$\sim10^{8}$-10^{13}
Wedge Range Filter (WRF)	OMEGA	Portable ($\sim$10)	4-20 MeV	$\sim10^{6}$-10^{11}
	NIF	Portable ($\sim$8)	4-20 MeV	$\sim10^{7}$-10^{12}
Step Range Filter (SRF)	OMEGA	Portable ($\sim$10)	1-3 MeV	$\sim10^{6}$-10^{11}
	NIF	Portable ($\sim$8)	1-3 MeV	$\sim10^{7}$-10^{12}

TABLE I. Operating parameters for the charged particle spectrometers (CPS),[5,7] wedge range filter (WRF) proton spectrometers,[7,11] and the new step range filter (SRF) proton spectrometer. CPS has a wide energy range, but is limited to two fixed positions on OMEGA. The WRFs are portable, but are limited to proton energies above 4 MeV. The SRF combines the portability of the WRF with a lower energy range. It should be noted that although the current SRF is limited to proton spectral measurements in the range of $\sim$1-3 MeV, it is capable of detecting protons up to $\sim$9 MeV.

Section V presents possible applications of this detector and concluding remarks.

II. DESIGN AND ANALYSIS PRINCIPLES

The SRF detector, designed to fit into a WRF spectrometer casing, consists of a thick aluminum frame (background plate), to which are adhered steps of thin tantalum filters, followed by a piece of CR-39. Photographs of a sample SRF setup and a cartoon front view of the foils, as seen from an implosion, are shown in Figure 1. Two separate designs have been implemented to make spectral measurements at slightly different energy ranges: a thicker set of foils, with quadrants covered by nominally 10, 14, 19, and 23 μm of tantalum, and a thinner set of foils, with quadrants covered by nominally 5, 10, 15, and 20 μm of tantalum. These particular filters were chosen to optimize measurement of DD protons in the energy range $\sim$1-3 MeV. The SRF is conceptually similar to the wedge range filter (WRF) proton spectrometers,[7,11,17] which use a continuous ramp, rather than discrete steps of different thicknesses. In each design, the aluminum background plate is 3180 μm thick to fully stop protons up to 25 MeV and to provide a region for characterization of intrinsic background in the CR-39.[18]

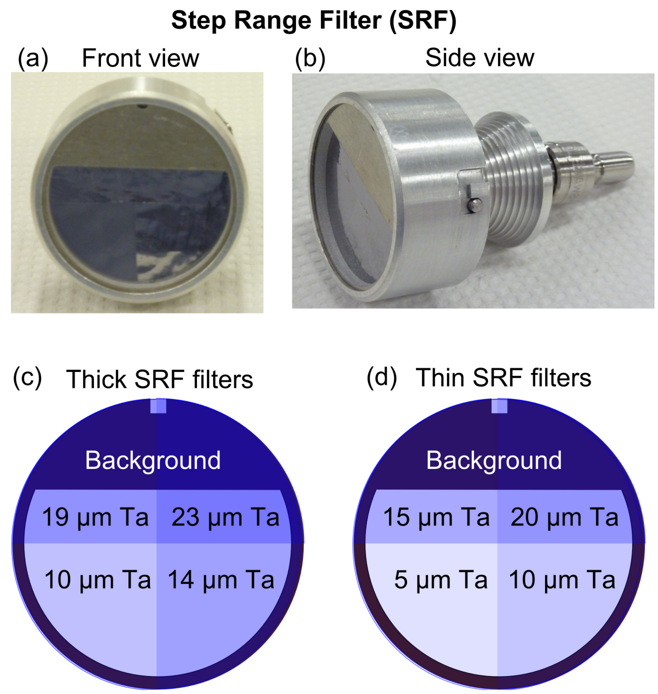

FIG. 1. (Color online) (a) Front and (b) side view of a representative step range filter (SRF) setup. Two different configurations, the (c) thick and (d) thin SRF, have been developed. The thickness of the different tantanlum filters is indicated. The aluminum background plate, 3180 μm thick, covers the upper $\sim$1/3 of the module and provides a background region on the CR-39 behind the filter stack.

The proton signal measured behind the four step filters is used to infer the total proton yield and to construct a spectrum based on modeling of the energy ranging through each Ta foil. Consider an example using the thick detector package, with an incident Gaussian proton spectrum at a peak energy of $E_0 = 2.5$ MeV and a spectral width of $\sigma = 0.25$ MeV, representative of a downshifted DD-proton spectrum. Figure 2 shows this incident spectrum (black) and the resulting spectra (red) after ranging through the different Ta filters. The SRIM stopping power tables[19] were used for these calculations, as well as a zeroth order treatment of energy straggling, which further broadens the spectrum. 100% of the protons pass through the 10-μm Ta foil above the $\sim$100 keV detection cutoff.[7] 99% are detected by the CR-39 behind the 14-μm-thick foil. The 19-μm foil permits 57% of the protons to be detected, while the 23-μm foil permits only 7% of the protons. The number of protons detected per cm^2 behind each filter, S_{10}, S_{14}, S_{19}, and S_{23}, are used to constrain the three parameters describing a Gaussian spectrum – the total yield Y, mean energy E_0, and the spectral width σ. Thus, in contrast to the WRF, which uses information about the number and diameter of proton tracks behind a filter with a continuous range of thicknesses, the SRF infers properties of the proton spectrum simply from the number of proton tracks behind discrete filters of different thicknesses. This analysis principle using four filters applies for any 3-parameter model spectrum, though for simplicity, the interpretation and discussion of the SRF results herein assume a Gaussian spectrum. For DD-protons around ∼1-3 MeV, affected by a small energy downshift, the assumption of a Gaussian spectrum is usually valid.

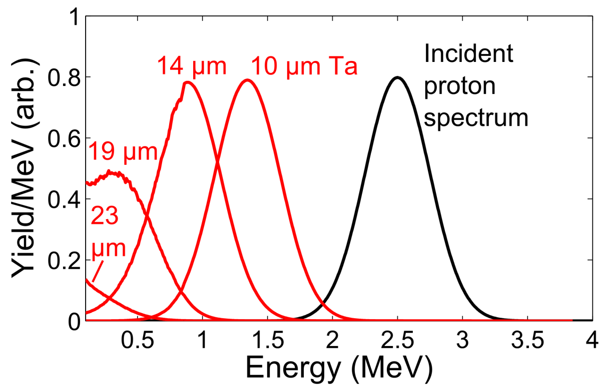

FIG. 2. (Color online) Simulated proton spectra behind 10 μm, 14 μm, 19 μm, and 23 μm Ta filters (red curves). The black curve represents the incident proton spectrum, with an average energy of 2.5 MeV and a Gaussian σ of 0.25 MeV. The CR-39 detection cutoff energy is 0.1 MeV.

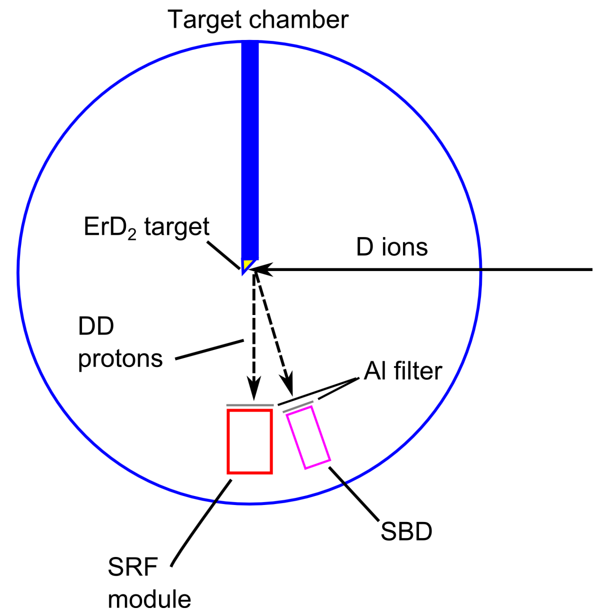

FIG. 3. (Color online) Diagram of experimental setup on the Linear Electrostatic Ion Accelerator (LEIA). A deuteron beam incident on a ErD_2 target generates DD protons, which are detected by both a surface barrier detector (SBD) and the SRF. Aluminum filters are used sometimes to range down DD protons to lower energies, as discussed in the text.

III. RESULTS

The SRF proton spectrometer has been tested on the Linear Electrostatic Ion Accelerator (LEIA)[16] and used to diagnose thin-shell D_2 and D^3He-filled implosions at OMEGA and the NIF.

A. Demonstration of the SRF Principle Using LEIA

Initial testing of the SRF was conducted on LEIA, as depicted schematically in Figure 3.[16] LEIA generates a beam of deuterons at energies up to 150 keV, which impinges on an ErD_2 target. The resulting DD fusion reactions (Equation 1) produce a spectrum of protons around 3.0 MeV, which are detected by the SRF and by a surface barrier detector (SBD) that records the energy and number of individual particles. Having an independent measurement of the DD-p energy[20] and yield allows for careful verification and uncertainty assessment of the SRF measurements.

Experiments on LEIA demonstrate the sensitivity of the SRF to proton spectra of different average energies. Figure 4 shows the resulting signal based on the proton fluence transmitted through each filter for a variety of incident proton spectra, ranging from $E_0 = 3.04$ MeV to $E_0 = 1.80$ MeV. The lower proton energies, measured by the SBD, are achieved by placing an additional filter in front of the SRF to range down DD protons that are born at 3.04 MeV.

At $E_0 = 3.04$ MeV (no additional filtering), nearly all protons pass through each filter and are detected on the CR-39. Only 5% fewer protons are detected behind the 19-μm and 23-μm filters than behind the 10-μm and 14-μm filters, though this measured loss of protons is only slightly outside of measurement uncertainty. Protons at the low-energy tail of the spectrum are ranged out in the thicker filters.

At $E_0 = 2.13$ MeV (∼40 additional μm Al filtering), all protons are ranged out by the 23-μm filter, while 98% of protons are ranged out in the 19-μm filter. The 14-μm filter permits 98% of the protons, within measurement uncertainty of 100%, while the 10-μm filter transmits 100% of the protons.

At $E_0 = 1.92$ MeV (∼45 μm additional Al filtering), no protons are detected behind the 23-μm or 19-μm filters, 88% of protons are detected behind the 14-μm filter, and 100% of the protons are detected behind the 10-μm filter.

The data using 1.80-MeV protons (∼50 additional μm Al filtering) further illustrates the effects of ranging, as only 71% of protons are detected behind the 14-μm filter and 100% of the protons are detected behind the 10-μm filter. For these fairly narrow spectra, σ∼0.10-0.13 MeV as measured by the SBD, the ranging out of part of the proton spectrum is observed behind only a single filter at a time. As at most one filter transmits a non-zero, non-unity fraction of the protons, the relative signal behind each filter is a sensitive measurement of the average energy of the proton spectrum.

These data have been analyzed using the SRF analysis technique (inferring the incident proton spectra based on the measured signal ratios) to compare to the known, SBD-measured spectral parameters. By contrasting the SBD spectral measurements to the SRF data, it is possible to estimate the uncertainties in the SRF-determined incident proton energy. A summary of the SRF-inferred spectral quantities and measured proton signals, and actual, SBD-measured spectral quantities, is presented in Table II. Given an incident proton mean energy and spectral width, a model of proton ranging[19] through each of the SRF filters produces modeled proton spectra and modeled proton signal behind each filter. The model used to analyze the LEIA data includes spectral dispersion and a zeroth order treatment of energy straggling.

The SRF data taken on LEIA show that the analysis captures the incident proton energy as measured by the SBD to within 150 keV, and to within 50 keV at energies of 2-3 MeV. It is shown in Section IV that this ∼100 keV error in the SRF energy measurement is roughly consistent with the energy uncertainty determined from uncertainty inherent in the modeling. Some of the uncertainty in the SRF-inferred energy based on the signal ratios stems from the degeneracy between E_0 and σ when matching one signal ratio. For example, in the 1.92 MeV experiment, it is only necessary to match one relative signal ratio (S_{14}/S_{10}) with two incident spectral parameters (E_0 and σ). The ranging model is able to produce $S_{14}/S_{10} = 0.88$ for several combinations of (E_0,σ) centered around (2.04, 0.12) MeV, within ±0.04 MeV for both E_0 and σ. This degeneracy issue is illustrated in Figure 5. It is a particular concern for inferring narrow spectra, as discussed further in Section IV.

Additionally, it is inferred from the spectral modeling that in these experiments, all protons are detected behind the 10-μm Ta filter, which means that the yield of the incident protons is simply that inferred behind the 10-μm Ta filter. Even though only one ratio is used and there is some degeneracy between E_0 and σ, the range of possible solutions is constrained by the fact that none of them allow for any fraction of the spectrum to be ranged out in the 10-μm Ta filter. For broader spectra, often observed at OMEGA and, especially, in NIF implosions, there can be multiple filters that allow through a non-zero, non-unity fraction of protons. Under these conditions, the inferred proton energy and linewidth are simultaneously constrained by multiple signal ratios. For a sufficiently low incident proton mean energy or sufficiently broad incident spectrum, a fraction of the proton spectrum may be ranged out even in the thinnest (e.g. 10-μm) Ta filter and modeling is necessary to infer the incident proton yield.

B. Use on OMEGA and NIF Implosions

The SRF was also used to diagnose thin-glass-shell ICF implosions at OMEGA and the NIF. Three experiments at OMEGA used ∼850-μm diameter, ∼2.3-μm-

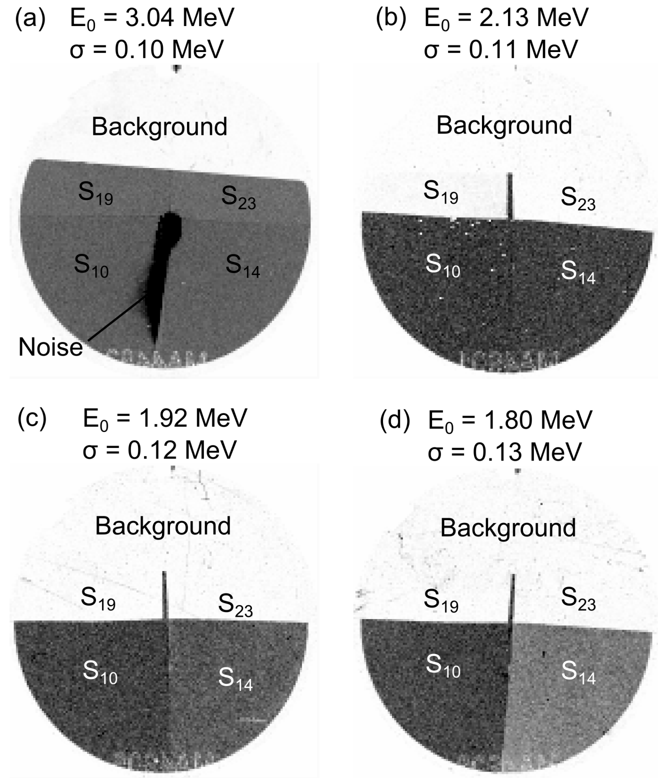

FIG. 4. SRF-measured DD-proton signal in LEIA experiments at incident mean proton energies of (a) 3.04 MeV, (b) 2.13 MeV, (c) 1.92 MeV, (d) 1.80 MeV, as determined by the SBD. Darker signifies a greater proton fluence. As the proton energy decreases, the relative signal between each window changes: S_{14}/S_{10} decreases as a larger fraction of the protons is ranged out in the 14-μm Ta filter. The relative signal ratios are presented in Table II.

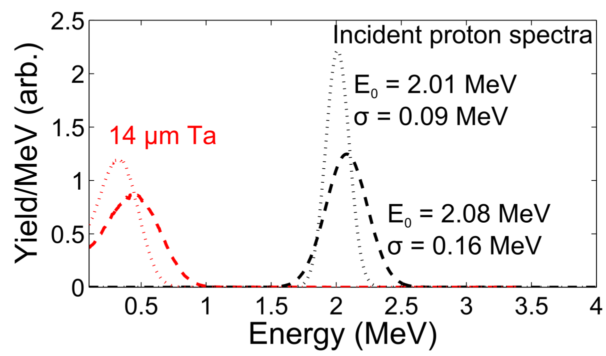

FIG. 5. (Color online) Simulated proton spectra incident on the SRF (black) and transmitted through the 14 μm Ta filter (red). For both a higher-energy, broader spectrum (dashed, $E_0 = 2.08$ MeV, $\sigma = 0.16$ MeV) and a lower-energy, narrower spectrum (dotted, $E_0 = 2.01$ MeV, $\sigma = 0.09$ MeV), 88% of the protons are transmitted through the 14 μm Ta filter. Thus, there is a degeneracy in inferring both E_0 and σ from one relative signal ratio (S_{14}/S_{10}).

SRF Measured Proton Signal Ratios			SRF E_0	SRF σ	SBD E_0	SBD σ
S_{14}/S_{10}	S_{19}/S_{10}	S_{23}/S_{10}	(MeV)	(MeV)	(MeV)	(MeV)
0.99	0.95	0.94	3.10±0.05	0.10±0.03	3.04	0.10
0.98	0.02	0	2.13±0.03	0.11±0.02	2.13	0.11
0.88	0	0	2.04±0.04	0.12±0.03	1.92	0.12
0.71	0	0	1.97±0.03	0.13±0.05	1.80	0.13

TABLE II. Measured SRF ratios of proton signal behind each of the four filters and the SRF-inferred average energy and spectral width based on modeling of spectral ranging through the different filters in LEIA experiments. The SBD-measured average energy and spectral width are shown for comparison. The difference between the SBD and SRF energy measurement helps identify uncertainties in the SRF analysis. Uncertainty in the SRF-inferred E_0 and σ represents degeneracy between those two quantities, as the two fitting parameters need to match only one proton signal ratio (the others being either 0 or ∼1 and, therefore, not highly sensitive to the incident proton energy). The overall difference between the SBD-measured E_0 and the SRF-inferred E_0 characterizes uncertainty in the SRF measurement, which is ∼100 keV. The uncertainty estimates are discussed in more detail in Section IV.

thick SiO_2 shells filled with ∼15 atm D^3He gas, imploded by 13.8-15.8 kJ laser energy in a ∼0.6 ns laser pulse. These implosions generated 2-3$\times10^{10}$ DD protons with an average energy of 3.1 MeV, which were detected by the "thin" SRF configuration at a distance of 175 cm from the implosion. At this position, the fluence was 5-8$\times10^4$ protons per cm^2 at the SRF spectrometer. On these implosions, and in general, 14.7-MeV D^3He protons were not detected by the SRF, as they pass through the CR-39 at an energy above the upper limit for proton detection.

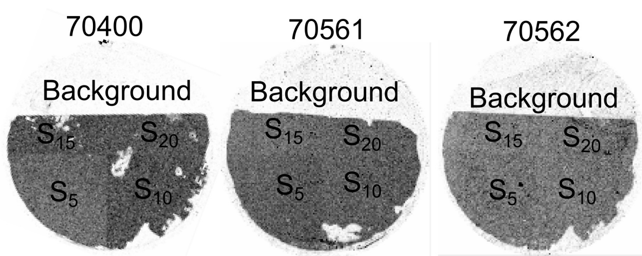

FIG. 6. DD-proton signal measured using the "thin" SRF (5, 10, 15, 20-μm Ta filters) on three D^3He-filled thin-glass-shell implosions on OMEGA (shots 70400, 70561, 70562). Dark signifies a greater proton fluence. In each experiment, the proton spectrum exiting the implosion has a mean energy ∼3.1 MeV, energetic enough that the entire spectrum is transmitted through each filter. The 5-μm Ta filter also transmits D^3He-α particles, which on shot 70400 produced significant track overlap[21] and loss of ∼20% of the proton signal.

DD-proton signal images obtained on three implosions on OMEGA, shots 70400, 70561, and 70562, are shown in Figure 6. All three images show a near-uniform proton signal behind the four different filters, which were made of 5 μm, 10 μm, 15 μm, and 20 μm thick Ta. On shot 70400, the signal behind the 5-μm Ta filter shows a reduced proton signal as a result of track overlap,[21] between D^3He-α and the DD protons. On the two subsequent shots, 70561 and 70562, the data were processed in such a fashion that track overlap behind the 5-μm Ta filter was insignificant. The fact that a nearly identical fluence was observed behind each filter suggests that no significant part of the proton spectrum was ranged out in any of the filters. The incident proton mean energy and spectral width can therefore be constrained to those solutions that permit 100% of protons through the 20-μm Ta filter. Furthermore, the determination of the proton yield is straightforward, and can be computed entirely based on the measured proton signal behind any of the filters. For example, on shot 70400, the proton fluence behind the 10-μm Ta filter fluence was $S_{10} = 6.63\times10^4/\text{cm}^2$. With the detector at a distance of 175 cm from the implosion, the proton yield inferred behind the 10-μm Ta filter is therefore $Y_{10} = S_{10}[4\pi(175)^2] = 2.55\times10^{10}$, which is in reasonable agreement with a separate DD-proton yield measurement of 2.71$\times10^{10}$ (see Table III).

The inferred proton yields, mean proton energy, and linewidth are summarized in Table III. The results are compared to measurements obtained on the same shots using the charged-particle spectrometers (CPS).[5,7] The CPS measurements are averages from two different spectrometers, CPS1 and CPS2, and as shown in Table III, the SRF-determined mean energy and linewidth agree with the CPS measurements. Differences in observed yield between different lines of sight may be due to electric and/or magnetic fields around the implosion that produce spatial anisotropies in charged fusion product fluence.[22] The CPS-measured DD-proton spectrum on shot O70561 was used as the incident spectrum on the SRF, and the spectrum behind each filter is shown in Figure 7. For the incident mean proton energy of $E_0 =$ 3.10 MeV and spectral width $\sigma = 0.13$ MeV, none of the protons are ranged out by any of the filters, as concluded from the SRF data.

The "thick" SRF configuration was used to measure the DD-proton spectrum from a D_2-filled, thin-glass-shell implosion at the NIF. The experiment (shot N130129) used a 4.6-μm-thick, 1533-μm diameter SiO_2 capsule filled with 10 atm D_2 gas, which was driven by 51 kJ laser energy in a ∼1.4 ns pulse in the polar-direct-drive[23,24] configuration. A DD(-neutron) yield of

OMEGA Shot	SRF Measured Proton Yields Y_5	Y_{10}	Y_{15}	Y_{20}	SRF E_0 (MeV)	SRF σ (MeV)	CPS Yield	CPS E_0 (MeV)	CPS σ (MeV)
70400	2.05×10^{10}	2.55×10^{10}	2.45×10^{10}	2.52×10^{10}	>2.84	<0.15	2.71×10^{10}	3.18	0.14
70561	2.74×10^{10}	3.01×10^{10}	2.61×10^{10}	2.89×10^{10}	>2.84	<0.15	3.06×10^{10}	3.10	0.13
70562	1.91×10^{10}	1.82×10^{10}	1.77×10^{10}	1.84×10^{10}	>2.84	<0.15	2.73×10^{10}	3.14	0.13

TABLE III. SRF- and CPS-measured DD-proton yield, mean energy, and spectral width for three D^3He thin-glass-shell implosions at OMEGA. The SRF-inferred E_0 and σ are bounds, based on a combination of energy and spectral width at which at least 95% of the proton spectrum is transmitted through the 20-μm Ta filter. Though the energy lower bound is fairly rigid, if the proton spectrum had a significantly higher energy, it could also permit a wider upper-limit on the spectral width.

Detector Position	SRF Measured Proton Yields Y_{10}	Y_{14}	Y_{19}	Y_{23}	SRF Signal Ratios S_{14}/S_{10}	S_{19}/S_{10}	S_{23}/S_{10}	SRF Inferred Yield	E_0 (MeV)	σ (MeV)
Position 1	1.78×10^{11}	1.22×10^{11}	2.42×10^{10}	2.85×10^{9}	0.69	0.14	0.016			
Position 2	2.02×10^{11}	1.49×10^{11}	2.52×10^{10}	2.34×10^{9}	0.74	0.13	0.012			
Position 4	2.17×10^{11}	1.53×10^{11}	2.98×10^{10}	3.18×10^{9}	0.71	0.14	0.015			
Average	1.99×10^{11}	1.41×10^{11}	2.64×10^{10}	2.79×10^{9}	0.71	0.13	0.014	2.07×10^{11}	2.05	0.34

TABLE IV. SRF-measured proton yields through each of the 10-μm, 14-μm, 19-μm, and 23-μm Ta filters, and ratios of proton signal behind each of the four windows, on NIF shot N130129. The average values are used to infer the incident DD-proton yield, mean energy, and spectral width (see Figure 9).

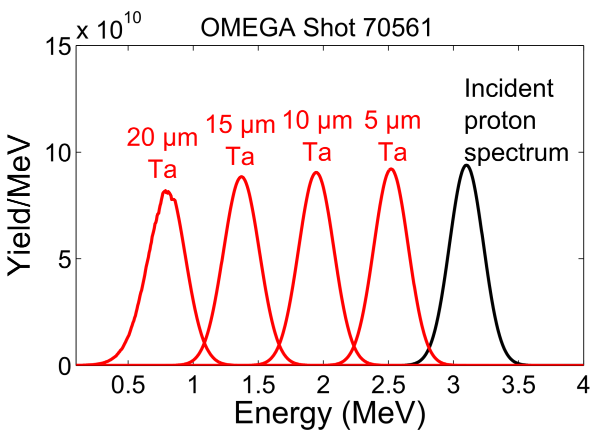

FIG. 7. (Color online) CPS-measured DD-proton spectrum from OMEGA shot 70561, transmitted through each of the four filters of the "thin" SRF. The incident spectrum has a mean proton energy of $E_0 = 3.10$ MeV, with a spectral width of $\sigma = 0.13$ MeV. The resulting proton spectra (red) ranged through the 5 μm, 10 μm, 15 μm, and 20 μm Ta (thick SRF filters) are shown. 100% of the protons are transmitted through every filter, as demonstrated in the SRF measurement.

FIG. 8. DD-proton signal obtained at three different detector positions using the "thick" SRF (10, 14, 19, 23-μm Ta filters) on NIF direct-drive D_2-filled thin-glass shell shot N130129. Dark signifies a greater proton fluence. A similar absolute fluence level and ratio of proton signals is observed at each detector. The gradation in fluence across the different windows, with a finite fraction of the proton spectrum permitted behind multiple windows, indicates a fairly broad proton spectrum.

2.5×10^{11} was measured by neutron time-of-flight (nTOF) detectors[25,26] and indium activation.[14] As this implosion had a total areal density of ~18 mg/cm^2, as inferred from the downshift of secondary proton spectra measured by WRF spectrometers,[3,7] the DD protons escaped the implosion and were detected by the SRF.

Three "thick" SRFs were fielded in close proximity to each other at a distance of 375 cm from the implosion; the proton fluence images are shown in Figure 8 and the raw proton yield measurements behind each filter and signal ratios are summarized in Table IV. Each SRF shows a gradually decreasing fluence of protons with increasing filter thickness. On average, the ratio of proton signal behind the 14-μm filter to that behind the 10-μm filter is $S_{14}/S_{10} = 0.71$, while $S_{19}/S_{10} = 0.13$ and $S_{23}/S_{10} = 0.014$. This reduction in fluence across the different filters, in contrast to sharp cutoffs in fluence demonstrated in tests at the LEIA accelerator, indicates a fairly broad DD-proton spectrum. Analysis of this data and the determination of the total proton yield, incident mean energy, and spectral width are summarized at the bottom of Table IV, with the resulting spectra shown in Figure 9.

Because three spectral parameters (total yield, mean energy, and spectral width) are fit by four measured quantities, the inferred spectrum is constrained. Based on the relative signal ratios of $S_{14}/S_{10} = 0.71$, $S_{19}/S_{10} = 0.13$ and $S_{23}/S_{10} = 0.014$, a mean incident proton energy of $E_0 = 2.05$ MeV and a spectral width of $\sigma = 0.34$ MeV are inferred. The resulting simulated signal ratios of $S_{14}/S_{10} = 0.71$, $S_{19}/S_{10} = 0.13$ and $S_{23}/S_{10} = 0.008$ are in good agreement with the measured values, to within uncertainties in proton signal measurement and spectral modeling. The mean proton energy in particular is well-constrained, as deviations in energy up to only 0.04 MeV are permitted before an additional deviation of 10% in the relative proton signal is produced, larger than the measured yield uncertainty. Based on the proton energy downshift in the implosion, to 2.05 MeV, from the birth DD-proton energy of 3.02 MeV, a total ρR of 13±3 mg/cm^2 is inferred, in agreement with the measured total ρR from the downshift of secondary D^{3}He protons, 18±5 mg/cm^2. Thus, the SRF proton spectrometer can be used as a ρR diagnostic on implosions with deuterium fuel and sufficiently low ρR (<30 mg/cm^2).

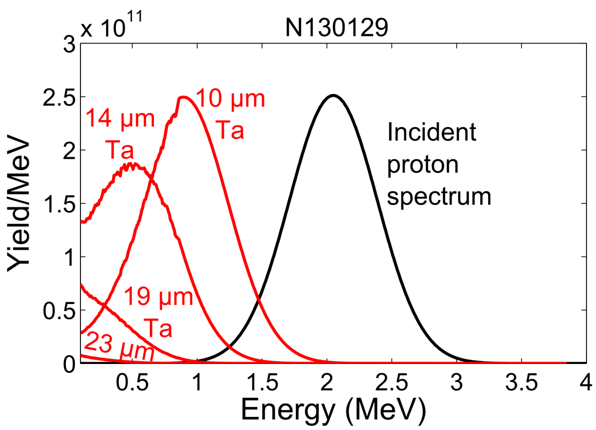

FIG. 9. (Color online) SRF-inferred DD-proton spectrum from NIF shot N130129, transmitted through each of the four filters of the "thick" SRF. The incident spectrum has a mean proton energy of $E_0 = 2.05$ MeV, with a spectral width of $\sigma = 0.34$ MeV. The resulting proton spectra (red) ranged through each of 10 μm, 14 μm, 19 μm, and 23 μm Ta (thick SRF filters), above the CR-39 detection cutoff energy of 0.1 MeV, are shown. A decreasing fraction of the proton spectrum is transmitted through the increasingly thick filters.

IV. DISCUSSION OF APPLICABILITY AND UNCERTAINTIES

Experiments at the accelerator-based DD-p source (LEIA) and at OMEGA and the NIF demonstrate the utility of the SRF for determination of the DD proton spectrum in the energy range of ∼1-3 MeV. These data also help identify uncertainties in the inference of proton yield, the mean proton energy, and the Gaussian spectral width.

A. Yield Uncertainty

The uncertainty in the SRF-measured proton yield is largely dictated by the degree to which spectral modeling is required to infer the incident proton yield. For incident spectra where the thinnest filter comfortably transmits the entire spectrum, the yield uncertainty is limited by counting statistics in the CR-39 (typically ∼±1% for protons at a fluence of 10^4/cm^2 over the ∼cm^2 area covered by each window) and by uncertainties inherent in analysis of proton tracks in CR-39, typically ∼3-5%.[27] This condition – conservatively, greater than 99.9% of the proton spectrum transmitted through the 10-μm Ta filter for the "thick" SRF – is satisfied when, for example, E_0>1.81 MeV for σ<0.12 MeV or when E_0>2.35 MeV for σ<0.34 MeV (spectral widths chosen to span those observed on LEIA, OMEGA, and NIF). These conditions are illustrated in part in Figure 10, which shows the simulated proton transmission (or signal) through the different filters of the "thick" SRF. For the "thin" SRF, >99.9% of the proton spectrum is transmitted through the 5-μm filter when, e.g., E_0>1.23 MeV for σ<0.12 MeV or when E_0>1.90 MeV for σ<0.34 MeV. These energy ranges for 100% proton transmission through the thinnest filters are consistent with the analysis of SRF data from the LEIA and OMEGA experiments.

The N130129 data is an example of a spectrum where modeling is required to infer the incident proton yield, as a fraction of the spectrum was ranged out even in the thinnest (10-μm Ta) filter. In that case, uncertainty in the modeling itself contributes to the overall yield uncertainty. The objective of the modeling is to determine what fraction of the proton spectrum is detected and, thus, to correct for the fraction of protons that is ranged out. With a perfect understanding of the ranging process through the filters, this uncertainty would be negligible. However, uncertainty in the filter thickness[28] contributes to the uncertainty in the modeled ratio of yield through the 10-μm filter to the actual yield (Y_{10}/Y_{actual}). The actual yield is inferred based on the measured Y_{10} and the modeling-inferred Y_{actual}/Y_{10} ratio, which is constrained by the measured signal ratios S_{14}/S_{10}, S_{19}/S_{10}, and S_{23}/S_{10}. In the case of N130129, adding 1 μm to the thickness of the 10-μm filter only slightly changes the relative signal ratios (S_{14}/S_{10} from 0.71 to 0.74, versus measured 0.71; S_{19}/S_{10} from 0.13 to 0.13, versus measured 0.13; S_{23}/S_{10} from 0.008 to 0.008, versus measured 0.014), while Y_{10}/Y_{actual} decreases from 0.97 to 0.93. Similarly, removing 1 μm from the thickness of the 10-μm filter only slightly changes the relative signal ratios (S_{14}/S_{10} from 0.71 to 0.70, versus measured 0.71; S_{19}/S_{10} from 0.13 to 0.13, versus measured 0.13; S_{23}/S_{10} from 0.008 to 0.008, versus measured 0.014), while Y_{10}/Y_{actual} increases from 0.97 to 0.99. Therefore, this change to the modeling based on the bounds of measurement uncertainty of the filter thickness causes a barely-perceptible shift in the modeled signal ratios, but produces a ±4% change in the inferred yield. The uncer-

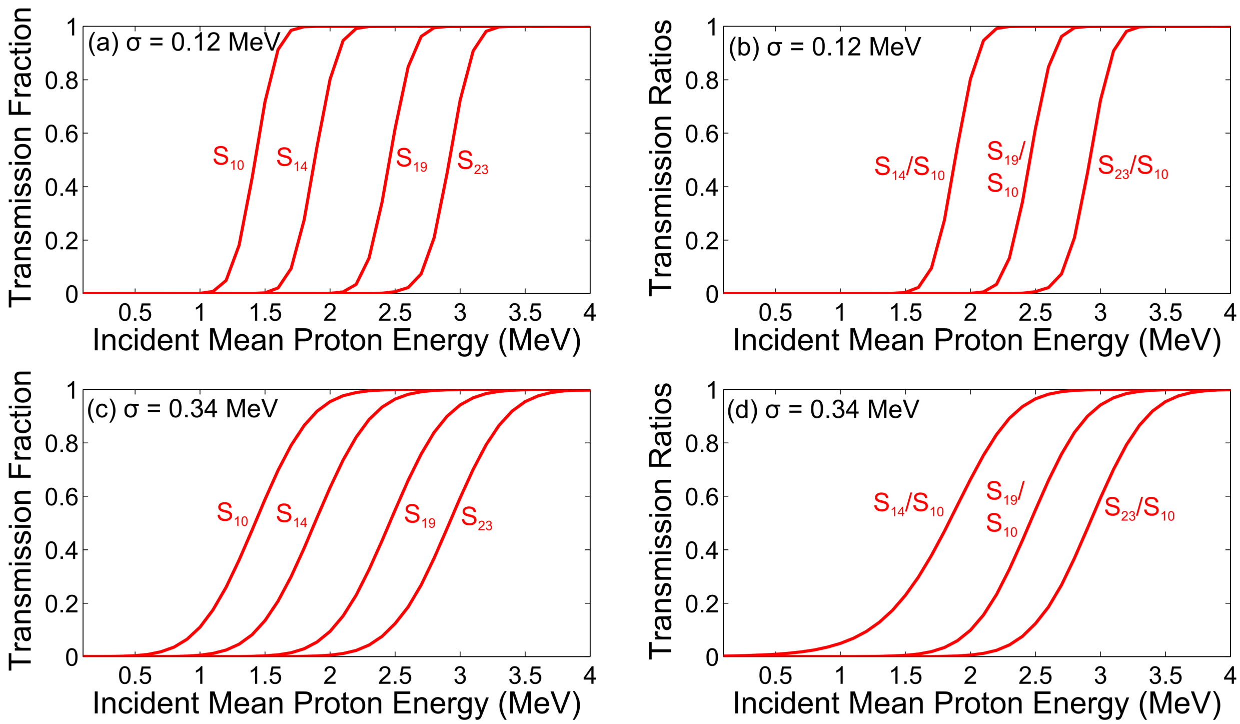

FIG. 10. (Color online) (a),(c) Fraction of protons transmitted through thick SRF filters (10 μm, 14 μm, 19 μm, and 23 μm Ta) and (b),(d) ratio of protons transmitted through the filters as a function of incident mean proton energy, for $\sigma = 0.12$ MeV (top) and $\sigma = 0.34$ MeV (bottom). A decreasing fraction of the proton spectrum is transmitted through the increasingly thick filters.

tainty in the inferred yield resulting from uncertainties in the modeling must be addressed on a case-by-case basis, but should be no greater than of order ±5-10%. This uncertainty is added in quadrature to the uncertainties in proton track counting as discussed above.

B. Energy Uncertainty

The ability to infer a mean proton energy likewise depends on the proton energy relative to the proton range in the different filters. When all protons are transmitted through the different filters (and the relative signal ratios are all 1), only a lower limit on the mean proton energy can be established, as was the case in the OMEGA data. A conservative upper limit on the energy range at which the mean energy can be determined is set by the energy at which a detectable loss of transmission can be observed through the thickest filter in the SRF, either 23 μm Ta for the current "thick" version or 20 μm Ta for the "thin" version. For purposes of this study, a detectable loss of transmission is considered to be below 97% of the protons transmitted (allowing for 3% uncertainty in the measured signal behind each filter). For the thick SRF, 97% transmission through 23 μm Ta is achieved when, e.g., $E_0 = 3.18$ MeV for $\sigma<0.12$ MeV (Figure 10a) or when $E_0 = 3.57$ MeV for $\sigma<0.34$ MeV (Figure 10c). The LEIA data shown in Figure 4a, at a mean energy of $E_0 =$ 3.04 MeV, is an example that is coming close to the limit below which a mean energy can be precisely inferred. For energies above these values, it is impossible to determine the exact mean energy. For the thin SRF, 97% transmission through 20 μm Ta is achieved when, e.g., $E_0 =$ 2.82 MeV for $\sigma<0.12$ MeV or when $E_0 = 3.23$ MeV for $\sigma<0.34$ MeV. The OMEGA data shown in Figure 6 are all above this energy limit and, thus, the most information that can be inferred is that the mean energy is >2.84 MeV (for $\sigma\lesssim0.15$ MeV). The use of thicker filters can extend the range of energies at which an accurate energy measurement can be made (beyond simply establishing a lower limit). For those spectra where only one filter transmits less than 100% of the proton spectrum, there is a degeneracy in inferring two spectral quantities (mean energy and spectral width) from only one relative signal ratio. Under these conditions, the inferred mean energy can be constrained by reasonable bounds on the spectral width (if known) or by the energy at which the second thickest filter begins to range out a detectable fraction of the spectrum.

The mean proton energy measurement is well-constrained when one or more filters transmits a fraction of the proton spectrum. As shown in Figure 10a,c, this condition is satisfied when the incident mean energy is ∼1-3 MeV. This is evident in the LEIA data shown in Figure 4b-d, where incident proton energy differences of 100-200 keV cause differences in the relative signal ratios (S_{14}/S_{10} in particular) of 10-20%, considerably larger than the uncertainty in proton track counting on the CR-39. This sensitivity is also illustrated by the slopes of the relative transmission (or signal) ratio curves in Figure 10b,d. Thus, the random uncertainty in the analysis (inferring E_0 based on the relative signal ratio) based on the ±3-5% random uncertainty in the proton signal measurement is ∼±50 keV. Allowing for up to a ±1 μm filter thickness uncertainty, the corresponding random uncertainty in the E_0 inferred from the modeling is ∼±110 keV. The total energy uncertainty is around ±120 keV,[29] of order the difference between the SBD-measured and SRF-inferred energy values as shown in Table II. This energy uncertainty is equivalent to an uncertainty of ∼±4 mg/cm^2 in a total ρR measurement based on the energy downshift of the DD-proton spectrum.

C. Linewidth Uncertainty

To simultaneously constrain both the mean proton energy and spectral width, it is necessary to have multiple windows where a measurable fraction of the incident proton spectrum has been ranged out. When the proton energy is too high and only the thickest filter transmits a fraction of the proton spectrum, there is a degeneracy between the mean energy and spectral width, as alluded to above. Under those circumstances, the relative signal ratio is much more sensitive to the mean energy than to the spectral width, resulting in a well-constrained mean energy, while the spectral width is poorly constrained. Thus, a spectral width measurement is only possible for the "thick" SRF when E_0<2.71 MeV (based on <97% of protons transmitted through the 19-μm Ta filter for σ = 0.12 MeV, see Figure 10a) or for the "thin" SRF when E_0<2.24 MeV (based on <97% of protons transmitted through the 15-μm Ta filter for σ = 0.12 MeV). The spectral width is most accurately inferred when the spectrum is broad enough (typically for σ>0.12 MeV) that there is significant overlap in energy space between the spectra ranged through different filters. This can also be understood as there being more than one window with a non-zero, non-unity fraction of the spectrum. If only one window at a time (and not the thickest filter) shows a non-zero, non-unity signal relative to the other windows, the spectral width can be constrained to $\sigma\lesssim$0.12 MeV for the present designs with ∼4-5-μm Ta filtering differences between windows. This narrow-spectrum condition was present in the LEIA data presented in Section III A. A different SRF design with more filters and less incremental filtering between windows could potentially be used to measure the linewidth of narrower spectra. A summary of the proton mean energy and spectral width bounds for SRF measurements of the proton yield, mean energy, and spectral width, for different values of the mean energy and spectral width, is presented in Table V.

When the proton spectrum is broad enough and sufficiently low in energy that signal behind multiple filters is a fraction of the number of incident protons (for example, in the N130129 data), the uncertainty in the inferred spectral width is based on the uncertainty in the relative signal ratios used to infer σ. As an illustrative example, the data from N130129 (S_{14}/S_{10} = 0.71, S_{19}/S_{10} = 0.13, S_{23}/S_{10} = 0.014) is analyzed to infer E_0 = 2.05 MeV and σ = 0.34 MeV, with modeled signal ratios of S_{14}/S_{10} = 0.71, S_{19}/S_{10} = 0.13, S_{23}/S_{10} = 0.008 (Section III B). If the modeled σ were changed to 0.37 MeV, the modeled signal ratios become S_{14}/S_{10} = 0.70, S_{19}/S_{10} = 0.15, S_{23}/S_{10} = 0.014. Conversely, for σ = 0.31 MeV, the modeled signal ratios become S_{14}/S_{10} = 0.72, S_{19}/S_{10} = 0.11, S_{23}/S_{10} = 0.005. Thus, a 0.03 MeV difference on top of σ = 0.34 MeV corresponds to a ∼15% departure for S_{19}/S_{10} and a ∼50% difference in S_{23}/S_{10}. These differences are well outside of the uncertainty of the raw proton signal measurement. Therefore, a reasonable, conservative estimate of the uncertainty in the spectral width under such conditions is ∼±50 keV. The approximate uncertainty in σ based on this kind of analysis is shown in Figure 11. The uncertainty in σ is inferred as the variation in the modeled σ that produces a ±0.03 change in any of the modeled signal ratios (S_{14}/S_{10}, S_{19}/S_{10}, and S_{23}/S_{10}). This analysis represents the maximum difference in σ that produces a non-observable (within measured signal uncertainties) change in the signal ratios. Typical uncertainty in σ over the energy range of interest is ∼±20-60 keV. Uncertainty in the filter thickness primarily translates to an uncertainty in the mean energy and does not substantially contribute to uncertainty in the inferred spectral width.

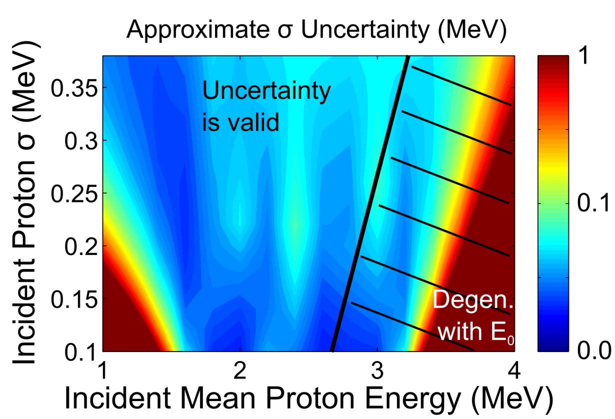

FIG. 11. (Color online) Approximate uncertainty in the inferred σ using the thick SRF as a function of incident proton mean energy and σ. This uncertainty calculation is based on the variation in the modeled σ that produces a maximum variation of ±0.03 in any of the modeled proton signal ratios (S_{14}/S_{10}, S_{19}/S_{10}, and S_{23}/S_{10}). To the right of the thick black line, there is a degeneracy between the inferred E_0 and σ, so that the linewidth cannot be uniquely inferred.

Observable	E_0 range (σ limit)	Comments on analysis
Yield	1.81<E_0<9 MeV (σ<0.12 MeV)	No modeling required
Yield	1<E_0<1.81 MeV (σ>0.12 MeV)	Inferred from modeling
Yield	2.35<E_0<9 MeV (σ<0.34 MeV)	No modeling required
Yield	1<E_0<2.35 MeV (σ>0.34 MeV)	Inferred from modeling
Mean Energy (E_0)	2.71<E_0<3.18 MeV (σ<0.12 MeV)	Measurement possible, but E_0/σ degeneracy
Mean Energy (E_0)	1<E_0<2.71 MeV (σ>0.12 MeV)	Measurement well constrained
Mean Energy (E_0)	3.10<E_0<3.57 MeV (σ<0.34 MeV)	Measurement possible, but E_0/σ degeneracy
Mean Energy (E_0)	1<E_0<3.10 MeV (σ>0.34 MeV)	Measurement well constrained
Spectral Width (σ)	1<E_0<2.71 MeV (σ>0.12 MeV)	Measurement well constrained
Spectral Width (σ)	1<E_0<3.10 MeV (σ>0.34 MeV)	Measurement well constrained

TABLE V. Summary of proton mean energy and spectral width bounds for SRF measurement of the proton yield, mean energy E_0, and spectral width σ. These are based on the "thick" SRF, with filters consisting of 10 μm, 14 μm, 19 μm, and 23 μm Ta. The energy ranges for the "thin" SRF are slightly lower, as discussed in the text.

D. Comments on Energy Range

It has been established that the SRF operates effectively as a spectrometer for proton spectra in the range ~1-3 MeV. This energy range is limited on the low end by the presence of "ablator" protons, which are accelerated to energies up to ~1 MeV by electric fields in the corona of ICF implosions for a variety of shell materials.[30,31] The yield of these ablator protons is much higher than the fusion-generated proton yields, and thus ablator ions overwhelm the DD-proton signal if not properly filtered. Based on the OMEGA (NIF) data using the thin (thick) SRF, it is determined that for the laser drive conditions in those experiments, with an intensity of $\sim 10^{15}$ ($\sim 5\times 10^{14}$) W/cm^2, the ablator protons were at low enough energies to be ranged out in the 5-μm (10-μm) Ta filter and, therefore, did not impact the detection of DD protons. If the SRF filtering were made thinner in an attempt to detect lower-energy protons, the ablator protons may be able to pass through the filters and wash out the fusion proton signal.

The energy upper-limit for SRF operation is dictated primarily by the thickest filtering. As CR-39 can detect protons at 100% efficiency up to ~8 MeV, the upper energy limit for simply detecting protons is the maximum incident energy of a proton such that, when ranged through the thickest SRF filter, it emerges on the CR-39 at an energy no greater than ~8 MeV. For the current SRF configurations, with thickest filters of 20 μm and 23 μm Ta, that energy upper limit for detecting protons and measuring a proton yield is ~9 MeV. As discussed above, this energy limit is not the same as that for spectroscopy, which relies on a differential in proton signal between different windows; for the current configurations, the upper limit for measuring the mean proton energy is ~3 MeV. In principle, both of these energy upper-limits can be increased by the use of additional or thicker filters.

V. CONCLUSIONS AND APPLICATIONS

A compact step range filter (SRF) proton spectrometer has been designed and implemented at OMEGA and the NIF for a yield, mean energy, and spectral width determination for the DD-proton spectrum in the energy range ~1-3 MeV. Unlike other low-energy proton spectrometers used on ICF facilities, the SRF is highly portable and can be fielded at multiple positions around the implosion inside the target chamber. This instrument is a lower-energy analogue of the well-established WRF proton spectrometer, which operates in the energy range of 4-20 MeV. The SRF has been tested on LEIA and in implosions at OMEGA and the NIF. These experiments have demonstrated the sensitivity of the detector response to the mean proton energy and width of the incident spectrum. For a proton spectrum with a mean energy E_0<3 MeV, a typical uncertainty in the mean energy is $\sim\pm 0.12$ MeV. For a sufficiently broad spectrum (σ>0.12 MeV) at a mean energy <2.7 MeV, the spectral width can be estimated with an uncertainty of $\sim\pm 50$ keV.

The SRF was designed for diagnosis of thin-glass-shell ICF implosions (<30 mg/cm^2) with deuterium in the fuel (either D_2 or D^3He gas), which produce DD protons at a birth energy of ~3.02 MeV. Measurements of the DD fusion yield and spectral width provide information about the ion temperature in the implosion, while the energy downshift is proportional to the areal density (up to a ρR of ~30 mg/cm^2, at which point the DD protons are ranged out). This technique can be extended to higher energy ranges through the use of thicker filtering. The SRF could be of great value at the NIF for an *in situ* calibration of DD-neutron detectors.[14,15,26] With an appropriate change in filtering, the SRF can also be applied to the detection of D^3He- or DT-α particles in the energy range of 1-4 MeV. On D^3He-filled implosions, a second piece of CR-39 placed behind the first and filtered appropriately can be used to simultaneously detect D^3He protons. The SRF can also be adapted for measurement of the ^{3}He^{3}He-proton spectrum in fundamental nuclear science experiments.

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[28] The thickness of each SRF filter is measured individually, with a conservative uncertainty of ± 1 μm.

[29] This energy uncertainty is roughly comparable to that of the WRF proton spectrometer used at a higher energy range,[7,11,17] 4-20 MeV, in contrast to the $\sim$1-3 MeV range for energy measurement using the present SRF spectrometer.

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