Top-level physics requirements and simulated performance of the MRSt on the National Ignition Facility

Cite as: Rev. Sci. Instrum. 92, 033514 (2021); https://doi.org/10.1063/5.0040745
Submitted: 15 December 2020. Accepted: 05 February 2021. Published Online: 04 March 2021

J. H. Kunimune, J. A. Frenje, G. P. A. Berg, C. A. Trosseille, R. C. Nora, C. S. Waltz, A. S. Moore, J. D. Kilkenny, and A. J. Mackinnon

COLLECTIONS

Paper published as part of the special topic on Proceedings of the 23rd Topical Conference on High-Temperature Plasma Diagnostics

ARTICLES YOU MAY BE INTERESTED IN

A time-resolved, in-chamber x-ray pinhole imager for Z
Review of Scientific Instruments 92, 033512 (2021); https://doi.org/10.1063/5.0040706

Three-dimensional reconstruction of neutron, gamma-ray, and x-ray sources using a cylindrical-harmonics expansion
Review of Scientific Instruments 92, 033508 (2021); https://doi.org/10.1063/5.0042860

High-resolution x-ray radiography with Fresnel zone plates on the University of Rochester’s OMEGA Laser Systems
Review of Scientific Instruments 92, 033701 (2021); https://doi.org/10.1063/5.0034903
Top-level physics requirements and simulated performance of the MRSt on the National Ignition Facility

J. H. Kunimune, J. A. Frenje, G. P. A. Berg, C. A. Trosseille, R. C. Nora, C. S. Waltz, A. S. Moore, J. D. Kilkenny, and A. J. Mackinnon

AFFILIATIONS
1 Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
2 Department of Physics, Notre Dame College of Science, Notre Dame, Indiana 46556, USA
3 Lawrence Livermore National Laboratory, Livermore, California 94550, USA

Note: Paper published as part of the Special Topic on Proceedings of the 23rd Topical Conference on High-Temperature Plasma Diagnostics.

Author to whom correspondence should be addressed: kunimune@mit.edu

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.

Published under license by AIP Publishing. https://doi.org/10.1063/5.0040745

I. INTRODUCTION

Neutron spectrometry is used routinely to diagnose burn-averaged properties of inertial confinement fusion (ICF) implosions, and in particular, the areal density ($\rho R$), ion temperature ($T_i$), and neutron yield ($Y_n$). The current Magnetic Recoil Spectrometer (MRS) is a neutron spectrometer fielded on OMEGA and the National Ignition Facility (NIF) that makes these measurements. 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. 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 $\rho R$, $T_i$, and $Y_n$ as functions of time. This allows for measurements of time-dependent burn parameters such as $\frac{d\rho R}{dt}$, $\frac{dT_i}{dt}$, 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
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 $\rho R(t)$, $T_i(t)$, and $Y_n(t)$ 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.

III. MRSt CONCEPTUAL DESIGN AND CONFIGURATIONS

The conceptual design of the MRSt is based on the combination of the MRS technique and the Pulse Dilation Drift Tube (PDDT) technique. 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 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. Unlike the

| Value | Requirement |
|-------|-------------|
| $\frac{d\rho}{dt}$ at BT | ±60 g/cm^2/100 ps |
| $\frac{dT_i}{dt}$ at BT | ±1.9 keV/100 ps |
| Absolute BT | ±10 ps |
| Burn width | ±7 ps |
| Burn skewness | ±0.3 |
| Burn kurtosis | ±3 |
| $\langle \rho R \rangle$ | ±7% |
| $\langle T_i \rangle$ | ±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) $\frac{dT_i}{dt}$ vs $\frac{d\rho}{dt}$ 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.

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 focal plane. Unlike the...
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.\textsuperscript{5,6} 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 ground levels. Three MRSt configurations have been identified: a high-yield implosions, and a medium-efficiency configuration as a compromise between these settings. These configurations and their efficiencies and resolutions at a neutron energy of 14 MeV.\textsuperscript{10}

| Quantity (units) | Reference $Y_n$ | Required | High-efficiency | Medium-efficiency | Low-efficiency |
|------------------|-----------------|----------|----------------|------------------|---------------|
| $\rho R$ at BT (g/cm\textsuperscript{2}/100 ps) | 60 | $1 \times 10^{16}$ | 60 | 210 | 220 | 320 |
| $\rho R$ 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 |
| $\langle T_i \rangle$ (% of total) | 7 | 2.4 | 2.4 | 4.4 |
| $Y_n$ (% of total) | 5 | 0.7 | 1.0 | 2.4 |

TABLE II. MRSt configurations and their efficiencies and resolutions at a neutron energy of 14 MeV.\textsuperscript{9,10}

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

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 $\rho R(t)$, $T_i(t)$, and $Y_n(t)$ 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 $1 \times 10^{16}$ and higher, the high-efficiency configuration fulfills all top-level physics requirements except $\rho R$. It also meets the $\rho R$ requirement above yields of $1 \times 10^{17}$. The medium-efficiency configuration performs similarly but produces more accurate bang time measurements and less accurate $\rho R$ and burn width measurements. At yields of $5 \times 10^{16}$ and higher, the low-efficiency configuration fulfills all requirements except $\rho R$.\textsuperscript{10}
FIG. 3. Implosion parameters inferred from synthetic MRSI data for varying neutron yields. These data are for the high-efficiency configuration of the MRSI. The shaded orange regions represent the current top-level physics requirements, and the red lines represent the 1σ envelope of the data; the MRSI 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 $\rho R$, $T_n$, and $Y_e$ 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

This work was supported, in part, by the U.S. Department of Energy NNSA MIT Center-of-Excellence under Contract No. DE-NA0003868 and Lawrence Livermore National Laboratory under Contract No. B635598. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DATA AVAILABILITY

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

REFERENCES

1. J. A. Frenje, “Nuclear diagnostics for inertial confinement fusion (ICF) plasmas,” Plasma Phys. Controlled Fusion 62, 023001 (2020).
2. D. T. Casey, J. A. Frenje, M. Gatu Johnson, F. H. Séguin, C. K. Li, R. D. Petrasso, V. Y. Glebov, J. Katz, J. Magoon, D. D. Meyerhofer, T. C. Sangster, M. Shoup, J. Ulreich, R. C. Ashabranner, R. M. Bionta, A. C. Carpenter, B. Felker, H. Y. Khater, S. LePape, A. MacKinnon, M. A. McKernan, M. Moran, J. R. Rygg, M. F. Yeoman, R. Zacharias, R. J. Leeper, K. Fletcher, M. Farrell, D. Jasion, J. Kilkenny, and R. Paguio, “The magnetic recoil spectrometer for measurements of the absolute neutron spectrum at OMEGA and the NIF,” Rev. Sci. Instrum. 84(4), 043506 (2013).
3. J. Kilkenny, “The ICF national diagnostic plan september 2018,” Technical Report No. LLNL-TR-759117, National Diagnostics Working Group, 2018, p. 10.
4. J. A. Frenje, T. J. Hilsabeck, C. W. Wink, P. Bell, R. Bionta, C. Cerjan, M. Gatu Johnson, J. D. Kilkenny, C. K. Li, F. H. Séguin, and R. D. Petrasso, “The magnetic recoil spectrometer (MRSt) for time-resolved measurements of the neutron spectrum at the National Ignition Facility (NIF),” Rev. Sci. Instrum. 87(11), 11D806 (2016).
5. J. A. Frenje, D. T. Casey, C. K. Li, F. H. Séguin, R. D. Petrasso, V. Y. Glebov, P. B. Radha, T. C. Sangster, D. D. Meyerhofer, S. P. Hatchett, S. W. Haan, C. J. Cerjan, O. I. Landen, K. A. Fletcher, and R. J. Leeper, “Probing high areal-density cryogenic deuterium-tritium implosions using downscattered neutron spectra measured by the magnetic recoil spectrometer,” Phys. Plasmas 17(5), 056311 (2010).
6. T. J. Hilsabeck, J. A. Frenje, J. D. Hares, and C. W. Wink, “A stretch/compress scheme for a high temporal resolution detector for the magnetic recoil spectrometer-time (MRS),” Rev. Sci. Instrum. 87(11), 11D807 (2016).
7. C. E. Parker, J. A. Frenje, O. H. W. Siegmund, C. J. Forrest, V. Y. Glebov, J. D. Kendrich, C. W. Wink, M. G. Johnson, T. J. Hilsabeck, S. T. Ivancic, J. Katz, J. D. Kilkenny, B. Lahmann, C. K. Li, F. H. Séguin, C. M. Sorce, C. Troscille, and R. D. Petrasso, “Response of a lead-free borosilicate-glass microchannel plate to 14-meV neutrons and $\gamma$-rays,” Rev. Sci. Instrum. 90(10), 103306 (2019).
8. C. W. Wink, J. A. Frenje, T. J. Hilsabeck, R. Bionta, H. Y. Khater, M. Gatu Johnson, J. D. Kilkenny, C. K. Li, F. H. Séguin, and R. D. Petrasso, “Signal and background considerations for the MRSt on the National Ignition Facility (NIF),” Rev. Sci. Instrum. 87(1), 01D808 (2016).
9. A. J. Sandberg, “Shielding design for the time-resolving magnetic recoil spectrometer (MRSt) on the National Ignition Facility (NIF),” M.S. thesis, Massachusetts Institute of Technology, 2019, p. 8.
10. C. W. Wink, “Characterization and optimization of signal and background for the time-resolving magnetic recoil spectrometer on the National Ignition Facility,” M.S. thesis, Massachusetts Institute of Technology, 2017, p. 6.