Review of Scientific Instruments

RESEARCH ARTICLE | SEPTEMBER 24 2024

Learning from each other: Cross-cutting diagnostic development activities between magnetic and inertial confinement fusion (invited)

Special Collection: Proceedings of the 25th Topical Conference on High-Temperature Plasma Diagnostics

M. Gatu Johnson ; D. Schlossberg ; B. Appelbe; J. Ball ; M. Bitter ; D. T. Casey ; A. Celora ; L. Ceurvorst ; H. Chen ; S. Conroy; A. Crilly ; G. Croci ; A. Dal Molin ; L. Delgado-Aparicio; P. Efthimion; B. Eriksson ; J. Eriksson ; C. Forrest ; C. Fry ; J. Frenje ; L. Gao ; H. Geppert-Kleinrath ; V. Geppert-Kleinrath ; E. Gilson ; P. V. Heuer ; K. Hill ; H. Khater ; F. Kraus ; F. Laggner ; Y. Lawrence ; S. Mackie ; K. Meaney ; A. Milder ; A. Moore ; M. Nocente ; N. Pablant ; E. Panontin ; M. Rebai ; B. Reichelt ; M. Reinke ; D. Rigamonti ; J. S. Ross ; M. Rubery ; L. Russell ; M. Tardocchi ; R. A. Tinguely ; C. Wink

Check for updates

Rev. Sci. Instrum. 95, 093533 (2024)
https://doi.org/10.1063/5.0218498

View Online
Export Citation

Articles You May Be Interested In

Quantifying the effects of neutron fluence on proton signal retention in CR-39

Rev. Sci. Instrum. (October 2024)

Preface to special issue: Private fusion research: Opportunities and challenges in plasma science

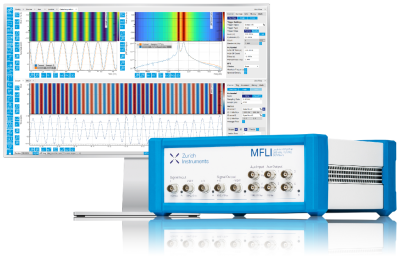
Phys. Plasmas (September 2024)

Determination of the response for the National Ignition Facility particle time of flight (PTOF) detector using single particle counting

Rev. Sci. Instrum. (October 2024)

14 October 2024 14:57:47

Challenge us.
What are your needs for periodic signal detection?
Zurich Instruments
Find out more



AIP Publishing

Review of Scientific Instruments ARTICLE pubs.aip.org/aip/rsi

Learning from each other: Cross-cutting diagnostic development activities between magnetic and inertial confinement fusion (invited)

Cite as: Rev. Sci. Instrum. 95, 093533 (2024); doi: 10.1063/5.0218498
Submitted: 11 May 2024 • Accepted: 13 July 2024 •
Published Online: 24 September 2024

View Online Export Citation CrossMark

M. Gatu Johnson,[1,a)] D. Schlossberg,[2] B. Appelbe,[3] J. Ball,[1] M. Bitter,[4] D. T. Casey,[2] A. Celora,[5] L. Ceurvorst,[6] H. Chen,[2] S. Conroy,[7] A. Crilly,[3] G. Croci,[5] A. Dal Molin,[8] L. Delgado-Aparicio,[4] P. Efthimion,[4] B. Eriksson,[7] J. Eriksson,[7] C. Forrest,[6] C. Fry,[9] J. Frenje,[1] L. Gao,[4] H. Geppert-Kleinrath,[9] V. Geppert-Kleinrath,[9] E. Gilson,[4] P. V. Heuer,[6] K. Hill,[4] H. Khater,[2] F. Kraus,[4] F. Laggner,[10] Y. Lawrence,[1] S. Mackie,[1] K. Meaney,[9] A. Milder,[6] A. Moore,[2] M. Nocente,[5] N. Pablant,[4] E. Panontin,[1] M. Rebai,[8] B. Reichelt,[1] M. Reinke,[11] D. Rigamonti,[8] J. S. Ross,[2] M. Rubery,[2] L. Russell,[1] M. Tardocchi,[8] R. A. Tinguely,[1] and C. Wink[1]

AFFILIATIONS

[1]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[2]Lawrence Livermore National Laboratory, Livermore, California 94551-0808, USA
[3]Centre for Inertial Fusion Studies, The Blackett Laboratory, Imperial College, London SW7 2AZ, United Kingdom
[4]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08540, USA
[5]Department of Physics "G. Occhialini," University of Milano-Bicocca, Milan, Italy
[6]Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
[7]Department of Physics and Astronomy, Uppsala University, SE-75237 Uppsala, Sweden
[8]Institute for Plasma Science and Technology, National Research Council, Milan, Italy
[9]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[10]North Carolina State University, Raleigh, North Carolina 27695, USA
[11]Commonwealth Fusion Systems, Devens, Massachusetts 01434, USA

Note: This paper is part of the Special Topic on Proceedings of the 25th Topical Conference on High-Temperature Plasma Diagnostics.

[a)]**Author to whom correspondence should be addressed:** gatu@psfc.mit.edu

ABSTRACT

Inertial Confinement Fusion and Magnetic Confinement Fusion (ICF and MCF) follow different paths toward goals that are largely common. In this paper, the claim is made that progress can be accelerated by learning from each other across the two fields. Examples of successful cross-community knowledge transfer are presented that highlight the gains from working together, specifically in the areas of high-resolution x-ray imaging spectroscopy and neutron spectrometry. Opportunities for near- and mid-term collaboration are identified, including in chemical vapor deposition diamond detector technology, using gamma rays to monitor fusion gain, handling neutron-induced backgrounds, developing radiation hard technology, and collecting fundamental supporting data needed for diagnostic analysis. Fusion research is rapidly moving into the igniting and burning regimes, posing new opportunities and challenges for ICF and MCF diagnostics. This includes new physics to probe, such as alpha heating; increasingly harsher environmental conditions; and (in the slightly longer term) the need for new plant monitoring diagnostics. Substantial overlap is expected in all of these emerging areas, where joint development across the two subfields as well as between public and private researchers can be expected to speed up advancement for all.

14 October 2024 14:57:47

© Author(s) 2024

© 2024 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 4.0 International (CC BY-NC-ND) license (https://creativecommons.org/licenses/by-nc-nd/4.0/). https://doi.org/10.1063/5.0218498

I. INTRODUCTION

The fields of Inertial Confinement Fusion and Magnetic Confinement Fusion (ICF and MCF) are separated by orders of magnitude in plasma parameters (10^{12} in time, 10^{11} in density, and similar temperatures). Nonetheless, obvious commonalities exist. Both use the fuels of deuterium (D) and tritium (T) to maximize fusion output through the D + T → α + n (DT) reaction, with the goal of using the emitted neutrons to generate electricity and the alpha particle to provide plasma self-heating. Both strive to minimize impurities entering the plasmas, as high-Z ions will lead to unintended cooling. Significant diagnostic advancements have resulted from collaborations between these groups that have benefited both communities, and historical precedent exists for cross-cutting efforts.[1,2] Still, many unexplored opportunities exist for further coordination, exploration, and cross-pollination of ideas and techniques that would benefit both scientific communities and the field of fusion science as a whole. This paper discusses several of these areas of research, focusing on cross-cutting diagnostic-development activities and their particular relevance to the burning and ignited plasma regimes that both communities are entering.[3–5] Common calibration, data acquisition, and synthetic diagnostic needs are also considered, along with overlapping needs for fundamental data needed for analysis.

Examples of successful cross-community knowledge transfer are discussed that highlight the potential gains from working together. This includes high-resolution x-ray imaging spectroscopy and magnetic recoil neutron spectrometry, both of which started in MCF and were subsequently adapted for ICF, with lessons from the ICF implementation then applied in new MCF designs. Neutron spectrum modeling is also discussed as an example.

Many opportunities for near- and mid-term collaboration are also considered, including in the areas of Chemical Vapor Deposition (CVD) diamond detector technology, using gamma rays to monitor fusion gain, handling neutron-induced backgrounds, and collecting fundamental atomic physics and nuclear cross section data that will benefit diagnostic analysis or system development in both fusion subfields.

Fusion research moving into the burning and igniting plasma regimes is posing new opportunities and challenges for MCF and ICF diagnostics. This includes new physics to probe, with the impact of alpha heating as a prime example. It also includes environmental conditions becoming increasingly harsher, not least in terms of neutron fluence, placing more stringent requirements on radiation hard technology. With many new fusion test facilities at the planning or early construction stages in the nascent private industry, a mid-term need for plant monitoring diagnostics is also anticipated, many of which will directly overlap between ICF and MCF-based designs.

The paper is organized as follows: Sections II–IV present case studies of demonstrated knowledge transfer with the results "greater than the sum of its parts." Sections V and VI discuss CVD diamond technology and gamma ray detection, two technology areas ripe for collaboration. Section VII discusses overlapping needs for fundamental data, including atomic physics data and nuclear cross sections. Section VIII tackles the challenge posed by high neutron flux, while Sec. IX discusses existing capabilities for detector testing and fundamental measurements. In Sec. X, opportunities to learn from each other in the area of data handling are considered. Finally, Sec. XI considers upcoming pilot plant-relevant needs and makes some concluding remarks.

II. DETECTOR CASE STUDY 1: THE X-RAY SPECTROSCOPY PROGRAM AT PPPL

High-resolution x-ray imaging crystal spectrometers (XICSs) were invented in MCF for the NSTX facility in the late 1990s.[6] Using a spherically bent crystal and 2D pixelated detector, enabled by the Bragg relation and rotational symmetry of spherical reflectors, XICS represented a substantial advance over previous systems, which measured the spectrum along a single narrow sightline and provided ion temperature (T_i) and toroidal plasma velocity (v_{tor}) at only one point on the spatial profile. After the first tests at Alcator C-Mod,[7–9] XICS systems have been implemented by PPPL for leading MCF facilities including KSTAR, EAST, LHD, W7X, WEST, and JT-60SA, providing routine measurement of electron temperature and density (T_e, n_e), T_i, and v_{tor}.

Following the successful MCF implementation, the XICS technology was adapted for high-resolution x-ray spectroscopy on both the High Energy Density (HED)[10] and ICF platforms. A spectrometer for OMEGA EP[11,12] (HiResSpec) and one for the Orion laser[13] (OHREX) were implemented that achieved high spectral resolution for the point-like HED source. A second system, dubbed dHIRES,[14] was developed for fielding in a NIF diagnostic insertion module (DIM). This system, with the crystals absolutely calibrated in the PPPL x-ray lab, provides full absolute calibration of the hotspot parameters from Kr-doped implosions, measuring T_e, n_e, and areal density (ρR) and implosion radius (R) as a function of time.[15] This is exemplified and contrasted to MCF data in Fig. 1, which shows high-resolution He-like Kr spectra obtained from TFTR[16] and NIF[15] plasmas, respectively. Kr was injected via a gas puff at the edge of the TFTR plasma discharges, and its x-ray emission from the plasma core was measured using the high resolution TFTR vertical crystal spectrometer.[17] The upper panel in Fig. 1 shows the experimentally measured Kr Heα complex plus lines from other charge states such as Li-, Be-, and B-like ions, all of which are nicely resolved. The forbidden line z near 12.98 keV, free from satellite line contamination, was successfully used to infer the central T_i via Doppler broadening. The team then applied a similar technique to ICF plasmas at the NIF. The lower panel shows time-resolved Kr Heβ spectra obtained using NIF dHIRES.[14] The high-quality spectral data allowed detailed line-shape analyses where n_e was successfully inferred from Stark broadening of the resonance line at 15.43 keV and T_e deduced from the intensity ratio between the Heβ complex and the Li-like satellite lines.[15,18]

14 October 2024 14:57:47

© Author(s) 2024

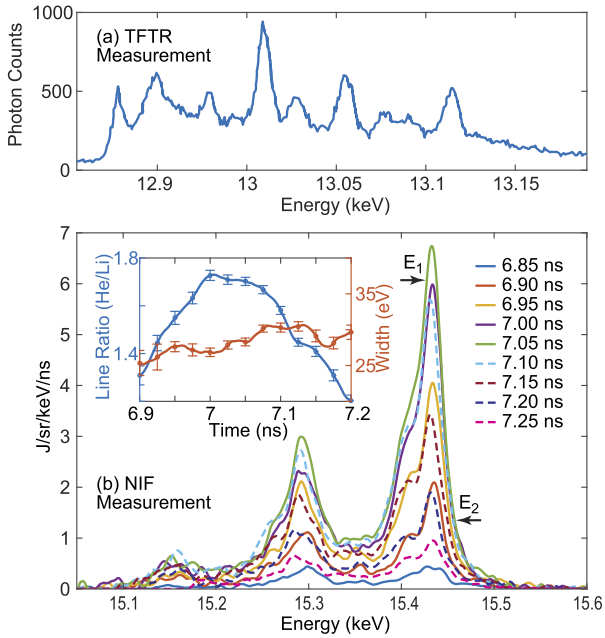


FIG. 1. He-like Kr spectra obtained from (a) TFTR and (b) NIF plasmas.

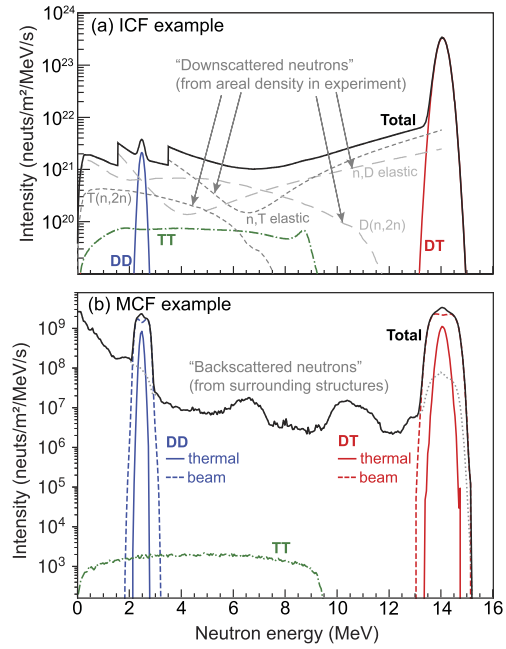


FIG. 2. (a) ICF example neutron spectrum calculated based on measured parameters for NIF shot N230508, with $Y_{DT} = 5.5 \times 10^{16}$, $T_i = 6.8$ keV, and $\rho R = 0.8$ g/cm^2, using the TT spectrum inferred from an OMEGA measurement at $T_i = 4$ keV,[35] assuming fuel ion number densities $n_T/n_D = 1$, and with the downscattered neutron spectrum calculated from cross sections only (no multiscatter or broadening). (b) MCF example neutron spectrum calculated based on measured parameters for JET discharge 98 044 with 100 keV D NB heating at 14 MW, $n_e = 5 \times 10^{19}$ m^{-3}, $T_e = 4$ keV, and trace T injection (inferred from data presented in Ref. 31). Both MCF and ICF intensity scales are calculated for a detector 19 m from the plasma; the ICF intensity scale assumes a measured 77 ps burn duration.

While dHIRES relied on conical and cylindrical crystals, advanced applications in Extended X-ray Absorption Fine Structure[19] (EXAFS) required optimizing both spectral resolution and throughput, hence the development of a new crystal shape, the VR-spiral. This was enabled through the collaboration PPPL–LLNL, which allowed the manufacturing of this new crystal to the required specifications. X-ray raytracing calculations demonstrate a 5× improvement in resolution using this crystal compared to previously used torus shapes.

A radiation hardened XICS is now in construction for ITER,[20] using a highly oriented pyrolytic graphite (HOPG) crystal as a pre-reflector.[21] The HOPG crystal reflects x-rays onto a second spherical crystal 9 m away from the plasma, allowing the second crystal to be protected from direct radiation. Plans are underway to test the resiliency of the HOPG crystal in high neutron flux at the OMEGA ICF facility. This design could also be implemented as a radiation hardened spectrometer for ICF.

Learning from each other will be crucial for developing the next generation of XICS under harsh environments for burning plasmas. Cross-cutting areas in XICS between MCF and ICF include source development, crystal innovation, handling harsh environments, calibration techniques, and advanced analysis techniques, including ray tracing and atomic physics calculations/benchmarking (see Sec. VII).

III. A "PHYSICS IN THE DATA" CASE STUDY: NEUTRON SPECTRUM MODELING

A. Similarities and differences

One obvious area of overlap between ICF and MCF is using neutron emission to diagnose conditions in the plasma. Counting neutrons provides a measure of total neutron yield (Y_{DT}) or fusion power (P_{fus}) output. Neutron spectrum measurements allow inference of T_i from the width of the primary spectrum and v_{rot}[22,23] (MCF)/flow velocity v_{flow}[24–26] (ICF) from its mean energy. Seminal work in the theory of inferring T_i and v from neutron spectra was published in MCF by Ballabio *et al.*[27] in 1998—15 years after publication, this paper had become a go-to reference for researchers in ICF. Knowledge of the impact of v_{rot} on neutron spectra from MCF allowed researchers to identify observed peak shifts in ICF spectra as signatures of directional capsule flow;[24] this turned out to be a primary diagnostic providing insight for optimizing ICF implosion symmetry and performance on the road to ignition.[28] Studying the relative intensities of the primary $D + D \rightarrow {}^3He + n$ (DD), DT, and, under certain conditions, $T + T \rightarrow \alpha + n + n$ (TT) neutron contributions to the spectrum is used as a method of inferring fuel ion ratios in both MCF[29–31] and ICF[32,33] (Fig. 2). Note that the TT measurement relies on knowing the shape of the TT neutron spectrum; efforts to measure this have been undertaken in both ICF[34,35] and MCF,[36] and results from the two were found to compare well but also to depend on the T_i of the plasma.

Figure 2 illustrates that while there are similarities, there are also differences. Neutron spectra in ICF are routinely used to infer the key performance parameter of ρR,[37] a measure of

14 October 2024 14:57:47

© Author(s) 2024

fuel compression obtained from the ratio of primary DT neutrons to neutrons that have lost energy through scattering in the assembled fuel. Methods to use these downscattered neutrons as a diagnostic of burn propagation have also recently been developed.[38,39] Given the 11 orders of magnitude lower density of MCF compared to ICF (10^{14}–10^{25} cm^{-3}), neutron scattering in the assembled MCF fuel is typically negligible. Instead, MCF neutron spectra provide information about fast ion populations from the auxiliary neutral beam[40,41] (NB) and radio frequency[42,43] (RF) heating and the ratio of thermal to non-thermal power output ($Q_{thermal}/Q_{non\text{-}thermal}$).

In both ICF and MCF, scattered neutron background also has to be considered (see, e.g., Refs. 44 and 45). This includes collimator inscatter, backscatter,[46] and scatter contributions from surrounding structures, including the impact of neutron-induced gamma.

B. Modeling tools

Analysis of neutron spectrometry data in both ICF and MCF is typically done through forward fit techniques (see, e.g., Refs. 47 and 48), where a model neutron spectrum is folded with the instrument response function and then compared to the measured data. Under certain conditions, neutron spectra can be modeled analytically, e.g., as shown in ICF by Appelbe and Chittenden.[49] However, in many cases, it is useful to be able to calculate neutron spectra from arbitrary fuel ion velocity distributions. A Monte Carlo framework for doing this—the DRESS code[50]—was developed in MCF. This code was validated against analytical calculations from Ref. 49 (Fig. 3) and is now being applied to physics problems on both the MCF and ICF[51] platforms. Modeling of ICF downscattered neutron spectra has made use of Monte Carlo,[52,53] deterministic,[54] and reduced[55] neutron transport models.

C. The burning plasma future

Using neutron spectrometry to diagnose alpha heating was first proposed[56] and demonstrated[57] in MCF. The principle behind this measurement is that the 3.5-MeV DTα can undergo a knock-on collision with a D or T fuel ion, increasing the energy of that fuel ion. These supra-thermal ions can then in turn react with a thermal D or T ion, giving rise to a supra-thermal alpha knock-on (AKN) component in the neutron spectrum.[58,59] The AKN tail extends to higher energies than thermal neutrons, becoming a signature of alpha heating in the plasma above a T_i-dependent cut-off energy. In MCF, this tail will compete with fast neutrons arising from RF heating;[59] in ICF, it will compete with a similar neutron knock-on (NKN) process. In both cases, fast tritons born in D + D → t + p reactions can also react with thermal D, giving rise to competing high-energy "triton burn-up" (TBN) neutrons. The AKN and NKN tails are now starting to be observed in ICF.[60] ICF-MCF collaboration in modeling, interpretation, and instrument optimization to observe this feature is expected to help both fields diagnose alpha heating going forward.

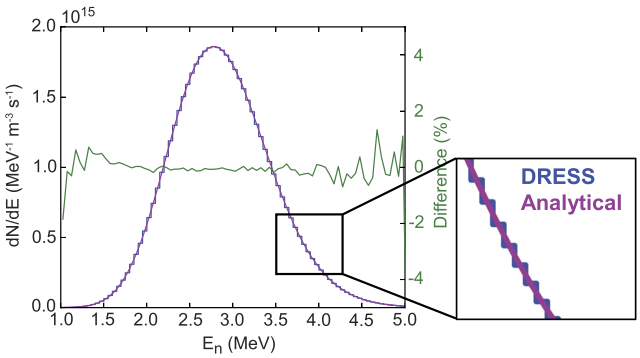


FIG. 3. The DRESS code for calculating neutron spectra from arbitrary fuel ion velocity distributions, developed for MCF, was validated against analytical calculations done for ICF. The code is now being used to model neutron spectra in ICF and MCF. Reprinted with permission from J. Eriksson *et al.*, Comput. Phys. Commun. 199, 40 (2016). Copyright 2015 Elsevier.

IV. DETECTOR CASE STUDY 2: MAGNETIC RECOIL NEUTRON SPECTROMETERS

A neutron spectrometer based on the magnetic proton recoil (MPR) technique was first proposed[61] and developed[62,63] for MCF, with installation on the JET tokamak in 1996. In this type of system, neutrons scatter elastically in a thin conversion foil at a set distance from the fusion experiment, knocking out recoil ions. Forwardly scattered recoils are then selected by an aperture and momentum-separated in a magnetic field to end up in a different location on the backend detector depending on their energy, with the incident neutron spectrum inferred from the recoil position histogram. The MPR, optimized for DT and later adapted for use with DD neutrons (MPRu[64]), uses selectable foils and apertures ~4 m from the plasma, electromagnets (tunable to study either the DD or DT energy range), and a detector hodoscope of scintillators coupled to photomultiplier tubes (PMTs). It was successfully used during the 1997 JET DT campaign[65] to infer fast ion physics, including the impact of NB and RF heating[66,67] and the first-ever measurements of the AKN tail.[57]

Given the success of MPR in measuring weak components of the neutron spectrum, the technique was subsequently proposed[68] for measurements of the critical (and notoriously hard to measure[69]) fuel ρR in ICF. Three key changes were made compared to the JET MPR to optimize for ICF conditions: (i) the conversion foil was fielded close to the experiment instead of close to the detector (the goal of this was to allow downscattered neutron measurements with maximal time separation to primary neutron background; efficiency in the two cases is comparable as it is determined by two solid angles, "plasma–foil" and "foil–magnet aperture"); (ii) recoil deuterons were added as an option (easier to separate from background on both time-resolved and time-integrating detectors); and (iii) a time-integrating CR-39-based backend detector was used (this was motivated by the very different facility shot durations and neutron rates in the two cases—10^{19} s^{-1} over seconds at JET vs10^{28} s^{-1} over of order 100 ps at NIF). Permanent magnets were used instead of electromagnets. Two systems, dubbed MRS, were built,[70] one for the OMEGA laser (2007) and one for the NIF laser (2010). Both systems have been running with CD conversion foils and time-integrating CR-39 backend detectors since their installation, providing key Y_{DT}, ρR,[71] T_i,[72] and v_{flow}[24] performance parameters and helping guide the primary programmatic DT implosion campaigns

14 October 2024 14:57:47

© Author(s) 2024

at each facility to ever-improving performance.[3,73] (Time-resolving detectors are being considered for ICF as well, but the short time scale places very different requirements on these compared to for MCF applications, see; e.g., Refs. 74 and 75.)

The MCF SPARC facility[76] under construction, planning to demonstrate Q = 11 in DT plasmas, will require the ability to infer P_{fus}, neutron emission rate, T_i, and $Q_{thermal}/Q_{non\text{-}thermal}$ and to study the impact of alpha heating. An MPR-like system is being designed to meet these needs,[77] with electromagnets to allow measurements of DD or DT neutron spectra and a scintillator hodoscope as the back-end detector. This system is being developed in conjunction with a new MRS being designed to handle higher yields on the NIF,[78] with the MCF and ICF design teams working closely together on problems including magnet design, optimal conversion foil geometry, and shielding needs.

In addition to magnetic recoil-based systems, both ICF and MCF also use time-of-flight-based systems to measure the neutron spectrum. However, given the different time scales, these systems differ significantly. With a continuous source of neutrons, MCF systems use "start" and "stop" detectors, inferring neutron energy from the time difference between the two,[79] while ICF systems[80] use the near-instantaneous implosion as "start" and infer the neutron spectrum based on time dispersion over the distance to the detector.

V. CVD DIAMOND TECHNOLOGY

Another area where the ICF and MCF communities can learn from each other is in Chemical Vapor Deposition (CVD) diamond technology, which is being used in both communities, although in different applications. In both cases, a CVD diamond wafer is biased to high voltage. When incident radiation strikes the diamond, electron–hole pairs are formed, leading to an electrical impulse that can be read out using an oscilloscope or digitizer. On the ICF side, CVD diamonds are used in the NIF particle time-of-flight (pTOF) detector[81] to measure the time of peak nuclear burn, recording the D^3He proton and/or DD and/or DT neutron emission from implosions with a yield of $<10^{14}$. In this case, the diamond is fielded 50 cm from the plasma and run in current mode, with the signal (flux $\leq 3 \times 10^{19}$ cm^{-2} s^{-1}) recorded on an oscilloscope as a function of time. In MCF, diamonds are used for high-resolution DT neutron spectrum measurements.[82,83] Three diamond detectors have been installed at JET along three lines of sight (one 12-pixel diamond matrix and two single pixel diamonds) to make such measurements. In this case, the diamonds record the total charge of single event pulses using a digitizer, and a deposited energy spectrum is reconstructed. For DT in particular, the $^{12}C + n \rightarrow \alpha + {}^{9}Be$ reaction gives rise to a narrow peak at 8.5 MeV deposited energy, which can be analyzed to infer P_{fus}, T_i, fast fuel ion tails, and $Q_{thermal}/Q_{non\text{-}thermal}$.[83] Because of the compactness of CVD diamonds, they are also being tested for implementation in each line of sight of the neutron camera being built for the SPARC tokamak (flux $\leq 6 \times 10^8$ cm^{-2} s^{-1}), with the intent of inferring the fusion power, alpha birth, and T_i profiles.[84]

The two different applications place different requirements on the diamonds. MCF diamonds should be optimized for high sensitivity with minimal charge trapping. ICF diamonds need to have a fast time response,[85] which is obtained with maximal charge trapping. The level of trapping can be tuned by varying the level of impurities in the diamonds; exactly how to optimize characteristics for the two fields is an area of active research.

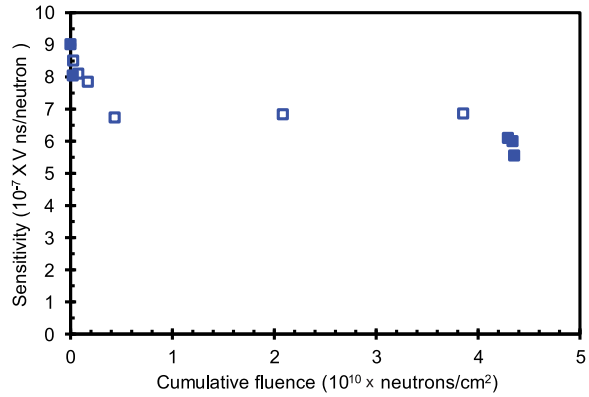


FIG. 4. Measured DT neutron sensitivity for a CVD diamond fielded on the OMEGA laser facility on October 19, 2011, as a function of accumulated neutron fluence on the detector. Each point represents one shot; solid (hollow) points represent shots where the peak signal amplitude was less (more) than 10% of the detector bias voltage.

In a direct demonstration of learning from each other, MCF and ICF teams working on diamond technology have been testing their diamonds together using a DT neutron source and radioactive button sources[86] in an MIT accelerator lab,[87] including testing the impact of using each other's amplifiers and digitizers and helping each other with calibration source characterization.

Diamonds have also been previously tested as high-yield neutron time-of-flight (nTOF) detectors in ICF,[88,89] but their response was found to degrade with neutron dose (longer decay tails and reduced sensitivity were observed after intense neutron exposure, see Ref. 80 and Fig. 4), and they are no longer used for this application. It is possible that the MCF scientists gearing up for the use of diamonds in high-yield DT experiments can learn from this experience.

VI. GAMMA MEASUREMENTS

In addition to the $D + T \rightarrow \alpha + n$ branch, there is also a much weaker ($<10^{-4}$) $D + T \rightarrow {}^{5}He + \gamma$ reaction branch. Currently implemented gamma detectors in ICF and MCF focus on different physics with gamma spectrometers in MCF used to study fast ion physics,[90,91] and gas Cherenkov detectors in ICF primarily used to measure implosion timing (from the γ emission history).[92] Both subfields recognize the potential of the DTγ to be used as an unperturbed Y_{DT}/P_{fus} measurement.[93] However, to enable this measurement, the DTγ branching ratio needs to be better understood. Both the ICF[94–96] and MCF[97,98] platforms are being used to constrain this ratio, and results from one will obviously be used in the other. In addition, there are two γ-rays emitted, one associated with the ground state (γ_0) and one with the excited state (γ_1) of ^{5}He. For this reason, there is a need to understand the DT-gamma spectrum, which is also being inferred from both ICF[99] and MCF[100] data.

14 October 2024 14:57:47

© Author(s) 2024

Another area of commonality between MCF and ICF gamma measurements is the need to understand interference from competing reactions. This can include gammas from 14 MeV DT neutrons scattering inelastically on relevant elements, e.g., C, Al, Si, and W; from neutron capture on elements such as C or W; or from processes such as HT and DD fusion. There is very limited data available on the cross sections for these reactions (see, e.g., Refs. 101 and 102); such data would help both subfields, which further motivates working together.

VII. FUNDAMENTALS: BASIC SCIENCE

In addition to detector technology, accurate measurements also require an understanding of the fundamental underlying physics. Examples of this have already been given in the text above, including an understanding of the shape of the TT neutron spectrum and accurate knowledge of the DTγ/DTn branching ratio. In this section, two additional examples of basic science areas with direct overlap between MCF and ICF are discussed: atomic physics and nuclear cross sections, including those relevant to tritium breeding.

A. Atomic physics

Analysis of x-ray spectroscopy (and other plasma emission-based) diagnostics relies on underlying atomic physics data.[103] There is a great deal of overlap between the atomic physics needs for x-ray diagnostics for ICF/HED/MCF. All cases have benefited from the development of atomic physics calculation codes pushed forward and motivated by the individual needs of various experiments. Perhaps more importantly, experiments in ICF, HED, and MCF have all helped to validate these atomic physics calculations in very different and complementary ways; each of these experiments tests the codes in different physics regimes and allows different aspects of the physics models and approximations to be explored, leading to overall improvements in code capabilities and accuracy.

The next frontier in advancing atomic physics calculations is the integration of uncertainty in the theoretical and computational chains.[104] As the quality of instrumentation and calibration has advanced for x-ray diagnostics in ICF/HED/MCF, the question of atomic physics uncertainty has come to the forefront. Important to all of these measurements is a way to estimate the systematic uncertainties that come from uncertainties in the underlying atomic physics. A dedicated effort, motivated by measurement needs from both the high-density and low-density plasma communities, to expand existing atomic physics codes to include uncertainty would dramatically improve the understanding of all such measurements.

B. Nuclear cross sections

Interpretation of nuclear diagnostic data as well as calculations of expected signal, background, and required shielding are examples of areas that require an accurate understanding of nuclear cross sections. Even simple calculations of expected signal levels (e.g., direct vs scattered neutrons or gamma signal vs background) vary based on the specific cross sections used. For example, based on available cross section extrapolations, 20% non-DT background contamination (from n,γ reactions in the materials surrounding the target) is expected in the NIF gas Cherenkov gamma detectors[92] run at a threshold of 10 MeV, while experiments suggest 5% contamination for a factor 4 discrepancy. Another example is cross sections relevant to MCF or ICF power plant blanket materials, such as FLiBe, many of which are poorly understood.[105] These cross sections are needed for an improved understanding of tritium breeding rates, which is of obvious relevance for both MCF and ICF on the road to realizing fusion as an energy source. As an example, more accurate knowledge of the ^{7}Li and ^{9}Be cross sections at 14 MeV is needed, including n + ^{9}Be → 2n + ^{8}Be and n + ^{7}Li → 2n + ^{6}Li (available data vary by factors of about 2 and 3, respectively[106]).

VIII. NEUTRON BACKGROUND

Improved fusion experiment performance is synonymous with more neutrons. This has implications as a background to be dealt with in data, for maintaining detector calibrations, as a source of damage to electronics and other hardware, and for general facility and personnel safety measures; some of these issues have already been encountered during DT operation in the past, e.g., at TFTR.[107] Examples of MCF-ICF overlap in dealing with high neutron fluence are discussed in this section.

A. Impact on measurements

Optimizing detectors to avoid neutron-induced background swamping the signal to be measured is a long-standing problem in both ICF and MCF, with obvious overlap between the two areas. An example is LaBr detectors. On the NIF, a system of 48 real-time activation detectors is used to measure the spatial distribution of the primary DT neutron emission, with Zr pucks activated through the ^{90}Zr(n,2n)^{89} Zr reaction and the γ emitted from ^{89}Zr read out by LaBr detectors.[108] After a high yield shot, the detectors are swamped with γ and β background from the activation of surrounding materials, preventing immediate analysis of the ^{89}Zr emission peak on the order of hours to days, depending on the experiment performance. While this is not unmanageable for a low-shot-rate facility such as NIF, it does place constraints on how close shots requiring this diagnostic can be scheduled (and presents obvious problems for future higher repetition rate facilities). A similar problem is anticipated for the hard x-ray (HXR) detectors being planned for SPARC, which require activity $<10^{6}$ Bq for runaway electron measurements at startup to work. Simulations show that using unshielded LaBr detectors, this condition may not be met until ~10 h after a reference Q = 11 discharge.[109] Efforts are underway to improve this number by adding shielding to the design and considering detector materials other than LaBr.

B. Radiation hardening

Increased neutron fluence brings the need to adapt detector technology and diagnostic layout (placement, shielding) to allow operation without radiation effects damaging diagnostic components or impacting reliability (stability and calibration).[110] Detrimental effects have been seen at DT facilities, including TFTR[107] and NIF,[111] and some mitigation strategies have been tested, including using radiation hard optical fibers[111] and heating transmission

14 October 2024 14:57:47

© Author(s) 2024

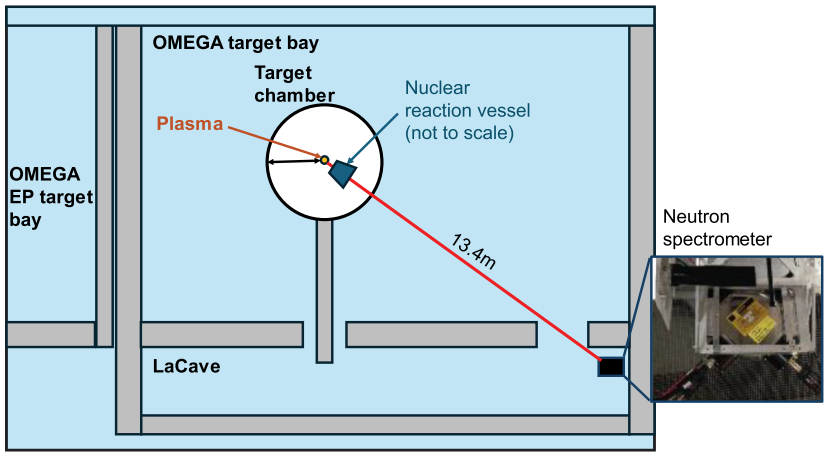


FIG. 5. Cartoon of the OMEGA target chamber (not to scale), illustrating the line-of-sight for cross section measurements using a nuclear reaction vessel and neutron spectrometer. Components for testing have also previously been placed in LaCave and could potentially be placed inside the target bay.

fibers.[107] There is a joint MCF-ICF need for component lifetime and shielding design studies and for tests to establish radiation effects on vulnerable electronics components, including cables, fibers, sensors, actuators, and shutters, as well as for finding radiation hard replacements. Such efforts are underway and can be accelerated by coordination.

C. Neutron transport modeling

The Monte Carlo N-Particle transport code[112] as well as the open-source Open Monte Carlo (OpenMC) code[113] are used to design diagnostic shielding and ensure the adequacy of radiation barriers in both ICF and MCF. Development and benchmarking of these codes as well as of facility models using the codes is another key area of overlap where the two fields can leverage each other's expertise to make more rapid progress.

IX. TESTING AT EXISTING FACILITIES

Several examples discussed in this paper highlight the need for testing or other offline measurements, including detector calibration, radiation effects, or fundamental physics such as cross sections needed for analysis or modeling. Existing facilities provide opportunities for testing that MCF, ICF, and other subfields can jointly take advantage of. This includes neutron irradiation facilities at National Labs such as the Los Alamos Neutron Science Center (LANSCE);[114] at universities such as the PULSTAR facility at North Carolina State University;[115] and in the industry such as Shine Technologies.[116]

High neutron flux is also available at some of the fusion facilities themselves. As an example, the OMEGA laser facility can generate on the order of 10^{14} neutrons/shot in up to 12 shots during a shot day (with a burn duration of order 150 ps, this means 5×10^{22} n s^{-1} sr^{-1}; samples can be fielded as close as 10 cm from the implosion). This platform has been previously used both for cross section measurements, using a nuclear reaction vessel with the material of interest fielded close to the plasma and a neutron spectrometer in the same line-of-sight, 13.4 m away,[117] and for detector component testing,[118] placing the components below the target bay floor (Fig. 5). As mentioned above, discussions are also underway to use this platform for testing the HOPG crystal for the ITER XICS. The SPARC facility plans to achieve $>10^{20}$ neutrons/2 s shot in its highest performing discharges, potentially providing future opportunities for higher fluence testing (outside an open port covering 1/18th of the plasma, the fluence would be $\sim 2 \times 10^{17}$ n s^{-1} sr^{-1}).

In terms of detector calibration needs, available platforms include an x-ray lab at PPPL and accelerator facilities[87] at MIT. All areas could benefit from central coordination of available calibration facilities, similar to the LaserNetUS consortium[119] coordinating access to short pulse laser facilities.

X. DATA HANDLING

ICF and MCF have similar data handling and analysis method needs, and expertise in one area can be leveraged in the other. In terms of data handling, cross-over is more easily facilitated if similar data formats and file structures are used across facilities. MCF uses the OMFIT software ecosystem;[120] this could inspire similar software for ICF, where different facilities currently have different systems in place. Common control system infrastructure, such as the open-source Experimental Physics and Industrial Control System (EPICS) project,[121] could also increase synergy and facilitate cross-over. In terms of analysis, an emerging focus area in both MCF and ICF[122] is methods for combining information from many diagnostics using machine learning techniques. This is another area ripe for fruitful collaboration going forward.

XI. MOVING FORWARD

Remarkable changes are happening in the field of fusion research. Within the last few years, the NIF achieved ignition;[3] new magnet technology was demonstrated that should facilitate magnetic fusion energy production on smaller scale machines;[4] and a fusion energy record was accomplished.[5] The White House announced the

14 October 2024 14:57:47

© Author(s) 2024

"Bold Decadal Vision," with the goal of bringing fusion power to the grid on a time scale that will help with the climate crisis. After decades of primarily public research, many private fusion companies have appeared on the scene within both ICF and MCF. With this, new facilities are expected to come online with new diagnostic needs, including infrastructure diagnostics. Many of these diagnostics will directly overlap between inertial and magnetic fusion energy. The field could move forward faster and cheaper with the different new facilities collaborating on common diagnostic development needs; "diagnostic consortia" have been proposed[123] as a path to making this happen.

Public-private collaborations are a key part of the new landscape. Finding ways of working together across the public-private dividing line is another area where MCF and ICF are already learning from each other. In this new era, workforce needs are also expected to grow; fusion energy would benefit from a thoughtful approach to how to equitably grow the workforce being developed jointly between ICF and MCF.

This paper makes no claim about covering all opportunities for overlap. The examples highlighted show the benefits of working together and are intended to stimulate further discussion; some of the listed examples, especially in the later sections, are speculative.

A key to the cross-cuts that have happened so far is the people involved. In the area of x-ray imaging spectroscopy, a close-knit team of scientists at PPPL, including experts in MCF and ICF/HED, are working together, learning from each other, and enabling the advances discussed. The initial transfer of neutron spectrometry from MCF to ICF was enabled by scientists transferring from one field to the other. Close connections between people on both sides are now facilitating further advancement, both in terms of detector technology and modeling. Similar collaborations can be initiated in other areas, including but not limited to gamma detection, which is an area ripe for collaboration, as highlighted in this paper.

ACKNOWLEDGMENTS

This work was supported in part by the U.S. Department of Energy NNSA MIT Center-of-Excellence under-Contract No. DE-NA0003868, by LLNL under-Contract No. B656484, and by Commonwealth Fusion Systems. This material is partly based upon work supported by the Department of Energy [National Nuclear Security Administration] at the University of Rochester's "National Inertial Confinement Fusion Program" under-Award No. DE-NA0004144. 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 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 the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

M. Gatu Johnson: Conceptualization (equal); Investigation (lead); Writing – original draft (lead). **D. Schlossberg**: Conceptualization (lead); Investigation (equal). **B. Appelbe**: Investigation (equal). **J. Ball**: Investigation (equal). **M. Bitter**: Investigation (supporting). **D.T. Casey**: Investigation (supporting). **A. Celora**: Investigation (supporting). **L. Ceurvorst**: Investigation (supporting). **H. Chen**: Investigation (supporting). **S. Conroy**: Investigation (supporting). **A. Crilly**: Investigation (equal); Writing – review & editing (equal). **G. Croci**: Investigation (supporting). **A. Dal Molin**: Investigation (supporting). **L. Delgado-Aparicio**: Investigation (equal). **P. Efthimion**: Investigation (equal). **B. Eriksson**: Investigation (supporting). **J. Eriksson**: Conceptualization (supporting); Investigation (equal). **C. Forrest**: Investigation (equal). **C. Fry**: Investigation (supporting). **J. Frenje**: Investigation (equal). **L. Gao**: Conceptualization (equal); Investigation (equal). **H. Geppert-Kleinrath**: Investigation (supporting). **V. Geppert-Kleinrath**: Investigation (supporting). **E. Gilson**: Investigation (supporting). **P.V. Heuer**: Conceptualization (supporting); Investigation (equal); Writing – review & editing (equal). **K. Hill**: Investigation (supporting). **H. Khater**: Investigation (equal). **F. Kraus**: Investigation (equal); Writing – review & editing (equal). **F. Laggner**: Investigation (equal). **Y. Lawrence**: Investigation (supporting). **S. Mackie**: Investigation (supporting); Writing – review & editing (supporting). **K. Meaney** Conceptualization (supporting); Investigation (equal); Writing – review & editing (equal). **A. Milder**: Investigation (supporting). **A. Moore**: Investigation (supporting). **M. Nocente**: Investigation (equal). **N. Pablant**: Investigation (equal); Writing – original draft (supporting). **E. Panontin**: Investigation (equal). **M. Rebai**: Investigation (supporting). **B. Reichelt**: Investigation (supporting). **M. Reinke**: Investigation (equal). **D. Rigamonti**: Investigation (supporting). **J.S. Ross**: Investigation (supporting). **M. Rubery**: Investigation (equal). **L. Russell**: Investigation (supporting). **M. Tardocchi**: Conceptualization (supporting); Investigation (equal). **R.A. Tinguely**: Conceptualization (supporting); Investigation (equal); Writing – review & editing (equal). **C. Wink**: Investigation (supporting).

DATA AVAILABILITY

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

REFERENCES

[1] A. J. Wootton, P. Stott, and D. M. Thomas, Rev. Sci. Instrum. **73**, 495 (2002).
[2] J. L. Bourgade *et al.*, Rev. Sci. Instrum. **79**, 10F304 (2008).
[3] H. Abu-Shawareb *et al.*, Phys. Rev. Lett. **132**, 065102 (2024).
[4] Z. S. Hartwig *et al.*, IEEE Trans. Appl. Supercond. **34**, 0600316 (2024).

14 October 2024 14:57:47

© Author(s) 2024

[5] J. Mailloux *et al.*, Nucl. Fusion **62**, 042026 (2022).
[6] M. Bitter, K. W. Hill, A. L. Roquemore, P. Beiersdorfer, S. M. Kahn, S. R. Elliott, and B. Fraenkel, Rev. Sci. Instrum. **70**, 292 (1999).
[7] M. Bitter *et al.*, Rev. Sci. Instrum. **75**, 3660 (2004).
[8] K. W. Hill *et al.*, Rev. Sci. Instrum. **79**, 10E320 (2008).
[9] A. Ince-Cushman *et al.*, Rev. Sci. Instrum. **79**, 10E302 (2008).
[10] H. Chen, M. Bitter, K. W. Hill, S. Kerr, E. Magee, S. R. Nagel, J. Park, M. B. Schneider, G. Stone, G. J. Williams, and P. Beiersdorfer, Rev. Sci. Instrum. **85**, 11E606 (2014).
[11] P. M. Nilson *et al.*, Rev. Sci. Instrum. **87**, 11D504 (2016).
[12] K. W. Hill *et al.*, Rev. Sci. Instrum. **87**, 11E344 (2016).
[13] P. Beiersdorfer *et al.*, Rev. Sci. Instrum. **87**, 063501 (2016).
[14] L. Gao *et al.*, Rev. Sci. Instrum. **89**, 10F125 (2018).
[15] L. Gao *et al.*, Phys. Rev. Lett. **128**, 185002 (2022).
[16] M. Bitter *et al.*, Phys. Rev. Lett. **71**, 1007 (1993).
[17] M. Bitter, H. Hsuan, J. E. Rice, K. W. Hill, M. Diesso, B. Grek, R. Hulse, D. W. Johnson, L. C. Johnson, and S. von Goeler, Rev. Sci. Instrum. **59**, 2131 (1988).
[18] K. W. Hill *et al.*, Plasma Phys. Controlled Fusion **64**, 105025 (2022).
[19] N. A. Pablant *et al.*, Rev. Sci. Instrum. **93**, 103548 (2022).
[20] K. Hill *et al.*, Rev. Sci. Instrum. **81**, 10E322 (2010).
[21] Z. Cheng *et al.*, Rev. Sci. Instrum. **93**, 073502 (2022).
[22] J. Frenje, L. Ballabio, S. Conroy, G. Ericsson, G. Gorini, J. Källne, P. Prandoni, M. Tardocchi, and E. Traneus, Rev. Sci. Instrum. **70**, 1176 (1999).
[23] M. Tardocchi, G. Gorini, H. Henriksson, and J. Källne, Rev. Sci. Instrum. **75**, 661–668 (2004).
[24] M. Gatu Johnson *et al.*, Phys. Plasmas **20**, 042707 (2013).
[25] D. H. Munro, Nucl. Fusion **56**, 036001 (2016).
[26] R. Hatarik, R. C. Nora, B. K. Spears, M. J. Eckart, G. P. Grim, E. P. Hartouni, A. S. Moore, and D. J. Schlossberg, Rev. Sci. Instrum. **89**, 10I138 (2018).
[27] L. Ballabio, J. Källne, and G. Gorini, Nucl. Fusion **38**, 1723 (1998).
[28] D. J. Schlossberg *et al.*, Phys. Rev. Lett. **127**, 125001 (2021).
[29] G. Ericsson, S. Conroy, M. Gatu Johnson, E. Andersson Sundén, M. Cecconello, J. Eriksson, C. Hellesen, S. Sangaroon, M. Weiszflog, and JET EFDA Contributors, Rev. Sci. Instrum. **81**, 10D324 (2010).
[30] C. Hellesen, J. Eriksson, F. Binda, S. Conroy, G. Ericsson, A. Hjalmarsson, M. Skiba, M. Weiszflog, and JET-EFDA Contributors, Nucl. Fusion **55**, 023005 (2015).
[31] B. Eriksson *et al.*, Plasma Phys. Controlled Fusion **64**, 055008 (2022).
[32] M. Gatu Johnson *et al.*, Phys. Rev. E **94**, 021202(R) (2016).
[33] C. J. Forrest *et al.*, Phys. Rev. Lett. **118**, 095002 (2017).
[34] D. B. Sayre *et al.*, Phys. Rev. Lett. **111**, 052501 (2013).
[35] M. Gatu Johnson *et al.*, Phys. Rev. Lett. **121**, 042501 (2018).
[36] B. Eriksson *et al.*, Phys. Rev. C **109**, 054620 (2024).
[37] J. A. Frenje *et al.*, Nucl. Fusion **53**, 043014 (2013).
[38] A. J. Crilly, B. D. Appelbe, O. M. Mannion, C. J. Forrest, J. P. Knauer, D. J. Schlossberg, E. P. Hartouni, A. S. Moore, and J. P. Chittenden, Phys. Plasmas **29**, 062707 (2022).
[39] A. J. Crilly *et al.*, Phys. Plasmas **31**, 042701 (2024).
[40] H. Henriksson, L. Ballabio, S. Conroy, G. Ericsson, G. Gorini, A. Hjalmarsson, J. Källne, and M. Tardocchi, Rev. Sci. Instrum. **72**, 832 (2001).
[41] C. Hellesen *et al.*, Plasma Phys. Controlled Fusion **52**, 085013 (2010).
[42] C. Hellesen *et al.*, Nucl. Fusion **50**, 022001 (2010).
[43] C. Hellesen *et al.*, Nucl. Fusion **50**, 084006 (2010).
[44] G. Ericsson, J. Fusion Energy **38**, 330 (2019).
[45] R. Hatarik *et al.*, J. Appl. Phys. **118**, 184502 (2015).
[46] M. Gatu Johnson *et al.*, Plasma Phys. Controlled Fusion **52**, 085002 (2010).
[47] E. Andersson Sundén *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **701**, 62 (2013).
[48] Z. L. Mohamed, O. M. Mannion, E. P. Hartouni, J. P. Knauer, and C. J. Forrest, J. Appl. Phys. **128**, 214501 (2020).
[49] B. Appelbe and J. Chittenden, Plasma Phys. Controlled Fusion **53**, 045002 (2011).
[50] J. Eriksson, S. Conroy, E. Andersson Sundén, and C. Hellesen, Comput. Phys. Commun. **199**, 40 (2016).
[51] N. V. Kabadi *et al.*, Phys. Rev. E **104**, L013201 (2021).
[52] F. Weilacher, P. B. Radha, and C. Forrest, Phys. Plasmas **25**, 042704 (2018).
[53] M. M. Marinak, G. D. Kerbel, J. M. Koning, M. V. Patel, S. M. Sepke, M. S. McKinley, M. J. O'Brien, R. J. Procassini, and D. Munro, Eur. Phys. J. Conf. **59**, 06001 (2013).
[54] A. J. Crilly, B. D. Appelbe, K. McGlinchey, C. A. Walsh, J. K. Tong, A. B. Boxall, and J. P. Chittenden, Phys. Plasmas **25**, 122703 (2018).
[55] A. Crilly (2024), "Neutron scattered spectra tool: A python tool for ICF neutron spectroscopy in the single scatter regime," see https://github.com/aidancrilly/NeSST.
[56] R. K. Fisher, P. B. Parks, J. M. McChesney, and M. N. Rosenbluth, Nucl. Fusion **34**, 1291 (1994).
[57] J. Källne, L. Ballabio, J. Frenje, S. Conroy, G. Ericsson, M. Tardocchi, E. Traneus, and G. Gorini, Phys. Rev. Lett. **85**, 1246 (2000).
[58] L. Ballabio, G. Gorini, and J. Källne, Phys. Rev. E **55**, 3358 (1997).
[59] M. Nocente, J. Källne, G. Grosso, M. Tardocchi, and G. Gorini, Nucl. Fusion **53**, 053010 (2013).
[60] J. Jeet *et al.*, "Diagnosing up-scattered DT neutrons produced in burning plasmas at the NIF," in 25th Topical Conference on High Temperature Plasma Diagnostics, 2024.
[61] J. Källne and H. Enge, Nucl. Instrum. Methods Phys. Res., Sect. A **311**, 595 (1992).
[62] J. Källne, L. Ballabio, S. Conroy, G. Ericsson, J. Frenje, G. Gorini, P. Prandoni, M. Tardocchi, and E. Traneus, Rev. Sci. Instrum. **70**, 1181 (1999).
[63] J. A. Frenje, Ph.D. thesis, Uppsala University, Sweden, 1998.
[64] E. Andersson Sundén *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **610**, 682 (2009).
[65] G. Ericsson, L. Ballabio, S. Conroy, J. Frenje, H. Henriksson, A. Hjalmarsson, J. Källne, and M. Tardocchi, Rev. Sci. Instrum. **72**, 759 (2001).
[66] H. Henriksson, S. Conroy, G. Ericsson, L. Giacomelli, G. Gorini, A. Hjalmarsson, J. Källne, M. Tardocchi, and M. Weiszflog, Plasma Phys. Controlled Fusion **47**, 1763 (2005).
[67] H. Henriksson, S. Conroy, G. Ericsson, G. Gorini, A. Hjalmarsson, J. Källne, M. Tardocchi, M. Weiszflog, and J. E. contributors, "Synergetic RF and NB heating effects in JET DT plasmas studied with neutron emission spectroscopy," Nucl. Fusion **46**, 244 (2006).
[68] J. A. Frenje *et al.*, Rev. Sci. Instrum. **72**, 854 (2001).
[69] J. D. Kilkenny *et al.*, Rev. Sci. Instrum. **94**, 081101 (2023).
[70] D. T. Casey *et al.*, Rev. Sci. Instrum. **84**, 043506 (2013).
[71] J. A. Frenje *et al.*, Phys. Plasmas **17**, 056311 (2010).
[72] M. Gatu Johnson *et al.*, Rev. Sci. Instrum. **87**, 11D816 (2016) **89**, 10I129 (2018).
[73] V. Gopalaswamy *et al.*, Nat. Phys. **20**, 751 (2024).
[74] J. A. Frenje *et al.*, Rev. Sci. Instrum. **87**, 11D806 (2016).
[75] J. H. Kunimune, M. Gatu Johnson, A. S. Moore, C. A. Trosseille, T. M. Johnson, G. P. A. Berg, A. J. Mackinnon, J. D. Kilkenny, and J. A. Frenje, Rev. Sci. Instrum. **93**, 083511 (2022).
[76] P. Rodriguez-Fernandez *et al.*, Nucl. Fusion **62**, 042003 (2022).
[77] S. Mackie *et al.*, "Ion optical design of the magnetic proton recoil neutron spectrometer for burning plasma diagnosis of the SPARC tokamak," Rev. Sci. Instrum. (in press) (2024).
[78] C. Wink *et al.*, "The next-generation magnetic recoil spectrometer (MRSnext) on OMEGA and NIF for diagnosing yield, ion temperature, areal density, and alpha heating," Rev. Sci. Instrum. **95**, 083548 (2024).
[79] M. Gatu Johnson *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **591**, 417 (2008).
[80] A. S. Moore *et al.*, Rev. Sci. Instrum. **94**, 061102 (2023).
[81] H. Rinderknecht *et al.*, Rev. Sci. Instrum. **83**, 10D902 (2012).
[82] D. Rigamonti *et al.*, Meas. Sci. Technol. **29**, 045502 (2018).
[83] D. Rigamonti *et al.*, Nucl. Fusion **64**, 016016 (2024).

14 October 2024 14:57:47

© Author(s) 2024

[84]J. Ball *et al.*, "Design of a spectrometric detector unit for the SPARC neutron camera," Rev. Sci. Instrum. (submitted) (2024).
[85]B. Reichelt *et al.*, "Ultra-fast single-crystal CVD diamond detectors for measurements of nuclear emission time histories at the National Ignition Facility," Rev. Sci. Instrum. (submitted) (2024).
[86]Y. Lawrence, B. L. Reichelt, C. W. Wink, G. Rigon, J. Ball, R. A. Tinguely, M. Gatu Johnson, C. K. Li, and J. A. Frenje, "Determination of the response for the national ignition facility particle time of flight (PTOF) detector using single particle counting," Rev. Sci. Instrum. (in press) (2024).
[87]N. Sinenian *et al.*, Rev. Sci. Instrum. **83**, 043502 (2012).
[88]V. Y. Glebov *et al.*, Rev. Sci. Instrum. **77**, 10E715 (2006).
[89]V. Y. Glebov *et al.*, Rev. Sci. Instrum. **81**, 10D325 (2010).
[90]M. Nocente *et al.*, Plasma Phys. Controlled Fusion **62**, 014015 (2020).
[91]M. Nocente *et al.*, Rev. Sci. Instrum. **93**, 093520 (2022).
[92]Y. Kim and H. W. Herrmann, Rev. Sci. Instrum. **94**, 041101 (2023).
[93]K. D. Meaney *et al.*, Phys. Plasmas **28**, 102702 (2021).
[94]Z. L. Mohamed, Y. Kim, J. P. Knauer, and M. S. Rubery, Phys. Rev. C **107**, 014606 (2023).
[95]J. Jeet *et al.*, Phys. Rev. C **104**, 054611 (2021).
[96]K. D. Meaney, M. W. Paris, G. M. Hale, Y. Kim, J. Kuczek, and A. C. Hayes, Phys. Rev. C **109**, 034003 (2024).
[97]M. Tardocchi *et al.*, "The new GETART method for measurement of the fusion power in DT magnetic confinement fusion based on absolute detection of 17 MeV gamma rays," in 25th Topical Conference on High Temperature Plasma Diagnostics, 2024.
[98]A. Dal Molin *et al.*, "Measurement of the gamma ray to neutron branching ratio for the deuterium-tritium reaction in magnetic confinement fusion plasmas," Phys. Rev. Lett. **133**, 055102 (2024).
[99]C. J. Horsfield *et al.*, Phys. Rev. C **104**, 024610 (2021).
[100]M. Rebai *et al.*, "First direct measurement of the spectrum emitted by the $^3H(^2H,\gamma)^5He$ reaction and assessment of the γ_0 and γ_1 relative yield," Phys. Rev. C **110**, 014625 (2024).
[101]B. Perot, W. El Kanawati, C. Carasco, C. Eleon, V. Valkovic, D. Sudac, J. Obhodas, and G. Sannie, Appl. Radiat. Isot. **70**, 1186 (2012).
[102]F. Maekawa and Y. Oyama, Nucl. Sci. Eng. **123**, 272 (1996).
[103]S. Loch, C. Ballance, D. Ennis, D. Maurer, C. Johnson, N. Pablant, T. Abrams, and M. O'Mullane, "White paper on atomic data needs for magnetically confined fusion," White Paper submitted to the Basic Research Needs Workshop on Measurement Innovation (2024), https://custom . cvent . com / DCBD4ADAAD004096B1E4AD96F3C8049E / files/event/c6850a6069dc489d93451d47a5d704d2/d0f40c80728243ad8163378215494553.pdf.
[104]M. O'Mullane, S. Loch, C. Ballance, and N. Pablant, "White paper on uncertainty quantification of atomic data for diagnosing magnetically confined fusion plasmas," White Paper submitted to the Basic Research Needs Workshop on Measurement Innovation (2024), https://custom . cvent . com / DCBD4ADAAD004096B1E4AD96F3C8049E / files / event / c6850a6069dc489d93451d47a5d704d2/664a1974b070473680f2e7e80084fafc.pdf.
[105]C. J. Forrest and M. A. Cusentino, "Verification of tritium breeding rates and migration in planned IFE/MFE blanket materials," White Paper submitted to the Basic Research Needs Workshop on Measurement Innovation (2024), https://custom . cvent . com / DCBD4ADAAD004096B1E4AD96F3C8049E / files /event/c6850a6069dc489d93451d47a5d704d2/34e64de8cdef4b8ab68d0528b362f8a4.pdf.
[106]M. B. Chadwick *et al.*, Nucl. Data Sheets **112**, 2887 (2011).
[107]A. T. Ramsey, Rev. Sci. Instrum. **66**, 871 (1995).
[108]R. M. Bionta, G. P. Grim, K. D. Hahn, E. P. Hartouni, E. A. Henry, H. Y. Khater, A. S. Moore, and D. J. Schlossberg, Rev. Sci. Instrum. **92**, 043527 (2021).
[109]E. Panontin, R. A. Tinguely, A. Carter, A. Martinez, J. Rice, S. Segantin, D. Vezinet, and X. Wang, "Development of the prototype for the SPARC hard X-ray monitor," Rev. Sci. Instrum. **95**, 083516 (2024).
[110]G. Vayakis, E. R. Hodgson, V. Voitsenya, and C. I. Walker, "Chapter 12: Generic diagnostic issues for a burning plasma experiment," Fusion Sci. Technol. **53**, 699 (2008).
[111]H. Khater *et al.*, "Radiation damage to electronics at the NIF," (LLNL-PRES-860688) Workshop for Applied Nuclear Data Activities, Arlington, VA, February 26-29, 2024.
[112]See https://mcnp.lanl.gov/ for information about the MCNP code.
[113]See https://openmc.org for information about the OpenMC code.
[114]See https://lansce.lanl.gov/ for information about the LANSCE facility.
[115]See https://nrp.ne.ncsu.edu/user-facilities/ for information about the PULSTAR facility.
[116]See https://www.shinefusion.com/ for information about the capabilities available at Shine Technologies.
[117]C. J. Forrest *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **888**, 169 (2018).
[118]C. E. Parker *et al.*, Rev. Sci. Instrum. **90**, 103306 (2019).
[119]See https://lasernetus.org/ for information about the LaserNetUS collaboration between small and medium scale laser facilities in the US and Canada.
[120]See https://omfit.io for information about the OMFIT software ecosystem.
[121]See https://epics-controls.org/ for information about the EPICS control system infrastructure project.
[122]J. Kunimune *et al.*, Rev. Sci. Instrum. **95**, 073506 (2024).
[123]Report from the Basic Research Needs Workshop on Measurement Innovation, to be published (2024).

14 October 2024 14:57:47

© Author(s) 2024