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ABSTRACT

The time-resolving Magnetic Recoil Spectrometer (MRSt) for the National Ignition Facility (NIF) has been identified by the US National Diagnostic Working Group as one of the transformational diagnostics that will reshape the way inertial confinement fusion (ICF) implosions are diagnosed. The MRSt will measure the time-resolved neutron spectrum of an implosion, from which the time-resolved ion temperature, areal density, and yield will be inferred. Top-level physics requirements for the MRSt were determined based on simulations of numerous ICF implosions with varying degrees of alpha heating, P2 asymmetry, and mix. Synthetic MRSt data were subsequently generated for different configurations using Monte–Carlo methods to determine its performance in relation to the requirements. The system was found to meet most requirements at current neutron yields at the NIF. This work was supported by the DOE and LLNL.

I. INTRODUCTION

Neutron spectrometry is used routinely to diagnose burn-averaged properties of inertial confinement fusion (ICF) implosions, and in particular, the areal density (ρR), ion temperature (T_i), and neutron yield (Y_n).[1] The current Magnetic Recoil Spectrometer (MRS) is a neutron spectrometer fielded on OMEGA and the National Ignition Facility (NIF) that makes these measurements.[2] MRSt is an extension of the MRS that has been identified by the US National Diagnostic Working Group as one of the transformational diagnostics that will reshape the way ICF implosions are diagnosed.[3] It is based on a deuterated plastic (CD) foil and an ion-optic system along with a time-resolving detector that will make measurements of ρR, T_i, and Y_n as functions of time.[4] This allows for measurements of time-dependent burn parameters such as $\frac{\mathrm{d}\rho R}{\mathrm{d}t}$, $\frac{\mathrm{d}T_\mathrm{i}}{\mathrm{d}t}$, burn width, burn skewness, and burn kurtosis, which can be used to probe the dynamic impact of alpha heating and various failure modes.

Critical to understanding the MRSt and its potential is determining its performance and evaluating whether it meets the current top-level physics requirements. To this end, numerous hydrodynamic simulations were used to determine top-level physics requirements. Monte Carlo simulations of the MRSt system response combined with simulated neutron spectra were then used to determine whether the system meets those requirements. This was done at many different yield levels and for several different MRSt configurations.

This paper is structured as follows: Sec. II discusses the top-level physics requirements as determined by HYDRA-simulations. Section III describes the MRSt system and its configurations. Section IV discusses the predicted MRSt performance as determined by Monte Carlo simulations and compares it to the requirements. Finally, Sec. V provides concluding remarks.

II. TOP-LEVEL PHYSICS REQUIREMENTS

Simulations of implosions with varying levels of alpha heating (yield amplification due to DT fusion cross section), P2 asymmetry, and mix width were performed to determine top-level physics requirements for the MRSt system. Each simulation generated values of $\rho R(t)$, $T_{\mathrm{i}}(t)$, and $Y_{\mathrm{n}}(t)$ for a particular level of alpha heating, P2 asymmetry, or mix. From the simulations, we examined the correlations between these evolving implosion parameters and their time derivatives and how they depend on the alpha heating, P2 asymmetry, and mix. A subset of these results is shown in Figs. 1(a) and 1(b). By looking at the sensitivity of implosion parameters of interest to the varying degrees of alpha heating, P2 asymmetry, and mix, the MRSt accuracies required to probe these effects, or the top-level physics requirements, are established. These requirements are summarized in Table I.

TABLE I. The current top-level physics requirements for the MRSt, based on the hydrodynamic simulations. Each implosion parameter, either measured at bang time (BT) or burn-integrated, must be measured with an accuracy (1σ) within these values. The requirements for $\langle T_{\mathrm{i}}\rangle$, $\langle\rho R\rangle$, and Y_{n} are based on the corresponding accuracies of MRS[5] and are defined as percentages relative to the total value.

Value	Requirement
$\frac{d\rho R}{dt}$ at BT	$\pm 60\ \mathrm{g/cm^2/100\ ps}$
$\frac{dT_{\mathrm{i}}}{dt}$ at BT	$\pm 1.9\ \mathrm{keV/100\ ps}$
Absolute BT	±10 ps
Burn width	±7 ps
Burn skewness	±0.3
Burn kurtosis	±3
$\langle\rho R\rangle$	±7%
$\langle T_{\mathrm{i}}\rangle$	±7%
Y_{n}	±5%

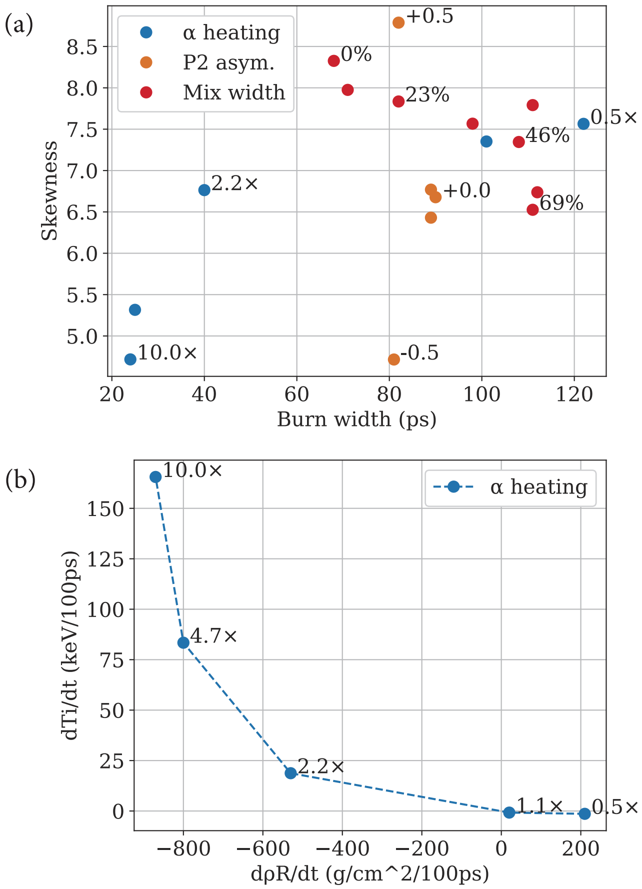

FIG. 1. (a) Burn width vs skewness trajectory of simulated ICF implosions with varying amounts of alpha heating, P2 asymmetry, or mix. The trends show that the two moments must be evaluated simultaneously to assess the impact of alpha heating and/or the different failure modes. (b) $\frac{dT_{\mathrm{i}}}{dt}$ vs $\frac{d\rho R}{dt}$ trajectory, measured at each implosion's bang time (BT). The dependency between these two parameters is totally dictated by alpha heating when alpha heating significantly enhances the yield, meaning that measuring these two parameters will make MRSt especially useful as an alpha heating diagnostic.

III. MRSt CONCEPTUAL DESIGN AND CONFIGURATIONS

The conceptual design of the MRSt is based on the combination of the MRS technique[2] and the Pulse Dilation Drift Tube (PDDT) technique.[6] A small fraction of the neutrons emitted from an implosion interact with a CD foil and generate recoil deuterons. Forward-scattered deuterons are selected by an aperture positioned in front of the magnetic ion-optical system about 600 cm away. The deuterons are focused and energy-dispersed onto a focal plane.[2] Unlike the

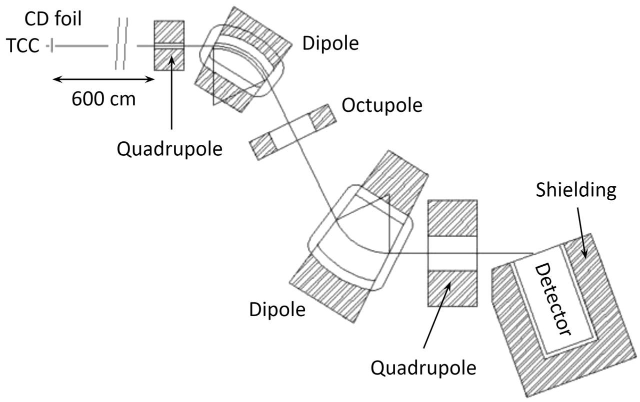

FIG. 2. The conceptual design of the MRSt system. A small fraction of the neutrons emitted from an implosion interact with the CD foil and generate recoil deuterons. Forward-scattered deuterons are selected by an aperture positioned in front of the magnetic ion-optical system about 600 cm away. The deuterons are focused and energy-dispersed onto a CsI photocathode, positioned at the focal plane of the spectrometer, where they are converted to secondary electrons. Due to the time skew of the deuterons at different energies along the focal plane, a pulse dilation drift tube (PDDT) detector will unskew and dilate the pulse of secondary electrons. At the back end of the PDDT, a series of anodes will be used to record a signal histogram.[6] The system will be sufficiently shielded to reduce the background levels to 2.8% of the down-scattered neutron signal level.[8–10]

TABLE II. MRSt configurations and their efficiencies and resolutions at a neutron energy of 14 MeV.

	High-efficiency	Medium-efficiency	Low-efficiency
Foil radius (μm)	400	300	100
Foil thickness (μm)	100	50	25
Aperture width (mm)	5	4	2
Time res. (ps)	100	75	40
Energy res. (keV)	780	390	190
Efficiency	4.90×10^{-12}	1.10×10^{-12}	3.10×10^{-14}

MRS, the MRSt will use multiple magnetic dipoles and quadrupoles to obtain excellent time resolution and significantly better energy resolution. Furthermore, rather than using CR-39 as the detector, the MRSt will use a CsI cathode and PDDT detector to unskew, dilate, and resolve the signal in time.[6,7] The design of the MRSt is illustrated schematically in Fig. 2.

The MRSt system will be tuned differently to obtain different resolutions and efficiencies depending on application and expected yield. The width of the aperture, and the radius and thickness of the foil, will be adjustable to modify efficiency and resolution. For high expected yield, foil will also be changed from CD to CH such that protons are scattered rather than deuterons to obtain better time resolution by a factor of two at the cost of higher background levels. Three MRSt configurations have been identified: a high-efficiency configuration for maximizing signal on low-yield implosions, a low-efficiency configuration to improve resolution on high-yield implosions, and a medium-efficiency configuration as a compromise between these settings. These configurations and their figures of merit are given in Table II.

IV. SIMULATION OF THE MRSt PERFORMANCE

Monte Carlo simulations were used to determine the MRSt performance. These simulations used analytically generated time-resolved neutron spectra, folded by the MRSt response function to obtain a time-resolved deuteron spectrum at the focal plane. The total signal level was set by the efficiency of the MRSt configuration. Using the same calculated response function and analytic model, a time-resolved neutron spectrum was inferred from the time-resolved deuteron spectrum, from which $\rho R(t)$, $T_{\mathrm{i}}(t)$, and $Y_{\mathrm{n}}(t)$ were inferred. A comparison to the original neutron spectrum was then made to check the fidelity of the inferred neutron spectrum. This type of calculation was repeated for different implosions where the original spectrum was scaled by neutron yield. For simplicity, the shape of the spectrum was not varied with yield. Through this approach, the MRSt performance was determined for different total neutron yields and compared to the current top-level physics requirements, as shown in Table III for the three configurations.

The results for the high-efficiency configuration over three orders of magnitude are shown in Fig. 3. The performance of all three configurations is summarized in Table III. At yields of 1×10^{16} and higher, the high-efficiency configuration fulfills all top-level physics requirements except $\frac{\mathrm{d}\rho R}{\mathrm{d}t}$. It also meets the $\frac{\mathrm{d}\rho R}{\mathrm{d}t}$ requirement above yields of about 1×10^{17} The medium-efficiency configuration performs similarly but produces more accurate bang time measurements and less accurate $\frac{\mathrm{d}\rho R}{\mathrm{d}t}$ and burn width measurements. At yields of 5×10^{16} and higher, the low-efficiency configuration fulfills all requirements except $\frac{\mathrm{d}\rho R}{\mathrm{d}t}$, and $\langle \rho R \rangle$.

TABLE III. Uncertainties in the implosion parameters inferred from the synthetic MRSt data, calculated as the standard deviation of measurements of each parameter at the stated reference yield. The MRSt in high-efficiency mode meets most requirements at a neutron yield of about 1×10^{16}; in medium-efficiency mode at a neutron yield of about 1×10^{16}; and in low-efficiency mode at a neutron yield of about 5×10^{16}.

Quantity (units)	Required	High-efficiency	Medium-efficiency	Low-efficiency
Reference Y_{n}		1×10^{16}	1×10^{16}	5×10^{16}
$\frac{\mathrm{d}\rho R}{\mathrm{d}t}$ at BT (g/cm^2/100 ps)	60	210	220	320
$\frac{\mathrm{d}T_{\mathrm{i}}}{\mathrm{d}t}$ at BT (keV/100 ps)	1.9	1.3	1.5	1.5
Absolute BT (ps)	10	3.2	2.3	2.5
Burn width (ps)	7	1.3	1.6	2.3
Burn skewness	0.3	0.22	0.18	0.21
Burn kurtosis	3	0.8	1.0	1.5
$\langle \rho R \rangle$ (% of total)	7	5	5	11
$\langle T_{\mathrm{i}} \rangle$ (% of total)	7	2.4	2.4	4.4
Y_{n} (% of total)	5	0.7	1.0	2.4

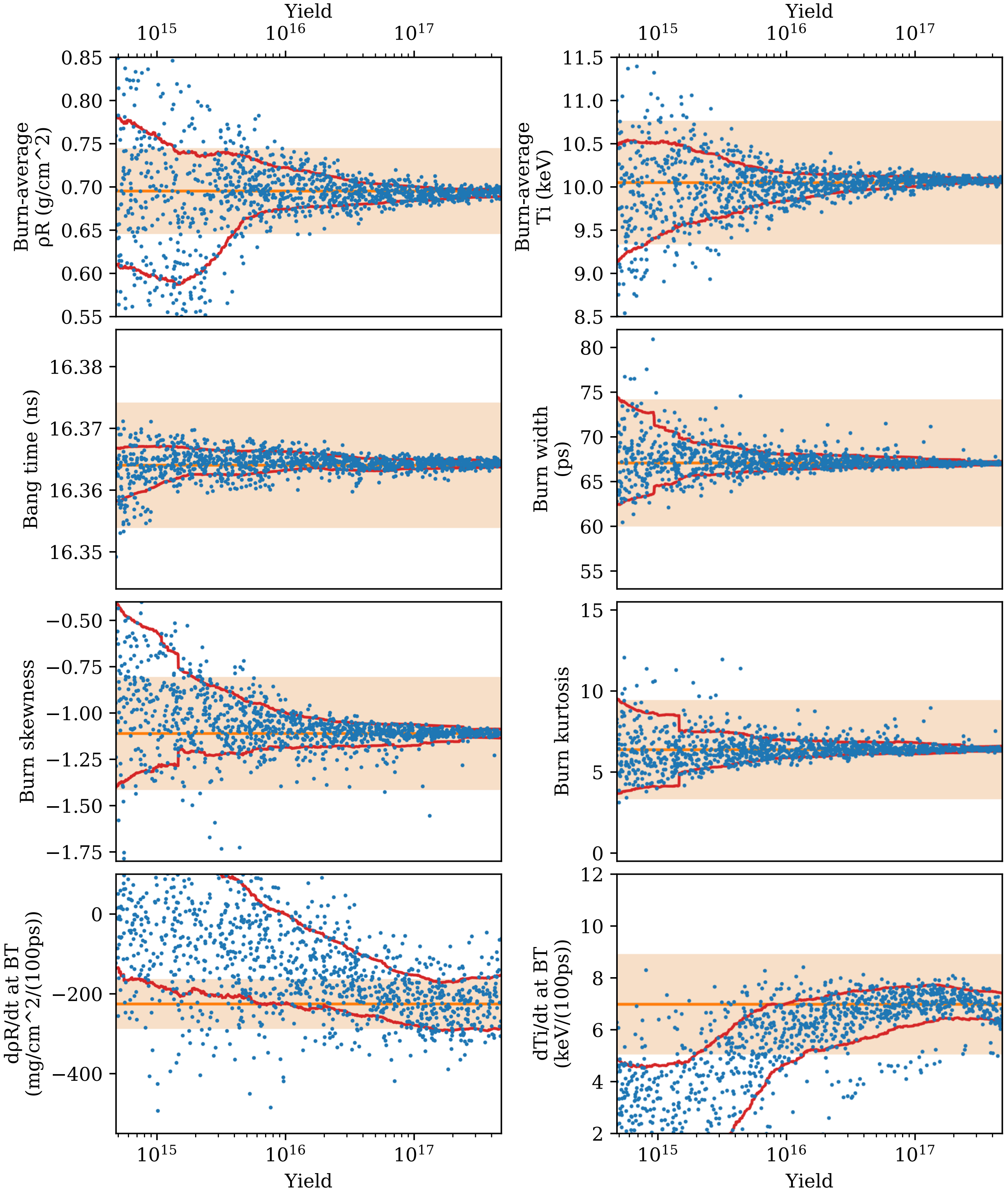

FIG. 3. Implosion parameters inferred from synthetic MRSt data for varying neutron yields. These data are for the high-efficiency configuration of the MRSt. The shaded orange regions represent the current top-level physics requirements, and the red lines represent the 1σ envelope of the data; the MRSt fulfills its requirements at yields where the red lines lie within the orange region.

V. CONCLUSIONS

The MRSt is a transformational neutron spectrometer that will provide time-resolved measurements of ρR, T_i, and Y_n to probe burn parameters hitherto unavailable. Top-level physics requirements for the MRSt were determined based on hydrodynamic simulations such that the system can probe alpha heating, P2 asymmetry, and mix. Synthetic MRSt data were subsequently generated and analyzed to evaluate the proposed system's performance against these requirements. It is predicted that the MRSt meets most of the determined requirements at current neutron yields at the NIF, indicating that it will be able to accurately diagnose the dynamic impact of alpha heating and various failure modes.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

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

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