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INTRODUCTION

In the first decade of the 21st century, the United States began operating three leading Inertial Confinement Fusion (ICF) and High-Energy Density Physics (HEDP) facilities.¹ The National Ignition Facility (NIF)^{2,3} began its quest to first surpass the Lawson Criterion⁴ and then reach thermonuclear ignition and thermonuclear gain. The Omega EP (Extended Performance) laser⁵ provides unprecedented energy, reliability, and consistency for petawatt (PW)-class laser experiments. The Omega laser⁶ continues to support over 1000 ICF and HEDP experiments each year. The Z pulsed power machine is a Z-pinch plasma confinement device that was refurbished to increase current drive and improve reliability.^{7,8}

The extreme states of matter created in these new facilities required advancement of many technologies. The most important among these was the significant improvement in instrumentation capabilities needed to diagnose plasma conditions and resulting nuclear products. The instruments needed a better temporal, spatial, and energy resolution. They also needed to be hardened against EMP and radiation.

Typical events in an ICF implosion include compressing the deuterium-tritium (DT) fuel to greater than 60 g/cm³ and heating the DT to a temperature greater than 10 keV (110 000 000 K). The DT atoms react to produce 14 MeV neutrons from a volume with a radius of ~30 μm. When the fuel ignites, the DT burn propagates into cold fuel and the neutron-emitting region can reach sizes of over 200 μm. The burn typically lasts less than 150 ps, but the burn duration will decrease as the DT yield increases. Burn durations as short as 90 ps have been recorded⁹ and are predicted to decrease still further to 20 ps. X-ray imaging diagnostics are needed to measure the acceleration and velocity of the capsule enclosing the DT, where the implosion velocities can reach over 400 km/s.

SUMMARY OF AREAS COVERED

The instruments described in this Special Topic can be divided into two broad categories: The first category consists of instruments that helped support the research and experiments leading up to ignition, and the second category includes those instruments that will be more useful after high-yield implosions are routinely produced. However, all these instruments play a role in both categories.

Fundamental measurements of capsule ablator material properties are made using the VISAR (Velocity Interferometer System for Any Reflector) instrument.¹⁰ This instrument has evolved from measuring velocities at a single point, to a line, and finally, to a two-dimensional surface. Not only is the VISAR used to measure material properties, but it is heavily used to tune the shock timing in an ignition experiment to maintain maximum possible fuel compressibility. VISAR is also a workhorse instrument for measuring the properties of materials under extreme conditions at laser, pulsed power, and x-ray free electron laser (XFEL) facilities.

To reach high neutron yields, the deuterium-tritium (DT) fuel is frozen inside the capsule. The ice layer must be very uniform with few irregularities. Since both high-density carbon (HDC) and beryllium capsules are optically opaque, novel methods needed to be developed to inspect the ice layer inside the capsule. A technique using phase-contrast imaging employing an x-ray micro-focus source was developed to view and characterize the ice layer.¹¹ This technique is now also used extensively for shock dynamics measurements.

During the period before reaching ignition, it became apparent that more precise knowledge of the experimental conditions was required to improve performance. Improvements could be gained by improving spatial resolution, improving temporal resolution, or decreasing uncertainties of existing instruments. In addition, new instruments could be invented and deployed. To pursue these

efforts, a National Diagnostic Working Group (NDWG) was formed to set priorities and to coordinate knowledge discovery and instrument development.¹² The team approach was very successful, resulting in an initial complement of diagnostics needed for the first set of experiments¹³ and leading to the development of many of the advanced instruments described in this Special Topic collection. Both the Z machine and the Omega benefited from the national effort as NDWG developed an advanced suite of diagnostics.¹⁴

High-neutron-yield attempts were made by extensive use of radiation-hydrodynamics simulation codes. However, due to limits in the codes, final attempts needed to be tuned using experimental measurements.^{15–17} First, Hohlraum conditions were assessed using a soft x-ray instrument, DANTE, to obtain the radiation temperature.¹⁸ Then, proper shock timing was established through the use of VISAR experiments.¹⁰ The symmetry of the implosion was subsequently measured using advanced x-ray imaging instruments.¹⁹

The results of high-yield experiments are typically represented by the neutron yield and ion temperature. These comprise an incomplete description of the experiment, however. More detailed measurements of plasma conditions, shape, and reactivity are required to understand the physical phenomena that allowed or inhibited thermonuclear performance.

Symmetry tuning was aided by using “pulse dilation” electro-optics technology,²⁰ where the image is formed on the cathode and an electron bunch is accelerated toward a microchannel plate (MCP). By ramping the accelerating voltage, the time base of the MCP output was stretched, enabling very short-duration x-ray images to be obtained. To contribute to our understanding of the implosions, a series of charged-particle diagnostics measured areal density symmetry and the timing of the implosion.²¹ The neutron spectrum and yield are measured by a neutron time-of-flight (nTOF).²² These instruments were also used during the preparation for ignition, as they showed that capsule compression was not as high as expected and that the burn width of the implosion was longer than predicted.

Megajoule neutron production was achieved at NIF in 2021.⁴ While instruments such as the nTOF and activation diagnostics confirmed the yield, other instruments demonstrated that we understood the qualitative behavior of thermonuclear ignition with burn propagation. For example, the FWHM of the fuel reactivity (the “burn width”) decreased by over 25%.⁹ The burn width is measured by a series of gamma Čerenkov detectors utilizing fast PMTs and a pulse dilation PMT with a temporal resolution of 10 ps.²³ The propagation of the burn wave from the initial fuel hotspot into the surrounding cold fuel was confirmed by the neutron imaging diagnostic.²⁴ The 2D image of the primary (14-MeV) neutron-emitting region grew from its typical 60- μm diameter to over 200 μm in diameter. These measurements not only showed that the neutron production was high, but also that ignition and sustainable burn was achieved.

Innovation and development of instrumentation will continue past the milestone of thermonuclear ignition. X-ray cameras using hCMOS sensors are now routinely deployed at NIF, Omega, and Z. These chips provide multiple frames of data with one ns gate and interframe times.²⁵ Future developments will increase the number of frames available. Radiochemistry for ICF applications²⁶ will become an important tool now that an extremely bright neutron source is

demonstrated. Initial experiments using radiochemistry techniques have already been carried out to examine stopping-power models²⁷ and other phenomena.²⁸ Finally, extensive modeling and analysis of the data collected can improve our understanding of the phenomena under study by significantly reducing the uncertainty in the data and by constraining theoretical and computational models.²⁹

CONCLUDING REMARKS

The reviews presented in this Special Topic cover a broad range of diagnostic instruments used in ICF and HEDP. The reviews include some of the most important for reaching ignition conditions on the NIF and those important for advanced research into the future. Important instruments from the Z pulsed power facility are also included. However, this collection is not comprehensive. For example, there is a need for articles that review specific areas of technology. Advances in x-ray spectrometers have not been reviewed in several decades,³⁰ and recent advances in spectrometers, such as those for opacity^{31,32} measurements and for high resolution,^{33,34} are not provided in context. Activation diagnostics to measure neutron fluences are already contributing to both high-yield experiments at NIF and to short-pulse neutron generation at smaller facilities. A general review of the types of diagnostics used in short-pulse laser–matter interaction experiments is a high priority. Optical diagnostics to measure the level of harmful laser–matter interactions and laser absorption have not been recently reviewed. A key part of those instruments is the development of streak cameras, which are being redesigned and improved. In the pulsed-power area, power flow diagnostics need to be discussed along with the categorization of their individual uses and importance. The topic of HEDP materials science was largely excluded from these reviews, apart from its mention in the development and use of the VISAR diagnostic. Finally, a discussion of how all these diagnostic instruments are calibrated and what types of facilities and equipment are required is needed.

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