Diagnosing Inertial Confinement Fusion Ignition

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Abstract

Fusion ignition by inertial confinement requires compression and heating of the fusion fuel to temperatures in excess of 5 keV and densities exceeding hundreds of g/cc. In August 2021 this scientific milestone was surpassed at the National Ignition Facility (NIF), when the Lawson criterion for ignition was exceeded generating 1.37MJ of fusion energy from a target driven by 1.9MJ of laser energy. On the NIF, ICF research primarily uses laser indirect drive in which the fusion capsule is surrounded by a high-Z enclosure ("Hohlraum") used to convert the directed laser energy into symmetric x-ray drive on the capsule. Precise measurements of the plasma conditions, x-rays, γ-rays and neutrons produced is key to understanding the pathway to higher performance. The paper discusses the diagnostics and measurement techniques developed to understand these experiments, focusing on three main topics: (1) key diagnostic developments for achieving igniting plasmas, (2) novel signatures related to thermonuclear burn and (3) advances to diagnostic capabilities in the igniting regime with a perspective toward developments for Inertial Fusion Energy (IFE).

Keywords: Inertial Fusion, Diagnostics, Ignition

1. Introduction

Hot-spot inertial confinement fusion ignition is achieved by minimizing radiation and thermal conduction losses, so that heating by the α-particles generated in the [D + T → n (14.1MeV) + ^{4}He (3.5 MeV)] fusion reaction dominates and the plasma begins to self-heat, burn, and ignite [1, 2]. On the NIF, ICF research primarily uses laser indirect drive (LID) in which the fusion capsule is surrounded by a high-Z enclosure ("Hohlraum") used to convert the directed laser energy into symmetric x-ray drive on the capsule. Precise measurements of the plasma conditions, x-rays, γ-rays and neutrons produced is key to understanding the pathway to higher performance.

Developments over the past decade have enabled diagnosing, understanding, and overcoming implosion failure mechanisms. Increased precision and 3D reconstruction of neutron hot-spot shape and motion have shown that imbalanced drive can degrade fusion performance. Quantification of x-ray emission imaging has identified

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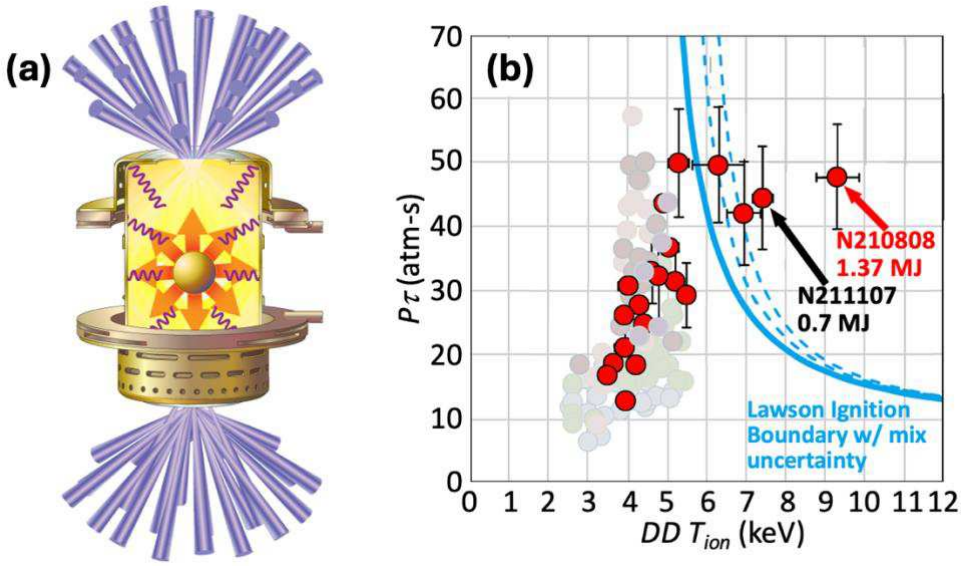

Figure 1. (a) Diagnosing the performance of the high-Z 'Hohlraum' enclosure surrounding the ICF capsule through measurement of x-ray emission and laser-beam propagation and instabilities is key to delivering the required energy to the capsule with sufficient symmetry. (b) Understanding the proximity of an ICF experiment to ignition involves inferring fundamental physical quantities, ion temperature, pressure and confinement time from a range of different x-ray and nuclear diagnostics [6].

target features such as the tube used to fill the capsule with DT gas as significant degradations and have driven capsule quality improvements. X-ray radiography of implosions together with down-scattered neutron energy measurements have provided evidence of lower-than-expected DT fuel compression limiting performance, and 2D shock velocity measurements have characterized the impact of diamond crystal structure on implosion quality. In combination advances in optical, x-ray and nuclear diagnostics [3-5], have all played a key role in improving understanding of Hohlraum energetics, capsule symmetry and mix, and overall implosion performance, which together impacted decisions and design choices that resulted in fusion ignition.

2. Key Diagnostic Developments

2.1 Diagnostics of Laser-heated Hohlraum Performance and Capsule Coupling

The LID-ICF scheme is illustrated in Fig. 1(a); thermal x-rays (radiation temperature ~ 300eV) generated by laser interaction with the Hohlraum walls, ablate the outer layer of the capsule which is typically, plastic (GDP), High Density Carbon (HDC) or beryllium. To minimize the entropy, multiple shocks are driven through the ablator and DT ice layer inside, all of which play a critical role in the overall performance.

Coupling of the laser into the Hohlraum is the first step in maximizing the x-ray power available to drive the capsule. LID-ICF Hohlraums are typically filled with a low atomic number gas to maximize the time during which the capsule can be effectively driven. During the National Ignition Campaign (NIC) high density gas fills were used that lead to significant energy loss through backscattering of the laser pulse and other laser-plasma instabilities such as Cross-Beam Energy Transfer (CBET). Key to diagnosing and understanding these losses were the suite of optical backscatter diagnostics that absolutely quantify the backscattered laser light in addition to measuring the spatial distribution, spectrum and time-history [7]. In addition to measurements to understand laser beam propagation inside the Hohlraum, diagnosing the plasma temperature (3-8keV) and electron density (~10^{21} cm^{-3}) inside the Hohlraum has been a many year effort through both x-ray spectroscopy [8] and optical Thompson scattering, both of which can provide unprecedented information with which to benchmark simulations of the Hohlraum.

The heated outer surface of the capsule ablates and creates a, 'rocket-effect' that drives the implosion, and so the maximum pressure achieved by the implosion is strongly dependent on the maximum velocity achieved by the rocket, and the x-ray power and uniformity driving the capsule. Consequently, in LID-ICF, in addition to diagnosing the delivered laser energy and pulse shape, measuring the soft x-ray power emitted through the laser entrance holes (LEH) and the size of the LEH, is necessary to determine the x-ray power driving the capsule. On NIF and many other HED facilities this is achieved through an array of filtered x-ray diodes called 'Dante' that measure x-rays in different energy bands and from which the x-ray spectrum vs. time can be unfolded [9]. Since the timing of the multiple shocks that are driven through the capsule and DT ice layer determine the final temperature and compressibility of the DT fuel, independent measurement of the shock arrival time is key to calibrating the simulations and material models. This is typically achieved using a 'Velocity interferometer system

for any reflector' (VISAR) and dedicated experiments that replace the capsule with a surrogate capsule and target hardware to image the shocks breaking out in the inside of the capsule [10].

In addition to measuring initial shock velocities and x-ray drive, direct measurements of the later stage of the implosion was a vital tool in understanding and improving the performance of ICF experiments. Several radiography measurements were developed in the path to ignition. In early experiments 1-dimensional, streaked radiography [11] and 2-dimensional convergent ablator radiography experiments measured the mid-phase of the implosion. More recently, narrow-band crystal backlit imaging techniques were developed to mitigate the x-ray emission of the hot-spot so that the dense shell can be observed [12], and then high-energy (100-200keV) Compton radiography techniques used to image the fuel assembly at peak compression [13]. All of these diagnostics inform not only the energetics of the implosion velocity, but also the symmetry with which the capsule is driven which is key to high performance.

2.1 Diagnostics of Capsule Performance

Measurements of the pressures and temperatures generated in the hot DT plasma are key to inferring the proximity of the implosion to ignition. Fig. 1(b) illustrates this point showing the ignition boundary on a plot of Pressure times confinement time ($P\tau$) vs. ion temperature (T_{ion}) for a large number of HDC ablator experiments over the past years[6]. Several metrics that build from the generalized Lawson criterion have been generated which use large suites of tuned simulations to establish a scaling tailored to inertial confinement conditions. One such is the 'eXperimental Ignition Threshold Factor' ITFX [14] that relates the amplification in yield from α-heating to a single metric that is a function of the neutron yield, the fuel areal density, and the fuel mass at stagnation. Neutron yield and areal density are measured and inferred from the neutron spectrum, while the fuel mass is inferred from a simple model that relies on measurement of the hot-spot size, temperature and burn duration. Fundamentally, however this really just further motivates the need to make direct measurement (or inference) of all the physical state variables of the system: pressure, temperature, density and confinement time. As such, x-ray and nuclear diagnostics that are capable of measuring these quantities were vital to reaching ignition.

Primary DT neutron yields at the NIF are measured by the neutron activation of zirconium (Zr) and a magnetic recoil spectrometry (MRS) technique which is discussed elsewhere[15]. Three Zr discs are positioned 4.5 m from the implosion. Neutrons emitted by the target travel to and interact with the ^{90}Zr atoms in the discs producing ^{89}Zr atoms via the (n,2n) reaction. The (n,2n) cross section rises nearly linearly with energy from a threshold of 12 MeV; therefore, the number of ^{89}Zr atoms produced is proportional to the number of DT neutrons. ^{89}Zr is unstable and decays, emitting a 909 keV γ-ray with a half-life of 78.41 hrs. This moderately-long half-life allows the discs to be collected and counted for a fixed amount of time by a dedicated, remote germanium detector[16]. Accounting for the solid angle and collection efficiency of the detector, this measures the number of neutrons that leave the target to an uncertainty of $1\sigma \approx 5\%$ [17].

The 14.028 MeV neutrons generated in the D+T reaction are doppler shifted to higher and lower energies by the ion velocity distributions and flows that are present in the hot-spot plasma. Consequently, the ion velocity distributions (or temperature if Maxwellian) and flows are encoded in the shape of the DT neutron spectrum. Similarly, as the neutrons exit the hot-spot plasma, they scatter to lower energy through the dense DT fuel that surrounds it, which means that a 'Down-Scatter Ratio' (DSR) of the number of neutrons between 10-12MeV compared to the number of primary fusion neutrons between 13-15MeV, is related to the fuel areal density (ρR). These facts place high significance on accurate measurement of the shape of the neutron spectrum to infer plasma flows, ion temperature and fuel ρR [18, 19]. One complication is that residual flows in the hot-spot tend to inflate the ion temperature above the thermal value. To mitigate this complimentary electron temperature measurements derived from spectral measurements of the hot-spot x-ray emission were developed [20].

Azimuthal drive asymmetries were identified in 2019-2021 through novel diagnostic measurements of the areal density asymmetry from an array of NAD's that surround the implosion, and correlated with measurements of laser drive imbalance, hot-spot velocity from neutron time-of-flight measurements and seeds from ablator non-uniformities [21-23]. These mode-1 drive asymmetries that push the capsule in a specific direction are coupled to higher mode asymmetries that capture drive imbalances that lead to non-spherical implosions.

In addition to using complex post-shot radiation hydrodynamics simulations, hot-spot pressure is inferred using simple isobaric models that incorporate direct measurements of hot-spot volume reconstructed in 3-dimensions using x-ray and neutron emission images [24, 25], and burn-averaged ion temperatures from the neutron spectrum measurements. X-ray and neutron imaging also provides a window into localised losses in the hot-spot and were key to identifying and quantifying a range of degradation mechanisms from injection of fill-tube mass into the hot-spot, to localized radiative cooling due to high-Z mix, to "meteors" of material entering the plasma from local imperfections in the HDC ablators, and even 'dark' mix of low-Z ablator material into the hot-spot [4, 26]. Nuclear

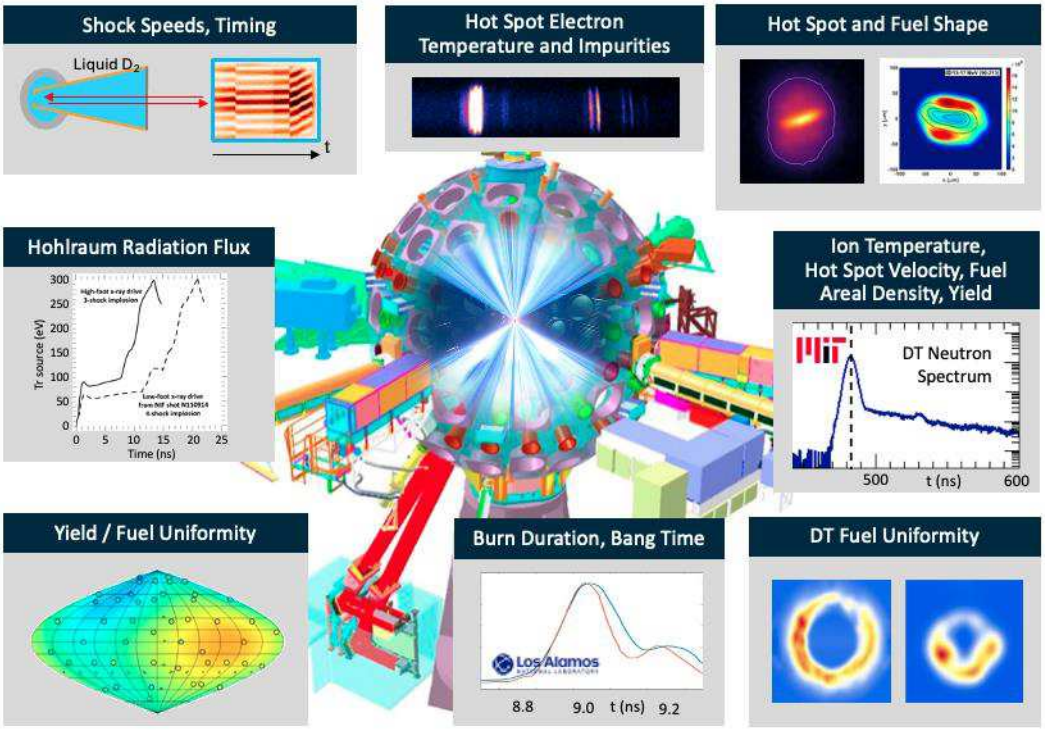

Figure 2. Achieving ignition required many diagnostics to probe the optical, x-ray and nuclear performance of a wide range of ICF implosions and other physics measurements.

imaging of the γ-rays produced by (n, γ) reactions in the ablator are another measurement that promises to help even more in the post-ignition era as the burning and igniting plasma interacts more with the remaining ablator and the state of which may provide a window into mechanisms that truncate burn or limit gain[27].

Confinement time is diagnosed through measurement of the DT fusion gamma-rays that are also emitted at a branching ratio of ~ 4.2 x 10^{-5} compared to the 14MeV neutrons. The Los Alamos National Laboratory (LANL) gamma reaction history diagnostics were key in measuring this burn duration [28]. A corollary metric of significant importance is the γ bang time that captures the time of maximum fusion reactions. Owing to inadequacies in models and simulations of the Hohlraum and other physics. Measurement of the bang time has been a key metric to understanding and benchmarking the fully integrated simulations against these highly complex experiments. Independent and correlated measurements from the multitude of diagnostics developed at NIF over the past decade, only some of which are captured in Fig. 2, have been critical to achieving the goal of ignition.

The success of diagnosing inertial confinement ignition is encapsulated by the dedicated researchers that worked from many institutions over decades to overcome significant technical and scientific hurdles and shed light on physical phenomena that were not expected at the outset of this journey to ignition. This effort was coordinated through a National Diagnostics Working Group [29], that was key to prioritizing and developing new diagnostics to falsify theories and provide the best available diagnostics to inform models and simulations in this grand endeavor of fusion ignition.

3. Diagnostic Signatures of Ignition

Signatures of the onset of burn and ignition are both evident in and connected across multiple types of measurements; this diagnostic consistency was key in determining that these experiments exceeded the Lawson-like criterion. In addition to the increased fusion neutron yield, Fig. 3 shows two such measurements derived from the neutron spectrum: ion temperature and down-scatter ratio (which is proportional to areal density, ρR). Plotted versus fusion yield, these two measurements alone demonstrate that when the capsule ignites the fuel temperature increases due to the rapid α-heating, and increased burning into the compressed fuel shell decreases the burn weighted areal density.

Images of the 14 MeV primary neutron emitting region increased substantially in size from 80μm to >100μm in diameter due to the burn propagation and increased mass of DT fuel participating upon ignition. Further evidence is that burn durations decreased to less than 100ps. Simulations have previously indicated that while the overall duration during which fusion reactions increases when the plasma ignites, the duration during which the majority of the fusions occur decreases leading to a sharper peak, and smaller full-width at half maximum burn duration.

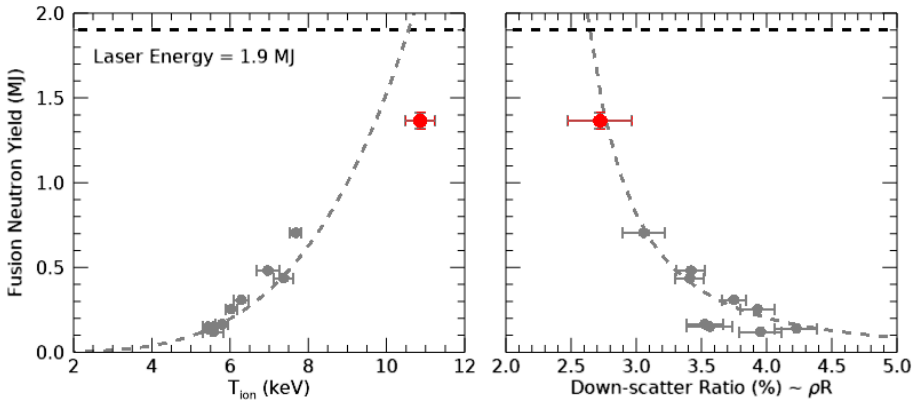

Figure 3. In addition to increased fusion neutron yield, signatures of the onset of a-heating, burn propagation and ignition are observed by multiple independent measurements of ion temperature and down-scatter ration (DSR) from neutron spectroscopy.

Fig. 4 shows one other independent, yet clear signature of ignition measured by the Dante diagnostic that is usually used to monitor the Hohlraum x-ray emission. In the time up to approx. 8ns when the laser pulse is on and heats the Hohlraum, the normal x-ray emission associated with the Hohlraum is observed. Now, in these igniting experiments a second sharp peak that correlates in time with the capsule bang-time is also observed as the fusion energy emitted by the igniting capsule is seen to reheats the hohlraum after laser turns off [30]. Note that the exact shape and amplitude of the reheating peak is dependent on the specific target geometry used in the implosion. Other novel signatures such as the possible signatures of kinetic effects in burning plasmas – as reported by Hartouni *et al.* [5] are also still observed and are under further investigation as further experiments explore the robustness of this novel igniting plasma.

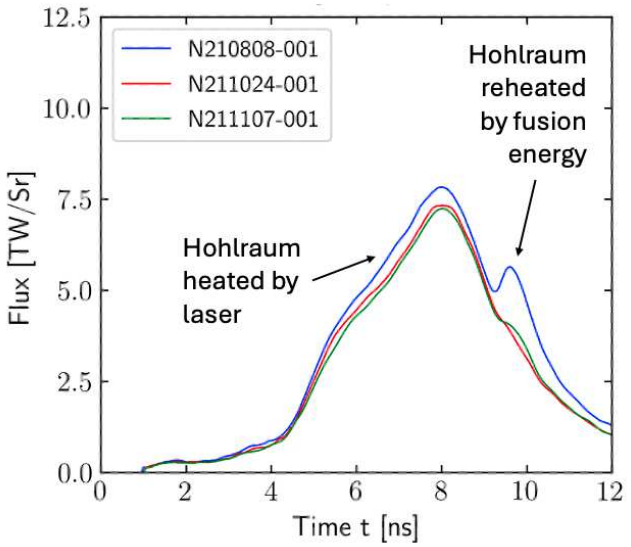

Figure 4. As the ignition threshold is reached, the x-ray emission from the igniting fusion capsule is observed to reheat the Hohlraum, by the Dante-2 soft x-ray power diagnostic that normally just observes x-ray emission due to laser-heating of the Hohlraum [30].

4. Diagnostic Advances Required for Inertial Fusion Energy

Interest in developing clean inertial fusion energy schemes have been buoyed by this ignition advancement and so thought must now begin to be given to how to diagnose not only fusion pilot plants (FPP) of the future, but the next generation of higher yield demonstration facilities. For economical power production, plants must operate at much higher gains than the target gain > 1 result discussed here, and must do so robustly and at high repetition rate. While it is not yet clear what the optimal platform or driver will be for inertial fusion energy, many of the diagnostic needs will be the same.

Significant diagnostic capability gaps exist at several levels that will need to be overcome to understand this novel regime. New diagnostics are required to understand the fundamental physics of ignition and how to move from a target gain of 1 to the 100 required for a FPP. This will require (1) from a physically motivated perspective the development of a new generation of ultrafast time-resolution diagnostics that have $>10^3$ dynamic range. The onset of α-heating and burn occurs on sub-100ps timescales and over multiple orders of magnitude in fusion yield, and (2) existing instruments to be further radiation hardened for the survivability of detectors and diagnostics as yields increase. Hardened diagnostics are already a challenge at the MJ yields at which NIF is operating, so diagnostics for a FPP in the 100 MJ-GJ range will require significant research and development.

Beyond diagnosing and achieving 100MJ outputs, the ultimate operation at repetition rates approaching 10Hz will present significant diagnostic challenges. Activation diagnostics that are counted over durations of hours to days are obviously not feasible, even the more robust neutron diagnostics such as neutron time-of-flight would require real-time analysis and incorporation into feedback control loops. Presumably the only real-time control parameter in most IFE power plants will be the laser pulse shape and energy since

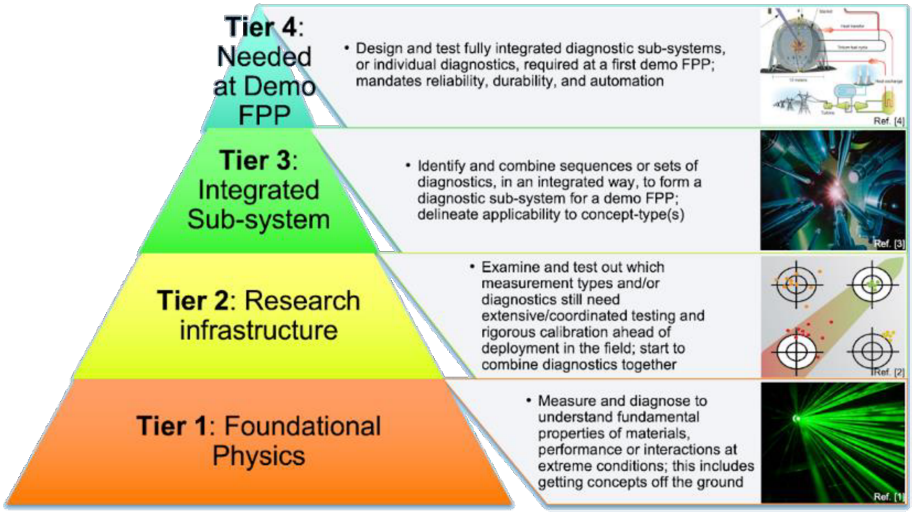

Figure 5. Going from fundamental ICF research to an IFE power plant will require a paradigm shift from many to minimal diagnostics.

targets will likely need to be pre-manufactured and metrologized to meet specification, thus simple instruments and models, the antithesis of the current sophisticated diagnostics and analyses, will be required. Another consideration will be diagnosing the turn-on period that will be needed to get the facility to an optimal operation point, likely before increasing repetition rate. A wider range of more complicated diagnostics will be be required for this 'warming-up' phase of operation, but then would need to be removed so as not to be unnecessarily exposed to the harsh environment at high repetition rate, and to maximize the solid angle for power production.

The recent Basic Research Needs Workshop [31] commissioned by the Department of Energy, Office of Fusion Energy Sciences began to lay the groundwork for some of these diagnostics considerations in a June 2022 report, and prioritized the following diagnostic areas:

- Leverage and develop diagnostics to assess factors limiting gain:
  - Diagnose which quantities are critical to propel implosions toward high gain;
  - Improve measurement resolution across energy, space & time for key diagnostics.
- Develop high repetition-rate diagnostics transformative for IFE (and ICF) research
- Develop radiation-hardened diagnostics critical for IFE power plants; leverage MFE and high-yield NNSA efforts.
- Adapt critical infrastructure diagnostics to IFE power plant environment.

The report recognized the need for diagnostics that prioritize the reproducibility of measurements and scientific quality, breaking down the goals into four tiers as shown in Fig. 5. Tier 1 focusses on the fundamental physics required for high gain and understanding the underlying properties of materials required for targets and future facilities. Tier 2 leverages the lessons learned in Tier 1 but aims to consider the direct application needs in a Fusion Power Plant, for example diagnostic reliability, measurement effectiveness and how it might be maintained in a (FPP). Tier 3 incorporates the diagnostic measurements successful in Tier 2 into a sub-system that could be implemented into an FPP, with Tier 4 down-selects to the limited diagnostic set required for a demo FPP. A new Basic Research Needs Workshop has been commissioned in 2023 by the U.S. Department of Energy to investigate priority research opportunities specifically for diagnostics relevant for a fusion pilot plant.

5. Conclusion

ICF experiments at the NIF have exceeded the Lawson criterion for ignition, with the production of 1.37MJ of fusion energy from a target driven by a 1.9MJ laser pulse. The development of new optical, x-ray and nuclear diagnostics at the NIF have been key to reaching this milestone result and have guided decisions on the path to ignition over the past decade.

This milestone experiment showed new signatures on a range of x-ray and nuclear diagnostics that together provide clear evidence that the ignition threshold was surpassed and that target gain > 1 should be achievable. In addition to multiple independent neutron yield measurements all confirming the fusion energy produced, neutron and x-ray imaging, neutron spectrum, burn duration and Hohlraum x-ray measurements all evidence clear, significant differences.

Having entered this new era of ignition, a new and exciting challenge is faced to meet the demands of clean inertial fusion energy. This requires energy output >100x that discussed here and at repetition rates approaching 10Hz. Spanning these gaps will be the stimulating, but difficult task

of the decades ahead, and undoubtedly developing a new range of radiation hard, high repetition-rate optical, x-ray and nuclear diagnostics compatible with power production will be key to meeting that challenge.

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