REPORT ON THE

2023 LaserNetUS Data & Diagnostics Workshop

Executive Summary

Diagnostics are essential to the growth of knowledge through experimentation as they are how the scientific community records or deduces information from a physical demonstration. In other words, diagnostics are the crucial link between laboratory experiments and theoretical understanding through computational modeling. For scientific advancement, it is vital to consistently enhance diagnostic tools to refine the precision and detail of data, especially to match the evolution of the experimental drivers. As facility capabilities progress, diagnostic improvements are needed to not only uncover new insights into complex systems that are now accessible but also supply the necessary information to challenge hypotheses appropriately. The LaserNetUS mission is to provide students and scientists with broad access to unique facilities and enabling technologies and advance the frontiers of laser-science research, thus necessitating some focus on diagnostics and innovation.

In October 2023, the LaserNetUS Diagnostics and Data Committee (committee) held a LaserNetUS community-research-needs workshop to discuss all aspects of diagnostics. In reviewing current state-of-the-art capabilities and their limitations, the workshop participants produced substantial feedback to detail community priorities and essential future research efforts in diagnostics. This report summarizes the workshop discussions and some subsequent refinement of ideas proposed during that meeting.

Attendees spent significant time discussing the establishment and operational details of a Common Diagnostic Program (CDP) within the LaserNetUS network, aimed at centralizing and standardizing diagnostic tools used to study high-intensity laser-plasma interactions. The CDP's primary goal would be to streamline the usage of diagnostics across different facilities by creating a common framework that should reduce redundant efforts and promote efficient and reliable instrumentation use. This includes developing a digital library of diagnostic resources, a community forum for sharing developments, a comprehensive database of diagnostics and their custodians, and a lending program for both diagnostic components and complete systems.

The CDP would seek to enhance the efficiency of LaserNetUS campaigns by facilitating the sharing of best practices in diagnostic implementation. The structure discussed in the report is also intended to address logistical challenges and improve the uniformity of measurements across facilities. By centralizing diagnostic resources, the CDP aims to uplift capabilities at smaller laboratories, making high-quality diagnostics accessible to a broader range of users and reducing the barrier to entry for innovative experimental techniques.

The program is also envisioned to evolve, adapting to new scientific challenges and technological advances, with a governance model that encourages feedback and participation from the entire LaserNetUS community. This adaptive approach ensures that the CDP remains relevant and effective in fostering scientific innovation and collaboration across various research institutions.

With the burgeoning high-repetition-rate (HRR) laser-driver capabilities in the high-energy-density physics community, some of which are nodes in LaserNetUS, the workshop focused heavily on the new and unique challenges this presents for diagnostics. Chapter B of this report delves into the operational challenges and technological requirements associated with increasing the throughput and fidelity of complex measurements under HRR conditions. The committee categorized various diagnostic tools required for experiments targeted for LaserNetUS-scale facilities, including target characterization, laser system diagnostics, charged particle diagnostics, X-ray diagnostics, and neutronics. Each category was analyzed for its current capabilities and readiness for HRR operations, from Hz repetition rates to autonomous operation without human intervention.

This report highlights the technological adaptations and innovations necessary to support HRR diagnostics. Among these is the transition from passive detection systems, like image plates, to active electronic detectors, such as charge-coupled device (CCD) and complementary metal oxide semiconductor (CMOS) sensors, that can quickly process high volumes of data. It also points out the need for robust computational infrastructure to handle the increased data flow, incorporating advanced processing units like GPUs to manage real-time data analysis efficiently. There is also a focus on integrating artificial intelligence (AI) that could revolutionize how HRR data is collected, processed, and interpreted in experimental research, leading to more precise and rapid scientific discoveries.

The infrastructural enhancements required to support these advanced diagnostics, such as improved calibration resources, reliable component supply chains, and skilled workforce development, are discussed. The findings also stress the importance of diagnostics for system monitoring and control to maintain the integrity and efficiency of HRR operations.

Chapter C summarizes the discussions held on developing and implementing diagnostics for Next-Generation Facilities (NGFs), which are evolving to accommodate lasers with higher intensities, energy levels, and repetition rates of 1 Hz or more. These advancements will enable further detailed studies of matter under extreme conditions and support applications like Inertial Fusion Energy (IFE). Diagnostics for these facilities must withstand harsh operational environments characterized by high neutron flux, extreme temperatures, and significant electromagnetic pulses (EMPs) and maintain precision in data collection amidst these challenges.

The chapter also details the specific challenges for x-ray, charged particle, optical, and neutron diagnostics, and suggests strategies for improving their robustness and resilience. For future readiness, the scientific community acknowledges the benefits of a multi-disciplinary approach involving collaborations across various scientific fields to develop these diagnostics such that they can operate effectively in the extreme conditions expected at NGFs. It stresses the importance of integrating cutting-edge technologies and innovative materials testing to enhance the reliability of these diagnostics systems. In addressing the necessity of strategic planning, much discussion on the implementation of robust diagnostic tools highlights the need for adaptability to the changing operational demands of these advanced facilities, ensuring that innovative diagnostics not only meet current scientific needs but are also scalable for future expansions and challenges.

With the discussion of HRR and NGFs, the committee also acknowledges the escalating challenges and evolving needs associated with data collection and processing, which is the focus of Chapter D. Key points discussed include the imperative for efficient and rapid data collection methods that keep pace with the output of HRR experiments. The report emphasizes that traditional data analysis methods are inadequate for the sheer scale of data produced, which can exceed 1 TB per day. This necessitates the development and integration of advanced technologies such as machine learning and artificial intelligence to automate and accelerate data processing. These technologies are crucial for analyzing data in real-time and extracting meaningful insights swiftly to inform ongoing experiments.

Furthermore, this committee advocates for standardizing data collection and processing protocols across different facilities within the LaserNetUS network to streamline operations and enhance collaborative research efforts. This standardization would facilitate the sharing of data and analytical tools, reducing redundancy, and promoting efficiency.

To address some of these challenges, the committee also emphasizes the benefits of creating a LaserNetUS-managed online resource center. This center could serve as a centralized repository for securely storing and accessing vast amounts of data, instrument calibration information, and peer-reviewed analysis tools. It would also support the standardization efforts by providing a platform for sharing best practices and methodologies across the network. By leveraging advanced computational tools and fostering a collaborative environment through a shared resource center, the LaserNetUS community could enhance scientific output and the operational efficiency of its facilities.

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Introduction

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1: The LaserNetUS Network

LaserNetUS is a network of high-power laser facilities supported by the Department of Energy Office of Fusion Energy Sciences (FES), which aims to advance the frontiers of laser-science research and foster collaboration amongst researchers worldwide. Its mission is to advance and promote intense, ultrafast laser science and applications by providing user access to these facilities through an established proposal review process. LaserNetUS is configured to adapt to changing priorities with a newly formed but large community of users and advisory groups. The thirteen network facility nodes have different but complementary capabilities for which they are suited to drive advances in high-energy-density science, laser and technology development, and inertial fusion energy. LaserNetUS is well-equipped to serve users developing new diagnostic capabilities, especially with high-repetition-rate (HRR) acquisition and state-of-the-art machine learning applications, as it offers various platforms for testing.

In 2018, FES established LaserNetUS with the following objectives: to provide students and scientists with enhanced access to cutting-edge laser capabilities and enabling technologies; to restore U.S. dominance in high-power laser science and applications; and to foster collaboration among researchers from various fields worldwide. As noted earlier, this network comprises thirteen prestigious institutions, including universities and national laboratories, renowned for operating advanced mid- to large-scale high-intensity laser facilities in North America. Over the initial five years, LaserNetUS has granted more than 140 experiments. Presently, the network boasts a registered user base of more than 1,475 individuals. Figure 1 shows the demographics of the LaserNetUS user group.

As of 2023, the LaserNetUS laser facility nodes are situated at Colorado State University, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, SLAC National Accelerator Laboratory, Ohio State University, University of Nebraska-Lincoln, Institut National de la Recherche Scientifique, University of Rochester, University of Texas at Austin, University of California Los Angeles, University of Maryland, University of Michigan, and the University of Central Florida through DE-FOA-0002982 "*LaserNetUS for Discovery Science and Inertial Fusion Energy*." All the facilities have multiple laser systems and/or modes of operation. These include different pulse energy and repetition rate ranges, different wavelengths, options for multiple beams active simultaneously, and more. The similarities and differences among the facilities provide unique staging opportunities to pursue scientific research thrusts. It is partially in the pursuits of multiple facility uses that the network coalesces its identity.

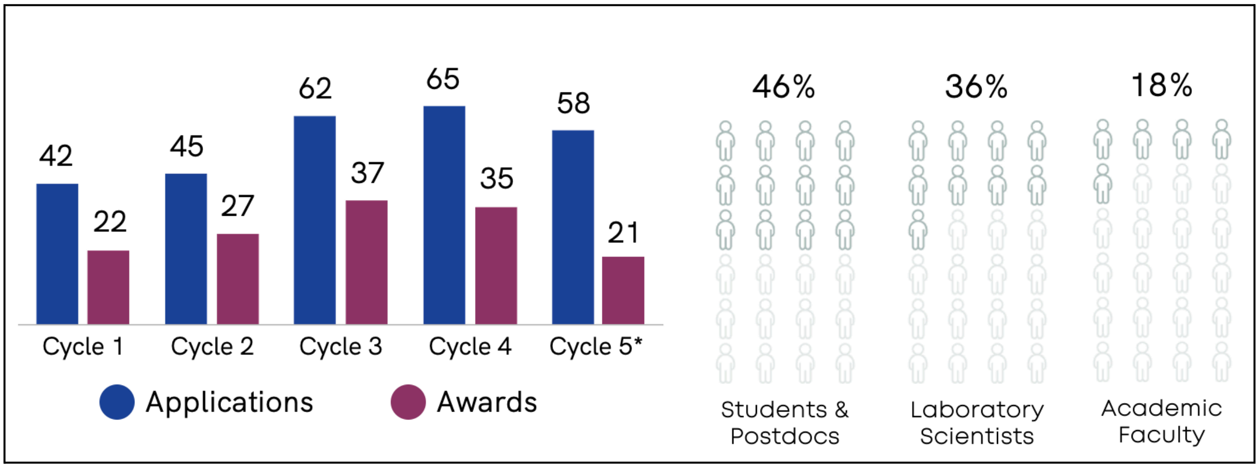

Figure 1. *(Left) Chart representing the number of experimental applications received and the number of awarded proposals during the first five cycles of facility time solicitation. (Right) The makeup of the LaserNetUS user base by professional title. *Cycle 5 was a limited 9-month solicitation.*

1.2: Key scientific and thematic research areas

Key scientific and thematic areas proposed by LaserNetUS users to date include those listed below:

- **Laboratory astrophysics**: study of astrophysical phenomena such as magnetic reconnection, collisionless shocks, particle acceleration, and others [1-4].
- **Opacity, warm dense matter, and particle transport**: energy flow through dense matter and its influence on fundamental material properties such as temperature, pressure, and ionization [5, 6].
- **Laser-plasma interactions (LPI)**: parametric instabilities that govern energy coupling to a plasma, which is crucial for understanding laser-driven inertial fusion platforms but also can be adaptive for a new class of plasma-based optical components and techniques for the next generation of ultra-high intensity/power lasers [7, 8].
- **Particle acceleration, secondary sources, and their applications**: utilizing high-intensity lasers to drive unique and compact sources of both fields and particles such as electrons and ions for use in radiography, light sources, and electric/magnetic field generation. This field is rapidly moving from understanding the underlying physics to branching into a new class of applications relevant to high-energy-density (HED) science and expanding into many other societal, industrial, and defense applications [9-13].
- **High-field physics**: as peak laser intensity capabilities increase, LPI studies enter a new regime in which the physics of relativistic plasmas is strongly affected by strong-field quantum electrodynamics (QED) processes, including hard photon emission and electron-positron (e-e+) pair production [14-17].

- **Nuclear physics and photonics**: the investigation of nuclear reactions using laser technology; applications range from fundamental understanding of the universe (Big Bang nucleosynthesis) to understanding fusion reactions for Inertial Confinement Fusion (ICF) and Inertial Fusion Energy (IFE) applications to industrial and national security applications with the interrogation of nuclear materials with high-energy photon and particle sources [18].
- **Inertial Fusion Energy (IFE)**: laser-target energy coupling, test unique target designs, develop new capabilities in targetry, materials development and testing, diagnostic development, driver technology, high-repetition-rate experimental capabilities, and simulations with a particular emphasis on machine learning. These capabilities can then inform the design and implementation at higher-gain IFE systems [19, 20].
- **Diagnostic development**: Diagnostics are a cornerstone of successful discovery and IFE science experiments. Their precision, resolution, efficiency, and reliability are essential for making quality measurements and providing enough observables and benchmarking codes. LaserNetUS facilities serve as a diagnostic development testbed for larger facilities, and the development can also augment its own suite of diagnostics for improved scientific output [21-24].

2: LaserNetUS Data & Diagnostics Committee

LaserNetUS has established multiple committees to enhance user experience, process user feedback, and expand the capabilities at its facilities. Among these committees is the Data & Diagnostics Committee (DDC), chaired by Christine Mariscal (chair) and Sophia Malko (vice chair). The committee consists of 12 members who represent different career levels, are research and industry partners, and are elected by the user community to represent their interests (see figure 2). The primary responsibilities of the DDC include collecting user feedback on diagnostics at LaserNetUS facilities, identifying user diagnostics needs (including logistics, developing new capabilities, and enhancing existing diagnostics), and providing recommendations to the LaserNetUS leadership. The DDC serves as a voice for the user community to make recommendations to LaserNetUS leadership for improvements on diagnostic-related topics, either logistical or technical.

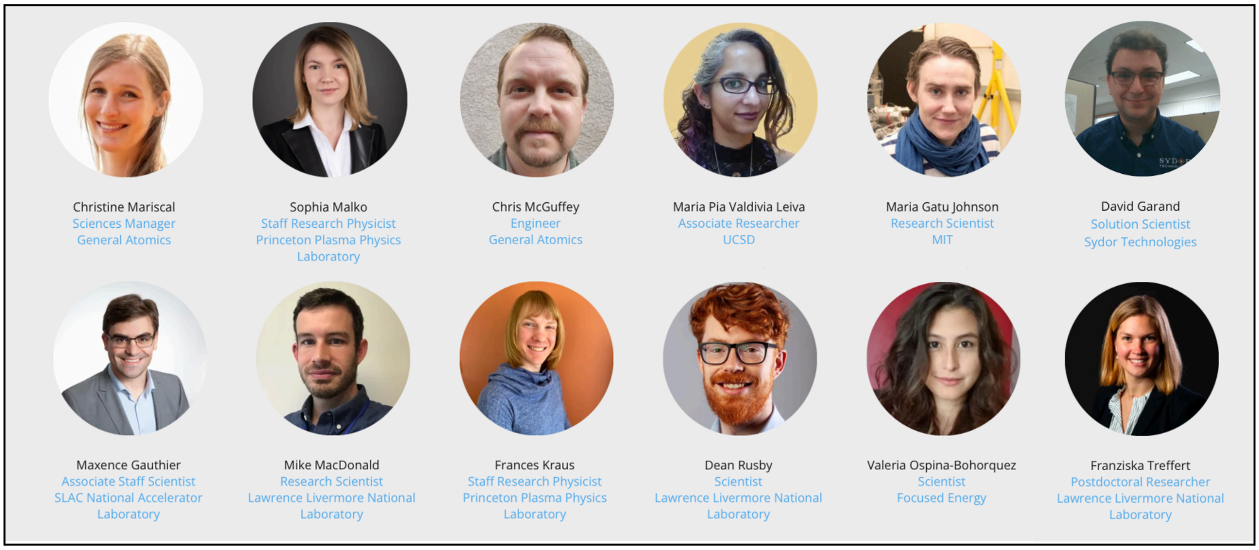

Figure 2. *Members of DDC*

3: LaserNetUS Data & Diagnostics Workshop

The LaserNetUS DDC conducted the inaugural Data & Diagnostics Workshop at Colorado State University in Fort Collins, CO, October 11-13, 2023. The main objective of this workshop was to bring together representatives from the LaserNetUS community to engage in focused discussions on the diagnostics needs and directions of the diagnostics program to–

- Identify a set of key scientific challenges that can be addressed with (novel) diagnostic technologies and the application opportunities they create;
- Assess the critical needs in diagnostic technologies required to address the challenges and enable the applications;
- Identify technical gaps between both present diagnostic and data handling capabilities (current state-of-the-art) and the performance required to address scientific challenges; and
- Identify diagnostic-related areas of strong mutual interest across LaserNetUS nodes that improve the community's ability to advance scientific research.

The workshop was attended by 44 invited participants from 22 institutions, which included committee members, principal investigators of LaserNetUS experiments, beamline scientists, user support personnel from all LaserNetUS facilities, facility points-of-contact (POCs), diagnostics engineers and developers, industry partners interested in collaboration on diagnostic development, and other individuals interested in the workshop's topics. The photo of participants of the DDW workshop is shown in figure 3.

Figure 3. *Photo of DDW 2023 workshop participants.*

This report is based on the outcomes of the DDW 2023 workshop and organized following the breakout sessions: Common Diagnostics Program (CDP), High-Repetition-Rate Diagnostics, Diagnostics for New Generation of Facilities, and Data Collection and Processing Tools. Table 1 provides the findings from each breakout session.

Table 1: *The summary of findings of the 2023 LaserNetUS Data and Diagnostics Workshop.*

Topic	Findings
Common Diagnostics Program (CDP)	● There is a high interest in the development of a CDP program, which will provide a suite of standardized and calibrated diagnostics available at all LaserNetUS facilities. ● An effort needs to be made for logistics, coordination, and proper documentation of diagnostics.
High-Repetition-Rate Diagnostics	● HRR operation requires active diagnostics with electronic readouts, excluding the use of passive diagnostics (film, image plate) for continuous data acquisition. ● There is a strong need to improve the dynamic range of detectors, develop in-situ calibrations, harden diagnostics to electromagnetic pulses (EMP), and develop ML/AI algorithms for data processing and analysis in real time. ● Collaborative efforts and knowledge sharing across research networks are vital for addressing common challenges.
Diagnostics for New Generation of Facilities	Diagnostics will need to– ● Work at the desired laser repetition-rate and have remote operation capability; ● Produce distinguishable output data amid strong and noisy signals and resist EMP perturbations caused by laser-target interaction; and ● Provide flexibility for various experiments or offer specific, groundbreaking capabilities to enhance measurements and understanding of specific physical problems.
Data Collection and Processing Tools	● Collaboration on standardization of data formats, metadata, and analysis tools. ● The importance of real-time data analysis for efficient use of high-repetition-rate facilities. ● Develop and enforce guidelines for data accessibility, retention, and archiving.

4: References

[1] A. Chien, L. Gao, S. Zhang, H. Ji, et al., “Non-thermal electron acceleration from magnetically driven reconnection in a laboratory plasma”, *Nature Physics **19**, 254–262 (2023).*

[2] G. Fiksel, W. Fox, M. Rosenberg, D. Schaeffer, J. Matteucci, A. Bhattacharjee, “Electron energization during merging of self-magnetized, high-beta, laser-produced plasmas”, *J. Plasma Phys.* **87**, 4 (2021).

[3] M. Bailly-Grandvaux, E. N. Hahn, T. R. Joshi, et al., “Laser-pulse-length–dependent ablation and shock generation in silicon at 10^{15}W/cm^2 intensities”, *Phys. Rev. Res.* (under review).

[4] S. Bolaños et al., “Laboratory study of the initial stages of quasi-parallel collisionless shocks at high Alfvén Mach number”, *Phys. Rev. Lett. (*under review).

[5] B. F. Kraus, Lan Gao, W. Fox, K. W. Hill, M. Bitter, P. C. Efthimion, A. Moreau, R. Hollinger, Shoujun Wang, Huanyu Song, and J. J. Rocca, "Ablating Ion Velocity Distributions in Short-Pulse-Heated Solids via X-Ray Doppler Shifts”, *Phys. Rev. Lett.* **129**, 235001 (2022).

[6] B. F. Kraus, Lan Gao, K. W. Hill, M. Bitter, P. C. Efthimion, T. A. Gomez, A. Moreau, R. Hollinger, Shoujun Wang, Huanyu Song, J. J. Rocca, and R. C. Mancini, "Solid-Density Ion Temperature from Redshifted and Double-Peaked Stark Line Shapes", *Phys. Rev. Lett.* **127**, 205001 (2021).

[7] S. Hakimi, L. Obst-Huebl, A. Huebl, K. Nakamura, S. S. Bulanov, S. Steinke, W. P. Leemans, Z. Kober, T. M. Ostermayr, T. Schenkel, A. J. Gonsalves, J.-L. Vay, J. van Tilborg, C. Toth, C. B. Schroeder, E. Esarey, C. G. R. Geddes, “Laser-solid interaction studies enabled by the new capabilities of the iP2 BELLA PW beamline”, *Phys. Plasmas* **29**, 083102 (2022).

[8] M.R. Shcherbakov, G. Sartorello, Zhang, S., et al., "Nanoscale reshaping of resonant dielectric microstructures by light-driven explosions", *Nat. Commun.* **14**, 6688 (2023).

[9] A. Zingale, N. Czapla, D. M. Nasir, S. K. Barber, J. H. Bin, A. J. Gonsalves, F. Isono, J. van Tilborg, S. Steinke, K. Nakamura, et al., “Emittance preserving thin film plasma mirrors for GeV scale laser plasma accelerators”, *Phys. Rev. AB* **24**, 1213012 (2021).

[10] F. Treffert, G. D. Glenn, H.-G. J. Chou, C. Crissman, C. B. Curry, D. P. DePonte, F. Fiuza, N. J. Hartley, B. Ofori-Okai, M. Roth, S. H. Glenzer, M. Gauthier; “Ambient-temperature liquid jet targets for high-repetition-rate HED discovery science”, *Phys. Plasmas* 1, **29 (12)**: 123105 (2022).

[11] P.K. Singh, F.-Y. Li.,.C.-K. Huang, et al., "Vacuum laser acceleration of super-ponderomotive electrons using relativistic transparency injection", *Nat. Commun.* **13**, 54 (2022).

[12] B. Miao, J. E. Shrock, L. Feder, R. C. Hollinger, J. Morrison, R. Nedbailo, A. Picksley, H. Song, S. Wang, J. J. Rocca, and H. M. Milchberg, "Multi-GeV Electron Bunches from an All-Optical Laser Wakefield Accelerator", *Phys. Rev. X* **12**, 031038 (2022).

[13] J. Strehlow, J. Kim, M. Bailly-Grandvaux, et al., "A laser parameter study on enhancing proton generation from microtube foil targets", **Sci. Rep.** 12, 10827 (2022).

[14] N. F. Beier, H. Allison, P. Efthimion, K. A. Flippo, L. Gao, S. B. Hansen, K. Hill, R. Hollinger, M. Logantha, Y. Musthafa, R. Nedbailo, V. Senthilkumaran, R. Shepherd, V. N. Shlyaptsev, H. Song, S. Wang, F. Dollar, J. J. Rocca, and A. E. Hussein, "Homogeneous, Micron-Scale High-Energy-Density Matter Generated by Relativistic Laser-Solid Interactions", *Phys. Rev. Lett.* **129**, 135001 (2022).

[15] H. G. Rinderknecht et al., "Relativistically transparent magnetic filaments: scaling laws, initial results and prospects for strong-field QED studies", **New J. Phys**. 23 095009 (2021).

[16] Qiang Chen, Dominika Maslarova, Junzhi Wang, Shao Xian Lee, Vojtech Horný, and Donald Umstadter, "Transient Relativistic Plasma Grating to Tailor High-Power Laser Fields, Wakefield Plasma Waves, and Electron Injection", *Phys. Rev. Lett.* **128**, 164801 (2022).

[17] P. Zhang, S. S. Bulanov, D. Seipt, A. V. Arefiev, A. G. R. Thomas; "Relativistic plasma physics in supercritical fields", *Phys. Plasmas* **27 (5)**: 050601 (2020).

[18] Colton Fruhling, Junzhi Wang, Donald Umstadter, Christoph Schulzke, Mahonri Romero, Michael Ware, and Justin Peatross, "Experimental observation of polarization-resolved nonlinear Thomson scattering of elliptically polarized light", *Phys. Rev. A* **104**, 053519 (2021).

[19] M. Schollmeier et al., "Investigation of Proton Beam-Driven Fusion Reactions Generated by an Ultra-Short Petawatt-Scale Laser Pulse", *Laser Part.*, **2022**, 2404263 (2022).

[20] A. Curtis, R. Hollinger, C. Calvi, S. Wang, S. Huanyu, Y. Wang, A. Pukhov, V. Kaymak, C. Baumann, J. Tinsley, V. N. Shlyaptsev, and J. J. Rocca, "Ion acceleration and D-D fusion neutron generation in relativistically transparent deuterated nanowire arrays", *Phys. Rev. Research* **3**, 043181 (2021).

[21] M.P. Valdivia et al., "Talbot-Lau X-ray deflectometer: Refraction-based HEDP imaging diagnostic", *Rev. Sci. Instrum.* **92**, 065110 (2021).

[22] D. A. Mariscal, B. Z. Djordjević, R. Anirudh, T. Bremer, P. C. Campbell, S. Feister, E. Folsom, E. S. Grace, R. Hollinger, S. A. Jacobs, B. Kailkhura, D. Kalantar, A. J. Kemp, J. Kim, E. Kur, S. Liu, J. Ludwig, J. Morrison, R. Nedbailo, N. Ose, J. Park, J. J. Rocca, G. G. Scott, R. A. Simpson, H. Song, B. Spears, B. Sullivan, K. K. Swanson, J. Thiagarajan, S. Wang, G. J. Williams, S. C. Wilks, M. Wyatt, B. Van Essen, R. Zacharias, G. Zeraouli, J. Zhang, T. Ma; "A flexible proton beam imaging energy spectrometer (PROBIES) for high repetition rate or single-shot high energy density (HED) experiments (invited)", *Rev. Sci. Instrum.* **94 (2)**, 023507 (2023).

[23] G. Zeraouli, D. Mariscal, E. Grace, G. G. Scott, K. K. Swanson, R. Simpson, B. Z. Djordjevic, R. Nedbailo, H. Song, J. Morrison, J. Park, R. Hollinger, S. Wang, J. J. Rocca, T. Ma; "Ultra-compact x-ray spectrometer for high-repetition-rate laser-plasma experiments", *Rev. Sci. Instrum*. **93 (11)**: 113508 (2022).

[24] M. J.-E. Manuel, H. Tang, B. K. Russell, L. Willingale, A. Maksimchuk, J. S. Green, E. L. Alfonso, J. Jaquez, L. Carlson, D. Neely, T. Ma; "Enhanced spatial resolution of Eljen-204 plastic scintillators for use in rep-rated proton diagnostics", *Rev. Sci. Instrum.* **91 (10)**: 103301 (2020).

A: Common Diagnostic Program (CDP)

Chapter Lead Authors: David Garand, Frances Kraus

Section A-1: Introduction

Every LaserNetUS campaign is ultimately aimed at making a particular measurement. Experimental teams, therefore, spend enormous effort on diagnostics: procuring them from other groups, building them based on the literature, developing them from earlier models, and adapting them to new facilities. Facilities, too, rely heavily on diagnostics to monitor their systems' health and gauge the impact of modifications. While many aspects of this diagnostic development work are highly specialized per facility and deployment, other elements are repeated across groups, facilities, and platforms.

An opportunity exists through LaserNetUS to centralize these aspects of diagnostic deployment and development into a Common Diagnostic Program (CDP). The CDP would bring a common framework to several or many sets of tasks that numerous groups presently perform in-house or coordinate across limited networks. For instance, a CDP might become a community-wide coordinator of the following resources:

- A digital library of common diagnostic drawings, instructions, and calibration procedures.
- A forum for facilities and users to connect over diagnostic development.
- A database of diagnostics and associated responsible scientists that can be contacted for collaboration on campaigns.
- A lending library of standard diagnostic components, such as detectors, filters, or optics.
- A lending library of complete diagnostics of varying complexity.

This chapter will discuss these tasks and other considerations that could be coordinated under such a framework, what criteria the CDP must satisfy, and how such a program might be grown.

Whatever forms the CDP takes over time, its purpose should be to increase the efficiency of LaserNetUS campaigns through sharing best practices in diagnostic implementation and reducing repeated work—especially where near-repetition introduces variations that prevent cross-facility comparisons or common calibration. There is also an opportunity for the CDP to help elevate capabilities at smaller laboratories in the network. The CDP has the potential to simplify diagnostic development where consensus exists, freeing scientists to direct their efforts on new ideas and pioneering breakthroughs.

Section A-2: What Does a CDP Program Look Like?

A-2.1 Defining the CDP

At its core, the CDP is an effort to coordinate the use of well-established diagnostics across the LaserNetUS community. Its scope is broad, aiming to establish best practices relevant to all facilities and all groups. It should be inclusive and driven by the community, meaning that its function and operation should be open to comment by LaserNetUS participants of any institution or career level. Still, while the CDP is shaped based on community input, it is centrally run and coordinated by an overseeing body in the same manner as the LaserNetUS proposal process. These characteristics should hold for any realization of the CDP, but the actual operation of the program will evolve depending on the resources it is given.

To build a cohesive, community-wide program overseen by LaserNetUS, the CDP must tie together many existing ideas at smaller scales, rectifying issues as a global coordinator. For instance, without the CDP, the status quo for diagnostic use often proceeds as follows:

- Common diagnostics are reinvented at many facilities and, for many campaigns, regenerated based on advice from the literature or informal conversations with experts. In each circumstance, the use, calibration, and interpretation of data from such diagnostics happens differently.
- Specialized diagnostics are lent from one group to another, often tied to a particular facility, and relying on diagnostic experts traveling in to support the diagnostic during a secondary user's campaign. Users can access these "borrowed" diagnostics by cultivating their own private networks.
- Each campaign's primary investigator (PI) is responsible for uniting diagnostic components into usable packages, sometimes cobbling together optics, detectors, filters, and other elements from different sources. If parts are damaged or broken, the PI works this out with the responsible owner on a case-by-case basis.
- Diagnostic development happens in individual labs, often by graduate students or technicians. Successful physics results from diagnostics are frequently published, but diagnostic details or failure modes are only sometimes captured for general use.

The CDP can resolve many such inefficiencies by building infrastructure that augments these individual arrangements. It can be used to share knowledge in accessible formats via online repositories (e.g., forums, Wiki-style open-access encyclopedias, calibration databases, and diagnostic histories). It can coordinate the lending of diagnostics from one group to another, even potentially owning its own diagnostic library. It can assign credit for diagnostic development and liability for diagnostic damage. It can coordinate centralized designs, operating procedures, and repairs, especially if one or more specialized technicians staff the CDP itself.

This menu of characteristics must evolve as the CDP grows. Once some aspects of the CDP are built (e.g., online infrastructure for a forum), other roles can be developed more easily (an online calibration library, a database of diagnostic contacts, a repository for analysis codes, etc.). The CDP can be built to adapt to user needs and grow with the resources it is given.

A-2.2 Elements of CDP

The CDP should be built from several key components, which vary in complexity and can be developed over time:

1. **An online infrastructure** for coordinating diagnostic information, including:
    a. A message board for user input and connectivity.
    b. A database of common diagnostics, engineering plans and CAD models, associated papers, calibration/operation procedures, and experts to reference.
    c. A repository for histories of particular diagnostics in common use within LaserNetUS, including calibration reports and upgrades over time.
2. **A diagnostic lending program** that coordinates the temporary transfer of diagnostics and diagnostic components from one group to another. This should include some infrastructure for liability in the case of damaged parts and allowance for diagnostic experts to travel to campaigns to educate new users on diagnostic best practices.
3. **A centralized diagnostic library** with diagnostics owned and controlled by LaserNetUS. This library could have the following roles:
    a. Design and/or construct well-established diagnostics that should be used across many LaserNetUS facilities for common measurements.
    b. Repair, maintenance, and standardized calibration of diagnostics.
4. **A set of funding opportunities** that encourage diagnostic development, either to realize any of the CDP elements enumerated above or to develop specialized, prototypical diagnostics into workhorse measurement tools for community-wide use.

As the CDP phases in one or more of these components, the key roles within the CDP can be distributed by need. Many of these activities should be performed by a centralized entity, but others may be better coordinated with a partner facility in the same way that the SLAC proposal system handles LaserNetUS proposals. The program participants' responsibilities should be clearly delineated in a readily accessible document on the CDP website.

A-2.3 CDP Variations

The elements of the CDP in figure 4 are general and flexible and can be built in phases based on available resources. As such, the program framework could be leveraged to target various problems. The path toward developing the CDP depends on which goals the institutional leadership targets first.

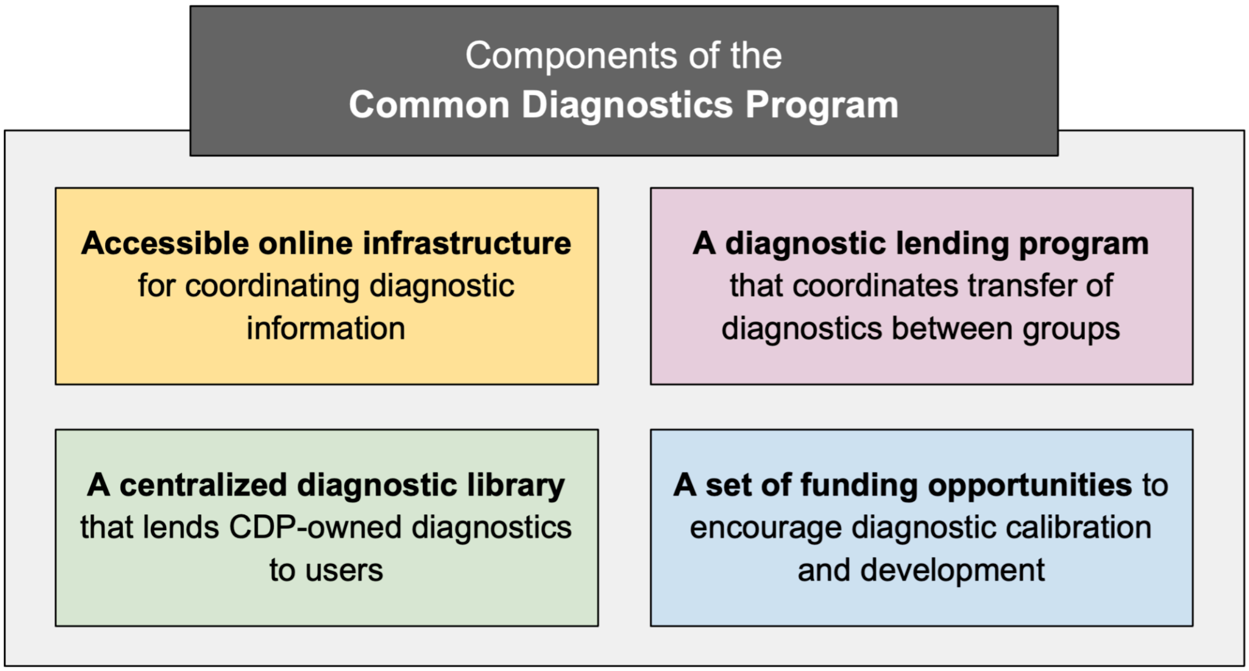

Figure 4. *Chart featuring key CDP components.*

For instance, many users see value in a "lending library" of common diagnostics for users to supplement their primary measurements. Typical diagnostics such as particle spectrometers or X-ray imagers may need not be innovative to make decisive measurements: the standard operating range of such a diagnostic, with commonly achievable resolution and easy-to-operate detectors, can add value to a wide variety of campaigns. Scientific output would benefit if users had ready access to a library of such diagnostics, especially if the diagnostics were pre-calibrated and the logistics of borrowing were not overly complicated.

Such a library could be coordinated through LaserNetUS, either by arranging the lending of preexisting setups or by taking ownership and maintaining a centralized collection. Especially if many users required multiple copies of similar diagnostics the latter would be preferable; well-established diagnostics could be added to this library in batches.

A centralized diagnostic lending program could also improve equity in diagnostic access. Some components of diagnostics–for example, streak cameras and specialized detectors–may be too expensive for many groups to purchase on their own, especially for one-off campaigns. A CDP could coordinate the lending of such components, even taking ownership of some more expensive components, and establish a system of liability that still allows groups to take advantage of these technologies. This program could look to what has already been accomplished at Rutherford, Vulcan, for additional insight. Such a program would need to track failure history and support interface modifications for successful deployment.

In addition, facilities could benefit from standardized measurements of key parameters with a common set of diagnostic tools. Presently, each laser facility lists a table of parameters on their web pages, such as “maximum energy” or “pulse duration.” Such parameters would be much more powerfully comparable from one facility to another if they were measured with identical diagnostics at each facility. It is easy to envision a set of calibration experiments performed at each LaserNetUS facility, with results published openly for the community to compare. The common measurements most useful to the community would need to be established with feedback from users, but the coordination of these campaigns would require buy-in from each facility and the direction of a well-resourced centralized CDP. Such an initiative would allow the development of agnostic experimental parameters that could define a universal framework for discussing experiments and standardizing data reporting.

Concerning more specialized diagnostics, the CDP could be the home of a “registration system” that tracks diagnostic use and development over time. Specific diagnostics might be identified with a serial number and a specialized validation procedure that users must undergo each time the diagnostic is employed in a new campaign. CDP-specific funding could cover routine maintenance and new upgrades to these specialized diagnostics, as well as the time of responsible personnel tracking the diagnostic and interface with users for installation, troubleshooting, and data analysis concerns. LaserNetUS-funded experiments could require users to document any new documentation, calibration data, and other findings that could be shared on a central database for the community.

A last example regards common calibrations and data analysis routines for some set of diagnostics. Many facilities already have their own diagnostics optimized for their home laser parameters and engineering constraints. Still, such instruments should be calibrated routinely to facilitate cross-comparison across the LaserNetUS network. Moreover, data output from such instruments should be analyzed in a routine way that is directly comparable from one facility to another. Repeatable, open-source-analysis routines could be adapted into an existing code base, such as PlasmaPy [1]. The CDP could consider the subcontracting or direct management of specific calibration facilities, especially where repeatable conditions for validating the operation of diagnostic components are not feasible at laser facilities themselves. A dedicated resource such as a mechanical engineer (full or part-time) could also be considered for this role.

Any of the program's possible goals can benefit from the common infrastructure specified in Section A-2.2: a centralized website, a lending program/library maintained by community members or LaserNetUS itself, and dedicated funding opportunities to allocate resources to this centralization.

Section A-3: What Diagnostics Should be Part of CDP?

A-3.1 Core Diagnostic Tools

Many users see the natural core of the CDP as “well-established” diagnostics that, by community consensus, are reliable and useful in many experimental contexts. These diagnostics would be the core of a lending program, especially one owned by LaserNetUS, because they could be produced in batches of several identical copies, and best practices for their operation are well known.

Such core diagnostics fit roughly into three categories: 1) laser diagnostics, 2) target diagnostics, and 3) key diagnostic components. Firstly, laser diagnostics are designed to measure key parameters of a laser system, such as pulse energy, duration, and contrast; while of interest to all parties, facilities would usually set up such diagnostics. Secondly, target diagnostics tend to be the responsibility of users, as they are designed for specific measurements on each campaign. They vary widely in purpose, complexity, and portability. Thirdly, diagnostic components are the building blocks of diagnostics on either side and may comprise detectors, optics, power supplies, or any other generally helpful item.

All of these diagnostic categories can easily fit into the CDP framework, even though the mechanisms of their lending and centralization may be somewhat different. Typically, laser diagnostics are more likely to be loaned or coordinated amongst facilities, and target diagnostics are more likely to operate for a particular user campaign. Nonetheless, the CDP should remain fluid enough in its organization that such categories do not limit scientific innovation. Some consensus examples of core diagnostics in each category are listed in table 2.

Table 2: *Core Diagnostic examples, by category.*

Core laser diagnostics	Core target diagnostics	Core diagnostic components
● Focal spot imagers (near- and far-field) ● Pulse history diagnostics: ○ FROG/STRIPED FISH ○ Temporal contrast measurements (SEQUOIA) ● Pulse energy diagnostics (calorimeters)	● Charged particle spectrometers (Thomson parabolas, magnetic spectrometers) ● X-ray imagers (pinhole, spherical crystal imagers) ● Neutron diagnostics (nTOF) ● X-ray photodiodes	● CCDs ● Image plates and scanners ● X-ray filters and crystals ● Pinhole arrays

These core diagnostics could be the basis of common calibration programs, especially those that directly compare performance at different facilities. They would also be the main diagnostics on loan to users, functioning in many campaigns as secondary to the primary measurement. Core diagnostics should have open-source engineering models and CAD drawings available online and should take priority as the CDP centralizes calibration and data analysis procedures.

An essential way that core CDP diagnostics can anticipate evolving scientific needs is by building in capabilities for high-repetition-rate operation. Many LaserNetUS facilities are already capable of or are on the brink of implementing shot rates in the order of 1 Hz or more. To be widely applicable, core CDP diagnostics must be compatible with these high repetition rates, such as by investing in fast-readout detectors and by considering data storage schemes that efficiently catalog large datasets.

A-3.2 Specialized Diagnostics

Many LaserNetUS campaigns center on more specialized diagnostics that are built for specific scenarios. These diagnostics may be under development, with central features being tested before and during campaigns, and they may be too specialized for general use at most facilities due to sensitivity to signal, noise, or EMP; inflexible chamber mounting; unwieldy footprint; or secondary power requirements. Regardless, many such diagnostics are broadly helpful, with appeal to different groups and campaigns at one or more facilities.

The CDP should encourage the broader use of such specialized diagnostics by coordinating a network through which they are shared. Currently, users must connect to specialized diagnostics on their own through private networks or careful reading of the literature, then reach out to assumed diagnostic experts individually. The CDP can centralize this process by compiling a database of specialized diagnostics, especially those that have been the basis of LaserNetUS campaigns or have received funding for diagnostic development through the CDP.

The database can feature contact information for experts, general requirements for use, essential capabilities of the measurement, standard calibration procedures, and references (published and informal). The same database should keep track of each specialized diagnostic over time, including development milestones, each use in a new campaign, and calibration result histories.

The CDP can devote resources to the sharing of specialized diagnostics through several mechanisms:

- Funding the development of specialized diagnostics, especially for adapting single-campaign, single-group efforts for broader use in the community.
- Centralizing information about specialized diagnostics in an accessible website.
- Coordinating the scheduling and transport of specialized diagnostics from one facility to another when applicable and sponsoring the travel of diagnostic experts to new campaign sites to help users adapt the diagnostic for their needs.

A-3.3 Emerging Technologies

As LaserNetUS and the CDP develop into the future, they will surely see the advent of new regimes of laser intensity, repetition rates, and facility capabilities, as well as the evolution of diagnostic capabilities in new, unforeseen directions. The CDP should anticipate this development by keeping avenues of communication open between the community and a centralized institution. These avenues should alert the CDP when–

- Previously novel diagnostics are gaining consensus support in the community and should be treated as core, common-use diagnostics.
- New directions in diagnostic development are either in progress or sorely needed. The CDP can prioritize development in specific directions through explicit funding calls.

The CDP must remain answerable to the community to serve a broad array of needs effectively. Therefore, it should be developed in a flexible way, anticipating that needs will change over time with scientific and technological progress. The CDP's phased growth should lend itself to adaptation if and when the community's central diagnostic needs shift.

Section A-4: What Logistical Elements are Essential to Ensure Efficiency?

A-4.1 Planning and Coordination

The CDP will only function with a centralized coordinating effort on a network-wide scale. The program's goal is to establish standards and best practices that operate across LaserNetUS, as determined by the needs of facilities and users. Therefore, the CDP must be operated as a central institution, with frequent opportunities for feedback from the community.

The planning stages for the CDP have already commenced, centered in the LaserNetUS Diagnostics and Data Committee. This committee's leaders have started identifying diagnostics across the community and tabulating them and the parameters under which they operate. They have also initiated this report, which outlines the importance, goals, and possible mechanisms of an eventual CDP. The next step is to form a coordinating body that builds the central components of the CDP from the top.

The phases of the CDP listed in Section A-2.2 are meant to build from the simple to the complex. The community could immediately benefit from a centralized online database of diagnostic resources; this is where the CDP should begin. LaserNetUS should allocate resources toward constructing this online infrastructure, establishing some institutional authority for building the website and its various facets.

Once an online repository has been constructed, the CDP can decide how centralized it wants to take its approach to developing centralized diagnostic information. The community could be tasked (and resourced) to generate drawings, procedures, and calibration documents for standard diagnostics, or the CDP could hire staff to build this common library itself. The CDP should be clear about assigning tasks to which teams and facilities, formally subcontracting work where appropriate, and designating user representatives to guide the work and its dissemination to the community.

As this process evolves, the CDP may begin to address specific concerns in the community–for example, those listed in Section A-2.3. It may plan for a system-wide set of calibrations to better compare capabilities at different facilities, or it may prepare for a lending library either coordinated between users or centrally owned by the CDP. These tasks should be coordinated with community representatives in a transparent process, taking advantage of the annual LaserNetUS Users Meeting and existing user committees.

A-4.2 Data Management and Analysis

The data generated by the CDP should be open source and broadly accessible as much as reasonably achievable. Especially for core diagnostics, the community benefits from common plans, CAD models, and documentation. Calibration procedures and the data they generate should be recorded in common formats to assess trends easily. Common analysis codes should be open source and written for easy sharing throughout the community.

A Code of Conduct on the CDP website could specify the data-sharing practices users agree to by posting on any CDP forum or other open resource. Care may be necessary when sharing information about specialized diagnostics, some of which may rely on proprietary processes or be critical to unpublished results. Some mechanisms should exist for users to embargo new data regarding the diagnostics they are developing while ensuring that information is shared with the community as needed, especially as diagnostics are lent to new users. Calibration data should be planned to be fully transparent without crossing any lines of intellectual property or otherwise.

As a centralized institution, the CDP will have some power to drive advancement across the LaserNetUS community. For example, efficient cataloging of data storage is one way the CDP can establish standards that different users and facilities can readily adopt. Such a focus will be vital for high-repetition-rate diagnostics, which the CDP should coordinate. Such diagnostics are much less helpful when data is not tagged and archived effectively; for users to leverage massive datasets generated by these diagnostics, data must be searchable and accessible. The CDP can adopt and disseminate best practices for data archiving, thereby increasing the usability of next-generation large datasets.

A-4.3 Safety and Resource Allocation

As with all other aspects of LaserNetUS operations, safety should be paramount to the CDP program. Some oversight by the centralized body is necessary to ensure that important safety information about particular diagnostics is clearly conveyed to new users. It is also crucial to establish transparent and fair equipment liability rules. The CDP must balance the need to protect expensive equipment with the reality that scientific development, innovation, and training may expose equipment to off-normal situations that lead to damage. Equity requires that users can access equipment without undue risk due to liability with expensive parts. However, the CDP could still consider a system of penalizing users who repeatedly damage parts while taking every reasonable precaution to ensure all users of any shared equipment are fully informed of the best practices that will keep all parties and equipment safe. In summary, the CDP can integrate safety into its activities by–

- Centralizing and disseminating safety protocols to users and facilities.
- Balancing equity in diagnostic access with a system to ensure careful treatment of equipment.
- Establishing clear guidelines for liability and equipment ownership.

Proper resource allocation is another reason the CDP should be centrally managed with frequent opportunities for community input. Some CDP initiatives would be most obviously realized with specific funding opportunities, such as diagnostic development or creating CAD models or procedures requiring facility and user personnel effort. This could also include access to calibration capabilities, such as synchrotrons, supporting specific beam times to calibrate, or even cross-calibrate similar diagnostics from different facilities. The priorities of the CDP should be decided on a rolling basis with community involvement, perhaps in the vein of the OMEGA Laser User Group (OLUG) community-driven prioritization process.

For emphasis, the CDP may leverage its position and distribute resources by–

- Soliciting proposals for funding for key diagnostic centralization activities.
- Organizing and enabling calibration of diagnostics.
- Requesting community input regularly to ensure investment in high-need areas.

Section A-5: Best Practices

The community notes some crucial points that the CDP should prioritize from its founding:

- Diagnostics should be paired with specific pre- and post-campaign validation tests that confirm the diagnostic components' status after shipping and exposure to experimental environments. These procedures need not be complete calibrations but should be sufficient to validate that the equipment's essential features function correctly at all stages.
- Diagnostic development work should be tracked and credited wherever possible. Key personnel in charge of particular diagnostic development should be included as co-authors on publications whenever their work impacts important results.
- Equity in information and diagnostic accessibility should be a top priority of the CDP. Diagnostic development should help smaller facilities with fewer resources to catch up to better-resourced facilities where possible. Groups without resources to field necessary but commonplace diagnostics should be prioritized in scheduling conflicts. Students should be fully involved in routine feedback for the CDP and have their needs acknowledged. Information that is important for users of diagnostics to understand should be transmitted to users as openly as possible, with some safeguards for the confidentiality of intellectual property as appropriate.

Section A-6: Challenges and Future Outlook

A-6.1 Challenges in Implementing CDP

The CDP is a community-wide enterprise that will require the coordination of many different teams and facility groups, all of whom have their own wishes and are often in direct competition for time and scientific results. The CDP will have to overcome these divisions to build a program that benefits everyone with minimal friction. The first step toward doing so is having a clear code of priorities, emphasizing equitable distribution of benefits across different facilities and groups, and properly funding the work that various LaserNetUS constituents do in service of the development of the CDP.

Some disputes are bound to occur in establishing a consensus, even for the core diagnostics that most users agree should be coordinated through the CDP. Groups with different priorities may have differing opinions about which diagnostics should be included or how those diagnostics are implemented. Such disputes could be resolved through consensus-building communication, centrally arranged by the CDP leadership, or more directly by central management and decision-making by CDP personnel. The array of diagnostics chosen to be included as core components of the CDP should be as broad as possible under a given funding profile so that all groups find something of value in the offerings. Disputes over details should include experts in the discussions so that all parties are heard and their qualms resolved to the greatest extent possible.

Liability for damage to expensive diagnostics is likely to be a sticking point, especially when sharing diagnostics with high monetary value or that represent the culmination of many years of effort. The CDP should clearly establish mechanisms for resolving liability disputes. Groups mustn't endanger themselves by borrowing equipment that may break under the many stresses of a unique implementation; the plan for repair or replacement of particularly expensive equipment should be discussed explicitly in advance and subsidized by funding from LaserNetUS where appropriate.

A-6.2 The Future of CDP

The CDP is bound to evolve with the community's needs and the advent of new technologies. This chapter anticipates the gradual growth of the CDP with the possible phases enumerated in Section A-2.2. However, such elements may be augmented or phased out as decided by leadership in conjunction with the community over time.

The primary metric for CDP success should be based on community input. LaserNetUS already holds network wide meetings that form an obvious opportunity for solicitation of feedback. The CDP should be the focus of particular sessions at the LaserNetUS Users Meeting as well as adjacent meetings that many community members attend, such as LaserNetUS Committee meetings, the APS Division of Plasma Physics meeting, the National Ignition Facility and Jupiter Laser Facility (NIF-JLF) User Group Meeting, or others. User representatives in frequent communication with CDP and LaserNetUS leadership should be empowered to suggest changes and have some oversight of the direction of the CDP. The CDP framework should accommodate these new directions, whether in the inclusion of new diagnostics, the formation of new information- or diagnostic-sharing programs, or in the synthesis and dissemination of best practices that are currently not anticipated.

Section A-7: Conclusion

Despite the wide variety of facility capabilities and scientific directions taking place under the LaserNetUS umbrella, centralized coordination of some diagnostic capabilities could ease the burden on facilities and users that presently repeat the work of others. Moreover, a set of common standards for calibrations and parameter measurements could make comparisons of facility capabilities more robust. As outlined in this chapter, the CDP is the product of a community trying to resolve these issues, taking advantage of the management infrastructure that LaserNetUS might provide.

While an effective CDP could have many possible ultimate goals, this report aims to show the common infrastructure needed to realize any selection of these goals and remain flexible as needs change. Whether the CDP focuses on cohering diagnostic information for common use, facilitating diagnostic collaborations, or lending common diagnostics from a centralized library, its existence will benefit the community and ultimately streamline scientific progress. As long as the CDP is designed with community feedback in mind, this committee sees an important place for it in the future of LaserNetUS.

Section A-8: References

[1] PlasmaPy Community et al. (2023). PlasmaPy, version 2023.10.0, Zenodo, https://doi.org/10.5281/zenodo.10011217.

B: Advanced Diagnostics for High-Repetition-Rate (HRR) Experiments

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Section B-1: Introduction

High-Repetition-Rate (HRR) experiments are a key area of interest for the future of high-energy-density physics [1-3], both in terms of developing competitive laser-driven secondary sources and maximizing the fidelity of complex measurements, necessitating the development of HRR diagnostics. The specific definition of HRR ranges from experiments faster than the typical shot rate of high-energy laser facilities, with shot cycles on the order of minutes, to extremely rapid experiments with kHz repetition rates, typically at sub-J laser energies on target. An alternative definition for HRR is an autonomous operation that does not require any human intervention for shots to be carried out in a continuous stream, which may or may not be at a constant frequency.

A concept related to HRR is burst-mode operation, in which the system runs in an HRR state for brief bursts, typically several minutes in current systems, with human interventions or checks possibly carried out between bursts. The repetition rate is generally limited by either the laser's shot rate, the availability of targets (e.g., inserting and aligning a new target versus a self-replenishing target), or the diagnostic capabilities. The development and commissioning of Petawatt-class laser systems, paired with the development of various HRR target systems, shifts the primary focus toward developing compatible diagnostic capabilities. Maximizing the output of HRR experiments will require developing and implementing diagnostics capable of collecting data without affecting the shot cycle.

Diagnostics types can be categorized based on the measurements they perform:

- **Target characterization:** Target characterization diagnostics assess the properties and conditions of targets before and after laser interaction, including shape, composition, and density.
- **Laser and system diagnostics:** These diagnostics monitor the parameters and performance of the laser system, including energy output, pulse duration, and beam quality.
- **Optical and non-optical probes:** These diagnostics use optical or non-optical techniques to measure parameters such as temperature, density, and pressure of plasmas.

- **Charged particle diagnostics:** These diagnostics measure the energy, velocity, and spatial distribution of charged particles (protons, ions, electrons) generated during experiments.
- **X-ray diagnostics:** These diagnostics measure the intensity, spectrum, and spatial distribution of x-rays emitted during high-energy-density physics experiments.
- **Neutronics:** Neutronics diagnostics measure the flux, energy spectrum, and spatial distribution of neutrons produced in fusion or other experiments.

This chapter will discuss the current state-of-the-art of staple diagnostics for each of those categories and their readiness for HRR operation. Key technologies to change the diagnostics landscape are identified together with the impact they can have on new diagnostics concepts. The operation of such novel diagnostics sets requirements for the infrastructure around laser-driven experiments, discussed below, and leads to new challenges that need to be addressed. The final sections of this chapter summarize potential approaches to overcome these challenges and offer an outlook on the future of HRR diagnostics.

Section B-2: Current State of HRR Diagnostics

B-2.1 Best Technologies for HRR Data Acquisition

Several mature technologies exist for detecting optical photons, including film, Charge-Coupled Device (CCD) cameras, and Complementary Metal Oxide Semiconductor (CMOS) detectors. For X-ray detection, options include those mentioned above, as well as image plates, scintillator screens, amorphous silicon, and energy-resolving semiconductors such as CdTe and HPGe (High Purity Germanium). Operation in HRR experiments excludes the use of passive detection media that need to be removed and processed for every single shot (e.g., image plates, film, CR39, etc.). Instead, active detectors capable of being read out on demand are required for HRR experiments. These are often electronic detectors (e.g., CCDs, CMOS, diodes, etc.) used alone or in combination with scintillators. Significant effort has already been documented in the literature regarding the commissioning of new scintillator-based X-ray spectrometers [4, 5], as well as their data processing [6]. Similarly, scintillator-based proton spectrometers have been constructed [7], and research has investigated spatially discriminating scintillator arrays for this application [8].

Standard X-ray diagnostics broadly fall into three primary categories: 1) imaging systems, 2) spectrometers, and 3) diodes. Imaging systems include pinhole imagers, crystal imagers, and various designs involving mirrors and diffraction gratings to image X-ray emission. X-ray spectrometers typically include a crystal dispersive element in the Bragg or Laue geometry, a diffraction grating for low-energy applications, differential filters such as Ross pairs, or occasionally use energy resolving detectors for low-count-rate measurements where individual detection events can be measured. These systems can be coupled directly to a detector or additional components such as X-ray streak cameras and are generally suitable for HRR experiments.

Charged particle diagnostics often implement single-shot detectors such as radiochromic film [9], image plates, or nuclear track detectors (CR39) [10]. A primary reason for this is their high-fidelity measurement capability, with numerous calibrations performed for these detectors in the past. Newer, HRR-compatible detector units include scintillators coupled to CCD cameras or microchannel plate amplifiers coupled to a scintillator and a CCD [11, 12]. Additionally, semiconductor-based detectors, Faraday cups, ionization chambers, and integrated current transformers are concepts borrowed from the accelerator community that are being implemented in laser-plasma experiments [13]. Although most current diagnostics can be easily adapted to HRR, their dynamic range and resolution at HRR fall short of what single-shot diagnostics can achieve.

Neutron detectors are generally distinguished between quasi-energy-independent, dose-sensitive detectors and energy-spectrum-sensitive detectors. Dose-sensitive detectors are usually single-shot diagnostics such as bubble chamber detectors, indium or zirconium activation detectors, or 3He detectors. Energy spectrum resolving detectors such as neutron time-of-flight detectors and magnetic recoil spectrometer detectors are inherently high-repetition-rate-compatible and can be read out electronically after each individual shot [14]. Such detectors sometimes rely on image plate detection for low-repetition-rate facilities but can be easily adapted by implementing scintillators that detect neutrons through light generated by knock-on protons within the image plate/scintillator material. This light is then collected by a CCD camera or collected and amplified using a photomultiplier tube. Compared to their dosimetry detector counterparts, detectors relying on scintillators as their detection unit suffer from high background due to sensitivity to x-rays and charged particles and the low detection efficiency of neutrons.

Most in-situ target-characterization diagnostics rely on optical diagnostics either using white light or monochromatic light. Here, multiple imaging lines, including optical elements such as mirrors, lenses, microscope objectives, and cameras, inform the user of the conditions of the target. While some facilities with standardized experimental platforms will have permanently installed target characterization systems, such as OMEGA or the NIF, smaller facilities usually rely on the user to partially or fully build their characterization setup. Such setups are inherently HRR-compatible but require additional infrastructure, such as shutters in front of cameras or motor systems to retract objectives close to the interaction and the underlying electronics to protect the imaging systems on shot. Such safety features can be slow to operate and, as such, pose a challenge to HRR operation with the need for frequent target characterization measurements.

Similarly, laser and systems characterization diagnostics are predominantly HRR-compatible such as energy meters, spectrometers, photodiodes, wavefront sensors, equivalent plane diagnostics for on-shot focal spot measurements and pulse duration measurements (autocorrelators). Most of those diagnostics use a fraction of the main laser pulse, produced by a leak through a mirror, to diagnose the laser parameters on target. Other diagnostics, such as third-order auto-correlators for contrast measurements, are challenging to run on every shot and are used typically before or after the experiment to inform the contrast of the laser for the experimental campaign.

Ordinarily, any type of detector will have to strike a delicate balance between sufficient resolution and high enough signal-to-noise ratio, which can be challenging especially in EMP-rich environments generated during laser-target interactions. Additional concerns are nuclear activation of components over hundreds to thousands of shots and the impact of high-peak fluxes on detector components.

B-2.2 High-Repetition-Rate Data Acquisition

Table 3 summarizes various aspects of diagnostics and its feasibility with HRR across different types, including Optical Diagnostics, X-ray Diagnostics, Particle Diagnostics (charged or neutron), Data Acquisition Systems, and Systems Operation.

Generally, the modest-repetition-rate (1-10 Hz) acquisition of optical data types is not seen as challenging. These include data from spectrometers, energy meters, photodiodes, wavefront sensors, and autocorrelators. However, for the functional use of these data types, some have limitations because of the time required to process the data.

The majority of neutron dosimetry detectors, except for some specific 3He detectors, need to be read out manually after each shot. However, due to the low detection efficiency of neutrons and lower laser energy on target at high-repetition-rate-capable facilities, accumulation measurements can usually be performed to obtain an average dose per shot. Efforts towards the development of repetition-rate-compatible dosimetry are minimal. Energy spectrum resolving detectors, on the other hand, are usually compatible with repetition-rate-capable detector units and are, as such, easy to integrate within an HRR setup. As repetition rates approach 10s of Hz, current setups of saving data locally on oscilloscopes or computers will become challenging due to data writing rates and file sizes.

***Table 3:** HRR assessment of the current state of diagnostics.*

	Optical Diagnostics	X-ray Diagnostics	Particle Diagnostics (charged or neutron)	Data Acquisition	Systems Operation
What is the exciting frontier with HRR?	Optical Thomson scattering and other probing techniques	Measuring the conditions of dynamic systems, imaging techniques	Dosimetry with immediate readout, large datasets, particle imagers	Single-shot-based saving system on local hard drives, no preprocessing	Automation of system safety, monitoring of delivered laser parameters
10 Hz feasible?	Yes	Generally no	Generally no	Generally no	Generally yes
kHz feasible?	Generally yes	Generally no	No	Generally no	Generally yes
Where is the biggest challenge?	Fast saving and processing of large 2D arrays	Supply of quality bent crystals, resolution	Calibration, dosimetry	Managing data rates and flows efficiently	Resources, data infrastructure, workforce
What technology might help?	CMOS, GPUs	Multi-gain detectors	Digitizers, SiPMs	Down sampling infrastructure and unified acquisition systems	Knowledge from accelerator community

Section B-3: Transformative Technologies for Diagnostics

B-3.1 Revolutionary Technologies

Technologies that improve the dynamic range and quantum efficiency of sensors would provide significant benefits to HRR experiments. The development of multiple gain mode detectors capable of providing effectively more than 20-bit detection is revolutionary. Technologies such as mmPADs (Megapixel Photon Avalanche Diodes) and PERCIVAL enable detectors to passively fill up multiple bins for different photon numbers and energy ranges. This enhances the resolution and accuracy of diagnostic measurements.

Advancements in detector technology include the development of vacuum-compatible solutions. Examples include Microchannel Plate (MCP) detectors capable of functioning in suboptimal vacuum conditions. Additionally, the integration of amorphous silicon detectors inside a vacuum environment further expands the applicability of diagnostics in various experimental setups.

Neutron detectors, specifically scintillator-based detectors, will benefit from novel photomultiplier technology such as more compact and robust silicon photomultipliers (SiPMs). However, in this specific case, the efficiency of SiPM-based detectors is two orders of magnitude below those of standard photomultiplier tubes, requiring further development towards enhanced detection efficiency to be a real alternative. Dosimetry detectors as a whole are challenging to adapt to higher repetition rates. It will be important to focus development on basic high-repetition-rate-compatible detection concepts with possibilities of taking inspiration from hard X-ray detection principles.

B-3.2 Potential Impact on Existing Diagnostics

The advancements in GPU (Graphics Processing Unit) technologies have revolutionized the landscape of data processing, particularly in handling image data, where GPUs have significantly outpaced CPUs in terms of speed and efficiency. This transformation presents a profound potential impact on existing diagnostic methodologies across various scientific disciplines.

Traditionally, data processing in experiments has often been conducted in batches, utilizing CPU-based systems. However, the advent of GPU processing opens up new possibilities for real-time data processing. This shift from batch processing to real-time processing has the potential to streamline experimental procedures and enhance the efficiency of data analysis. By enabling real-time processing of scientific data, experiments can become more self-directed, allowing researchers to make rapid decisions and adjustments based on real-time feedback.

In the realm of HRR operations, the impact of GPU-accelerated processing is particularly pronounced. HRR operations introduce novel diagnostic methods that were previously not feasible with single-shot operation. Some examples are listed below:

- **Cumulative data processing techniques:** With GPU-accelerated processing, experiments can accumulate data in real-time over multiple shots, allowing for more comprehensive analysis and understanding of phenomena that evolve over time.
- **Laser-induced fluorescence measurements:** Real-time processing facilitated by GPUs enables rapid analysis of fluorescence data, providing insights into chemical reactions, material properties, and biological processes with unprecedented speed and accuracy.

- **2-D and 3-D mappings of Thomson scattering:** GPU-accelerated processing allows for the rapid reconstruction of Thomson scattering data into detailed two-dimensional and three-dimensional mappings, providing valuable information about plasma properties and dynamics in fusion research and other fields.
- **Scanning diagnostics (e.g., Sequoia):** GPU-accelerated processing enhances the capabilities of scanning diagnostics, such as the Sequoia system, by enabling real-time processing of large volumes of data acquired during scanning operations. This allows researchers to quickly extract meaningful information from complex datasets, facilitating the study of diverse phenomena ranging from fluid dynamics to plasma physics.

Integrating GPU technologies into data processing workflows can revolutionize existing diagnostic methodologies by enabling real-time processing and analysis of scientific data. This transformation enhances the efficiency and accuracy of experiments and opens up new avenues for discovery and innovation across a wide range of scientific disciplines.

Section B-4: Emerging Diagnostics for HRR

B-4.1 Evolving Diagnostic Needs

The transition to High-Repetition-Rate (HRR) experiments necessitates the development of new diagnostics to meet the unique challenges and opportunities presented by this operational mode.

Single photon counting emerges as a critical requirement for constructing X-ray spectra and images across numerous shots while minimizing background noise. Integrating single photon counting with energy-resolving detectors enables the collection and integration of single photon events over multiple shots, facilitating high-dynamic-range measurements that are unattainable in single-shot experiments.

In the realm of charged particle detection, there is a pressing need for high-dynamic-range particle imagers, ideally equipped with variable filters, to resolve different energy levels. Additionally, the development of scanning magnetic spectrometers with variable magnetic fields holds promise for enhancing the capabilities of particle detection diagnostics. These advancements will necessitate concurrently developing robust analysis tools to extract meaningful insights from the collected data. Furthermore, addressing the degradation of detector units over time, particularly in scintillator-based detectors, will require the implementation of dynamic or in-situ calibration protocols to maintain measurement accuracy and reliability.

Achieving a high signal-to-noise ratio and resolution is paramount in developing HRR-capable neutron detectors. While existing diagnostics can characterize neutron beams adequately, there is a need to increase the repetition rate and sensitivity of these detectors to keep pace with the demands of HRR experiments. Moreover, focusing on applications of neutron beams, developing efficient detectors for neutron imaging, and catering to both fast and epithermal neutrons is essential. Drawing inspiration from the neutron source community, where robust and sensitive detectors for laser-driven neutron beams are being developed to handle lower fluxes, offers valuable insights for advancing neutron detection capabilities in HRR experiments.

B-4.2 Cutting-Edge Diagnostics

Cutting-edge diagnostics tailored for HRR applications leverage advanced techniques to enhance resolution, efficiency, and data processing capabilities. Examples of such diagnostics include:

- **Image Dithering:** Image dithering represents a groundbreaking capability for improving imaging resolution in HRR experiments. This technique involves the subtle shifting of a detector at distances smaller than the pixel size, enabling the discernment of sub-pixel signal changes. By incorporating image dithering into experimental setups, researchers can capture finer details and achieve higher-resolution imaging than previously possible. This technique relies on many experimental measurements, making it particularly well-suited for deployment in HRR experiments where rapid data acquisition is essential.

- **Digitizer Units for Signal Processing:** Efficient processing of electronic diagnostics signals is crucial for maximizing data throughput and minimizing processing bottlenecks in HRR experiments. Implementing digitizer units in the signal processing chain enhances data processing efficiency by enabling higher data rates without encountering processing delays or dropped shots on the computing side. Researchers can streamline data acquisition and analysis workflows by digitizing signals at the source, ensuring that valuable experimental data is captured and processed in real time with minimal latency.

Section B-5: Essential Capabilities and Resources

B-5.1 Infrastructure Requirements

Calibration Resources

Adequate resources for calibration are essential to collect reliable experimental results, necessitating both funding and access to HRR laser systems. Calibration experiments should be conducted as often as possible to assess the degradation rate for diagnostics. Establishing a systematic calibration process would significantly improve facility reliability and quickly identify any issues that need to be addressed due to the increased load created by HRR experiments. At HRR, calibration and background capture processes may need to occur frequently and be automated. Ideally, facilities could incorporate "standard candle" experiments to serve as reference points for calibration activities and to quantify any changes in facility performance.

Calibration resources also include access to conventional ion and neutron sources to calibrate detectors' responses as a function of incident ion/neutron energy and flux. This eliminates the need for cross-calibration or in-situ calibration to determine detector responses. Additional research should target understanding the degradation processes of common detection units and modeling support for new detectors coming online.

System Monitoring

With HRR operation comes faster changes to the laser and experimental system. It is necessary to monitor in real time certain non-science data related to machine health, system safety, and source stability. System diagnostics, including monitoring laser near-field profiles for surface damage identification and tracking the buildup of debris or damage on optics, are crucial for maintaining system integrity and throughput. Monitoring may be necessary for debris buildup [15] and damage on optics or amplifiers, which can be a machine safety hazard and affect system throughput.

Data may be needed for environmental awareness, such as temperature monitoring of gain media, gratings, and final optics, and radiation monitoring (potentially solved at XFELs). Wavefront stability may need to be assessed on a per shot or regular basis. Drawing inspiration from established facilities like ELI and the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS), robust monitoring infrastructure should be implemented to support HRR experiments effectively. Additional system monitoring includes vacuum levels and gate-valve status between individual segments of the laser chain up to the target chamber that are kept under vacuum.

System Control

Efficient system control mechanisms are paramount for seamlessly managing HRR operations. HRR operation often requires high-speed alignment, which may be performed by machine vision. This would typically require an optical image system diagnostic to be acquired, the data analyzed for some focus criterion, and feedback passed to a target motor. (An example of system control and monitoring for the BELLA LaserNetUS facility is presented in the *IEEE Journal of Quantum Electronics* [16]).

This example is a case where a repetition rate of ~10 Hz is not expected to be a significant challenge. Other common system control processes for laser systems include shuttering to protect equipment and filter changes. Shuttering can be accomplished with mechanical shutters for a repetition rate of 10 Hz for small aperture lines of sight but becomes challenging for faster or larger beams. Faster shutter technologies like PEPC and Pockels' cells may help here. Fast steering operations can be performed with voice coils. Developing advanced shift registers can also facilitate the automation of fast-system control processes, further optimizing experimental workflows.

Reliable Suppliers for Components

Established and reliable supply chains for consumable components are essential, especially for components subjected to harsh conditions in HRR experiments. Ensuring a consistent and sufficient supply chain for these materials is crucial for maintaining uninterrupted diagnostic operations. A particular area of need for the community is the ability to fabricate high-quality crystals for X-ray spectrometers and imaging systems. Bent crystals, in particular, are highly desirable, but the expertise required for their fabrication is diminishing. Addressing challenges in lead times and fabrication quality is paramount to prevent delays in experimental setups and ensure the availability of essential components when needed. Investing in training and retaining skilled personnel is crucial to address current challenges.

Computational Infrastructure

Additional needs from the facility side for efficient HRR diagnostics operation are the availability of computational capacity and local infrastructure. As data rates grow due to HRR operation, it will be essential to have a framework targeted at reducing data rates using digitization of signals, data compression, or strategic selection of ROIs, especially applicable to camera image data. While initial research and development can be done using "traveling" setups, having a permanent and dedicated setup installed at HRR facilities will be crucial.

B-5.2 Skilled Workforce and Collaboration

Shifting towards HRR operation and automation control demands a substantial investment in training and hiring personnel with specialized information technology skills. Individuals with expertise in controls and open-source data flow designs are indispensable for advancing into HRR experiments. They play a crucial role in developing and implementing automated control systems essential for managing the intricacies of HRR operations.

Leveraging existing expertise in HRR operation within LaserNetUS, particularly at facilities like MEC and BELLA, provides a valuable foundation for transitioning into HRR experiments. Moreover, drawing insights from other scientific communities, such as XFELs and colliders, through workshops and collaborative efforts fosters the exchange of best practices and facilitates the adoption of innovative approaches in HRR experimentation. External bodies of knowledge include those listed below:

- EUV expertise in monitoring the endline throughput of the system.
- Air Force and the astronomy fields on the application of wavefront characterization and compensation.
- National Ignition Facility (NIF) and others on optical degradation causes/fixes and collective strategies/best practices to mitigate.
- Accelerator and neutron source communities (spallation sources, reactors) can inform advanced detector designs and operations in high-radiation environments.

Furthermore, promoting collaboration and knowledge sharing among community members is essential for accelerating progress in HRR experiments. Emphasizing the development and sharing of common diagnostic analysis tools and statistical treatments facilitates efficient data processing and ensures transparency in data interpretation. This will either include users being trained in the HRR tools developed at each facility or establishing shared documentation and user-friendly interfaces for operation. These could become more complicated than they are currently.

There is also a strong need for IT infrastructure upgrades to support fast data transfer and processing. IT experts may not be available at each facility. More personnel with controls expertise will be needed to build and maintain automation tools and alignment processes.

Section B-6: Challenges and Considerations

B-6.1 Challenges in HRR Diagnostics

Survivability and robustness are paramount concerns for active detectors deployed in HRR experiments, given the hostile environment generated by high-intensity laser experiments. With HRR operation, diagnostics face exposure to high average fluxes of high-energy particles like hard x-rays, fast electrons, and neutrons. Qualifying diagnostics for deployment must entail assessing the conditions under which they can operate effectively. Designing new diagnostics should incorporate sufficient shielding to withstand the expected conditions. Moreover, for seamless operation in a dynamic system, automating maintenance processes—such as remote replacement of failed optics and adjustment of filtration—may become necessary.

Using fiber bundles and scintillators to transport signals away from the interaction region is crucial for mitigating the effects of EMPs while maintaining HRR operation. This approach ensures the reliability and longevity of diagnostic systems in challenging electromagnetic environments.

However, transitioning certain diagnostics from single-shot-mode to HRR poses significant challenges due to iterative or slow processes, such as in the following examples:

- Deformable mirror/wavefront sensor loop processing
- Scanning autocorrelator
- Optical streak cameras
- Thomson scattering
- Raman spectroscopy
- Neutron dosimetry detectors

These systems often require human or mechanical intervention and multiple shots followed by analysis and feedback, hindering their compatibility with HRR operation. The deformable mirror is also slowed by the response time of a large number of piezoelectric actuators. These may be made faster with voice coils. Quick FROG is capable of ~1 Hz, due to post-processing. GPU processing will help with many of these, which are image-based. Other detectors are incompatible with HRR operation; new detector designs are needed to allow for HRR operation.

In summary, the primary challenges in HRR experiments include ensuring the survivability of active detectors in hostile environments, qualifying diagnostics for suitable operational conditions, and incorporating sufficient shielding in new designs. Additionally, transitioning certain diagnostics to HRR mode, addressing response time limitations, and mitigating the effects of electromagnetic pulses pose significant hurdles. Automating maintenance processes, exploring alternative technologies for faster response, and overcoming incompatibilities with HRR operations are also fundamental challenges that need to be addressed.

B-6.2 Ethical and Safety Considerations

The use of the HRR diagnostics raises several ethical and safety considerations; here are some potential points to consider:

- **Safety Protocols**: Implementing stringent safety protocols to ensure the well-being of researchers and personnel working with diagnostics is essential. This includes proper training, hazard assessments, detailed diagnostics documentation, and adherence to safety guidelines to minimize the risk of accidents or injuries. Assigning a responsible person or institution to assist with fielding the diagnostic can facilitate and ensure safe operation.
- **Regulatory Compliance**: Adhering to relevant regulatory frameworks, including national and international regulations governing laser safety, radiation protection, and research ethics, is essential to ensure compliance and accountability in HRR experiments.
- **Documentation and Record-Keeping**: Maintaining accurate documentation and records related to the diagnostic equipment, safety procedures, training, and incident reports is key. This ensures accountability and provides a reference for future operations and regulatory compliance.
- **Diagnostics Management:** Establishing a comprehensive system for documentation and information sharing is critical. For example, any shared diagnostic should always have a regularly updated manual traveling with the diagnostics.
- **Data Security and Privacy**: Ensuring the security and privacy of experimental data, particularly in sensitive research areas, is important. Safeguarding data from unauthorized access, breaches, or misuse is essential to maintain the integrity and confidentiality of research findings.
- **Equitable Access**: Promoting equitable access to HRR technologies and diagnostics, particularly in collaborative research efforts and international collaborations, is essential. Ensuring that benefits and opportunities derived from HRR research are accessible to diverse communities and researchers worldwide fosters inclusivity and fairness. For example, any concerns about intellectual property and publishing rights should be resolved prior to the use of any diagnostic from another institution or group.

Section B-7: Future Prospects

B-7.1 The Future of HRR Diagnostics

The future prospects of HRR diagnostics at LaserNetUS facilities envision a shift towards real-time readout of electronic detectors, marking a significant advancement from current practices. Direct collection of optical and X-ray photon data will become standard, while the conversion of particle and gamma data will be seamlessly integrated into diagnostic processes. To achieve this, many existing diagnostics at LaserNetUS facilities will undergo adaptation to incorporate fast scintillators for efficient conversion. Data from these diagnostics, along with comprehensive metadata and optional operator input, will be saved after each shot using robust computer infrastructure, facilitating easy access and analysis through a queryable database.

Looking ahead, there are promising areas for growth and innovation within HRR diagnostics:

- **Advanced Gain Detectors:** Highly sensitive measurements enabled by single-photon counting; this is accomplished by utilizing advanced gain components like avalanche diode arrays and Microchannel Plate (MCP) detectors.
- **Integration of Artificial Intelligence (AI)**: Implementing AI algorithms for data analysis, such as the Bayesian approach, and interpretation can enhance the efficiency and accuracy of diagnostic processes. Machine learning techniques can help identify patterns, anomalies, and correlations in large datasets, leading to deeper insights and more informed decision-making.
- **Enhancing Predictive Capabilities:** Linking datasets to models enables researchers to anticipate experimental outcomes and optimize experimental parameters for improved results.
- **Miniaturization and Portability**: Advancements in miniaturization technologies can lead to the development of compact and portable diagnostic systems. These portable devices enable diagnostics to be deployed in remote or challenging environments, expanding the scope of HRR research to new locations and applications.
- **Development of Multi-Purpose Diagnostics**: Combining multiple diagnostic techniques, such as spectroscopy, imaging, and particle detection, into integrated systems can provide comprehensive characterization of experimental conditions.
- **Interdisciplinary Collaboration**: Fostering collaboration between different scientific disciplines, such as physics, chemistry, biology, and materials science, can spur innovation in HRR diagnostics. Cross-disciplinary approaches bring together diverse expertise and perspectives to address complex scientific challenges.

Section B-8: Conclusion

Transitioning to HRR diagnostics comes with challenges but also opportunities such as better utilization of the laser offerings with existing systems, collection of more powerful datasets, and some new diagnostic capabilities.

The key findings discussed above are listed here:

1. Several technologies are ready to be applied for HRR acquisition of scientific data. Optical data, in particular, can be taken at HRR with inexpensive, off-the-shelf technologies, making it straightforward to build HRR optical diagnostics for laser health, target inspection, and optical signals.
2. Development of low-risk diagnostics is needed to adapt the large volume of X-ray and particle diagnostics to active detectors that can be read out on demand at HRR.
3. Neutron detectors, especially dosimetry detectors, will require significantly more development work to be adapted to HRR.
4. Increased data collection will need to be supported by larger, fast data storage, higher computing power for real-time analyses (e.g., with GPU systems), and expansion of the teams' skills.
5. The need for system monitoring diagnostics increases as HRR operation becomes routine.
6. HRR data collection can be transformative when it can be easily compared to model data. As such, experimentalists and modelers should agree to mutually accessible data formats.
7. Some HRR diagnostics will advance the data-taking capabilities even at single-shot experiments, such as the mapping and scanning types discussed above.

Section B-9: References

[1] P.W. Hatfield et al., “The data-driven future of high-energy-density physics”, *Nature*, **593,** 351, (2021).

[2] P. V. Heuer et al., “Preface to special topic: The High Repetition Rate Frontier in High-Energy-Density Physics”, *Physics of Plasmas*, **29**, 110401 (2022).

[3] T. Ma et al., “Accelerating the rate of discovery: toward high-repetition-rate HEDscience”, *Plasma Physics and Controlled Fusion*, **63**, 104003, (2021).

[4] D. R. Rusby, C. D. Armstrong, C. M. Brenner, R. J. Clarke, P. McKenna, and D. Neely, “Novel scintillator-based x-ray spectrometer for use on high repetition laser plasma interaction experiments,” *Review Sci. Instrum.*, **89**, 073502, (2018). doi: 10.1063/1.5019213.

[5] G. Zeraouli et al., “Ultra-compact x-ray spectrometer for high-repetition-rate laser–plasma experiments”, *Review Sci. Instrum.*, **93**, 113508, (2022). doi: 10.1063/5.0100970.

[6] R.A. Simpson et al., “Development of a deep learning based automated data analysis for step-filter x-ray spectrometers in support of high-repetition rate short-pulse laser-driven acceleration experiments”, *Review Sci. Instrum.*, **92**, 075101, (2021).

[7] N. P. Dover, M. Nishiuchi, H. Sakaki, et al., “Scintillator-based transverse proton beam profiler for laser-plasma ion sources”, *Rev. Sci. Instrum.* **88**, 073304, (2017). https://doi.org/10.1063/1.4994732.

[8] M. J.-E. Manuel et al., “Enhanced spatial resolution of Eljen-204 plastic scintillators for use in rep-rated proton diagnostics”, *Review Sci. Instrum.*, **91**, 103301 (2020).

[9] F. Nürnberg et al., “Radiochromic film imaging spectroscopy of laser-accelerated proton beams”, *Rev. Sci. Instrum.*; 80 (3): 033301, (2009). doi: 10.1063/1.3086424.

[10] J. S. Yadav, “Charged particle identification using CR-39(DOP) detectors”, Radiation Measurements, Volume 24, Issue 2, 1995.

[11] D. A. Mariscal et al., “A flexible proton beam imaging energy spectrometer (PROBIES) for high repetition rate or single-shot high energy density (HED) experiments”, *Rev. Sci. Instrum.*, 94 (2): 023507 (2023).

[12] R. Nedbailo et al., “Compact high repetition rate Thomson parabola ion spectrometer”, *Rev. Sci. Instrum.*, 94 (2): 023505 (2023).

[13] L. D. Geulig et al., “Online charge measurement for petawatt laser-driven ion acceleration”, *Rev. Sci. Instrum.*, 93 (10): 103301 (2022).

[14] J. H. Kunimune et al., “Phased plan for the implementation of the time-resolving magnetic recoil spectrometer on the National Ignition Facility (NIF)”, *Rev. Sci. Instrum.*, 93 (8): 083511 (2022).

[15] N. Booth, S. Astbury, E. Bryce, et al., "Debris studies for high-repetition rate and high-power laser experiments at the Central Laser Facility", *Proc. SPIE 10763, Radiation Detectors in Medicine, Industry, and National Security XIX*, 107630S (2018). https://doi.org/10.1117/12.2318946.

[16] K. Nakamura et al., "Diagnostics, Control and Performance Parameters for the BELLA High Repetition Rate Petawatt Class Laser”, *IEEE Journal of Quantum Electronics*, **53**, 1200121, (2017). doi: 10.1109/JQE.2017.2708601.

C: Diagnostics for Next-Generation Facilities

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Section C-1: Introduction

The Next-Generation Facilities (NGFs) include new laser facilities and upgrades of current facilities that involve lasers with higher intensities or energies or offer higher-repetition-rate capabilities. The forthcoming NGF will facilitate studies of matter in extreme conditions (MEC), laying the groundwork for new high-energy-density (HED) platforms that can support Inertial Fusion Energy (IFE) research, among other applications.

Current and future laser facilities rely on laser, optical, X-ray, charged particles, and neutron diagnostics for numerous tasks. Laser characterization allows the facility to deliver good-quality laser beams that comply with the demands of the experimental teams. At the same time, X-ray, optical, charged particles, and neutron diagnostics are essential tools for understanding the physics at play when a laser interacts with a target.

These diagnostics must 1) be able to work at the desired repetition rate, in the best-case scenario, at the repetition rate of the laser; 2) produce output data that can be distinguished from a strong and noisy signal background; 3) be resistant to EMP perturbations caused by strong currents triggered by the laser-target interaction; 4) allow for remote operation and data readout; and 5) be a flexible solution for numerous experiments or an extremely specific instrument that can, for example, perform a measurement that has never been done or drastically increase the temporal or spatial resolutions of a previously performed measurement leading to a greater understanding of a specific physical problem.

This chapter discusses the requirements for diagnostics to work at these Next-Generation Facilities by first understanding the harsh conditions they will be subject to (Section C-2) and how these conditions will challenge the diagnostic's operation in these new facilities (Section C-3). Based on the harsh conditions and linked challenges identified in Sections C-2 and C-3, respectively, Section C-4 dives into the diagnostics needs for the upcoming facilities, emphasizing the capabilities to be developed within the facilities and the general guidelines to follow throughout the process.

The end of Section C-4 summarizes specific topics that should be researched to overcome some of the challenges and develop robust diagnostic solutions for the NGFs. Section C-5 is dedicated to presenting specific cutting-edge technologies that could be developed in the NGFs related to material testing, EMP and radiation handling, coping with debris and related damage, and performing measurements in extreme environments. Finally, the conclusions are summarized in Section C-6.

Section C-2: Requirements for Effective Diagnostics in Harsh Conditions

C-2.1 Harsh Conditions Overview

The significant challenges generally expected to impact diagnostics at next-generation facilities are EMPs and damage due to high neutron flux and other radiation. Temperature will also be a factor for diagnostics placed close to an experiment, and for optical diagnostics, stray light of multiple wavelengths can be a concern. Environment cool-down times and limited access to diagnostics will necessitate remote handling and recording techniques.

EMP poses a particular challenge, especially at kJ-class facilities, and is a problem that diagnostics of all types will need to address or mitigate. Close proximity to the target chamber center typically exacerbates this issue. Photomultiplier tubes (PMTs) and charge-coupled devices (CCDs) are particularly susceptible to EMP. Many diagnostics operate under bias conditions, which could also pose challenges in a harsh EMP environment, potentially impacting the stability of diagnostic output over time. This concern may be more pronounced for modern Silicon Photomultipliers (SiPMs), which operate at lower bias voltages than PMTs.

Options for managing EMP effects (discussed in more detail in the following sections) could include using EMP-proof mesh or solid boxes to limit damaging effects (though this requires electrical engineering expertise and thermal management), employing umbilical shielding and flex conduits to mitigate at the source (such as dipole antennas) or mitigating return currents (as attempted in France). Alternatively, less-sensitive technologies can be utilized, such as using fiber bundles for signal transport.

Below, some specific considerations for X-ray, charged-particle, optical, and neutron diagnostics are discussed.

C-2.1.1 X-Ray Diagnostics

For the X-ray diagnostics, a particular challenge will be the ability to distinguish X-ray signals from other species (neutrons, secondary x-rays, etc). It is not yet clear how to ensure the integrity of diagnostic components in terms of, for example, damage from neutrons. Either the survivability of diagnostic components has to be improved, or facilities have to accept that some components will have to be expendable and replaced often. High aperture diagnostics can be designed for sitting far away from the interaction but still perform (long working range diagnostics). Best practices from current facilities (AND experiments) that can guide future steps and planning for sustainability will be critical. Single-shot experiments could still rely on passive detectors. High-repetition rate could be supported by improving X-CCD electronics as has been done at the LLE, for example.

C-2.1.2 Charged-Particle Diagnostics

In addition to contending with a more challenging environment, charged-particle diagnostics will also have to deal with higher fluences of the charged particles themselves. This will likely necessitate having detectors fielded further from the source and considering detection methods that allow for higher flux and remote detection, e.g., activations and decay. Indirect measurements, such as isochoric heating, are another alternative. It will be essential to consider detector damage thresholds in the design.

C-2.1.3 Optical Diagnostics

Optical diagnostics and the data they obtain must survive in the new harsh environments (in terms of EMP, debris, and prompt and delayed radiation) while matching existing signal-to-noise ratios. It will also be important to minimize downtime and/or specify an acceptable lifetime between needed maintenance (e.g., 2 weeks like LCLS). In addition to the standard challenges of high neutron flux, such as single-event upsets and personnel protection requirements, optical diagnostics also have to address light of all wavelengths adding troublesome background, fluorescence, and unwanted back reflections into the system.

The good news is that many laser diagnostics are immune to these problems because of lower flux at a distance, but experimental diagnostics are typically on or in the target chamber. Measurements may be more challenging at higher average power. Measuring intensity/spot on target at full energy is harder at higher energy, and thermal effects in the leak-through optic may also be challenging. Concerns include fiber fluorescence and the fact that BNC cables act as antennas that can fry electronics or ruin shots.

C-2.1.4 Neutron Diagnostics

Neutron diagnostics are designed to handle high neutron flux and are generally less sensitive to radiation damage effects than other diagnostics. The limit for neutron damage is unlikely to be reached at next-generation LaserNetUS-class facilities; at OMEGA, issues with electronic single-event upsets occur around ~1e14 and at the NIF at ~1e17 neutrons per shot. Interference from gamma flash may be a concern but can be handled by optimizing detector stand-off distance.

C-2.2 Diagnostics Suitability

Diagnostics' suitability to operate in harsh conditions can be improved by, for example, increasing stand-off distances, using more passive components, finding ways to operate remotely, improving EMP resilience and/or shielding against radiation (neutrons), such as using concrete bricks, boron, or polyethylene. Another option is using simple off-the-shelf components that can be directly replaced when they fail.

For optical diagnostics, relay systems can move detectors back to a bunker using image-preserving fibers, optical mirrors (if f/# allows), and electron optics. Rejection of unwanted light of all wavelengths can be improved using wavelength discrimination/polarization discrimination or tighter bandwidth discrimination, for example.

Several of these mitigation techniques are already used in some form or other, but as the transition to NGF is made, mitigation schemes must be improved or implemented for more systems than currently use them. Some of the remaining challenges are highlighted in the next section of this chapter (Section C-3).

Section C-3: Challenges in Implementing Effective Diagnostics

C-3.1 Technological Challenges

Identifying technological hurdles in developing diagnostics for the NGFs is of primary importance for the correct development of these facilities and wise effort allocation in the process. Hereinafter, some of these technological challenges related to X-ray, charged particles, optical, and laser and neutron diagnostics are discussed.

C-3.1.1 X-ray Diagnostics

The spatial resolution of X-ray sources is determined by their original size. Apart from distinguishing the X-ray signal from the strong background, discussed in the following section, higher spatially resolved sources also need to be developed. The latter can be obtained from 1) the development of new solid target technologies or 2) betatron sources where the wiggling electrons inside a plasma wakefield generate specific X-ray sources.

Better characterization of the betatron sources that will be produced in the NGFs will be needed. It may also be interesting to develop diagnostics that can carry out autocorrelation operations in the X-ray range. Finally, it is important to keep in mind that single-shot components are expensive but their cost might lower when purchasing several for high-repetition-rate operation.

C-3.1.2 Charged-Particle Diagnostics

Charged particle diagnostics are essential for understanding the physical processes that occur when a laser interacts with a material. As X-ray sources, the NGFs will convey several technical challenges for charged particle detection. The higher energies and shot repetition rates expected in the new NGFs will trigger strong material degradation processes that need to be understood. Materials will also be radiologically activated from the interaction with x-ray and secondary particles such as neutrons. Hence, activation studies will need to be conducted.

The effects of shooting in burst mode or single-shot regarding material degradation and activation should also be explored. Electromagnetic lenses may be used to refocus charged particle beams [1], although cool-down time must be optimized for high-repetition-rate systems. Since these challenges are the subject of research within fields such as the Accelerator and Materials Science community, strategic collaborations should be established. Furthermore, new physics will be accessible with the laser energy and intensity levels available in the NGFs. Studies on particle energy deposition and particle scattering in these new regimes will be highly important.

C-3.1.3 Optical and Laser Diagnostics

Regarding optical and laser diagnostics, bigger and higher-repetition-rate laser facilities will have compounded debris problems on all the equipment close to the interaction point. Damage-identification algorithms could be applied to understand, among others, the coatings' lifetime and degradation in these new conditions. Current laser characterization techniques, such as leaking mirrors, could be hindered by the thicker glasses (and the corresponding B-integral) that will be used for such components in the NGFs. At the same time, post-compression measurements may be more difficult if the peak power is higher. In general, at larger beam apertures, the laser characterization becomes more difficult and expensive. High-energy on-shot intensity measurements are almost impossible in modern lasers and will be even harder moving forward.

Here are two examples of how this is accomplished in current high-energy/intensity lasers: 1) the Texas PW laser (Austin, TX, USA) takes a 0.003% laser leakage from the last steering mirror that goes to the on-shot diagnostic located behind a shield wall and 2) the ELI L4 laser (Czech Republic) has an output package based on reflection from a window before compression. Finally, the emission of multiple sources at multiple wavelengths will require wavelength and polarization discrimination techniques. Everything previously mentioned will need to be developed flexibly, allowing the laser system to be adapted to a large variety of user needs.

C-3.1.4 Neutron Diagnostics

Neutron diagnostics need to inform about particle spectrum, yield, spatial profile, and time-resolved emission. Spatially-resolved spectral information using a SiPM/pixelated approach with a digitizer for each pixel could be interesting. Total neutron yields exceeding 1e14 and 1e18 total (spread into 4pi over ~100ps burn duration) are observed at OMEGA and NIF, respectively. The NGFs will probably not reach their neutron production levels, so neutron damage at the facility level may not be critical. However, there could be challenges in implementing pitcher-catcher schemes linked to the catcher degrading very quickly over time.

Neutrons can be used as a diagnostic for plasma conditions in deuterated targets. They can also be employed for probing transient phenomena such as short-lived HED states, for which pulsed neutron sources are instrumental. However, it will be challenging to mass-produce deuterated targets like cryogenic jets or deuterated water used for secondary neutron generation at a high-repetition-rate since this is an expensive and under-developed technology.

C-3.2 Data Acquisition and Analysis Challenges

Several technological challenges will directly relate to data acquisition and analysis complexities in the NGFs' challenging environments. The following section discusses some strategies for managing and interpreting data under harsh conditions.

C-3.2.1 X-ray Diagnostics

X-rays are produced intentionally during experiments seeking to develop X-ray sources for numerous applications or from secondary species produced during the laser-target interaction. These species, such as neutrons, interact with the surrounding materials (e.g., vacuum chamber, diagnostics located in the vicinity, etc.), generating a high X-ray background which makes detecting the primary x-rays difficult. Hence, correct signal detection will rely on specific diagnostics' shielding and the study of the entire vacuum chamber and surrounding diagnostics that can contribute to the X-ray signal background through secondary interactions.

Tied to the emission of x-rays and secondary particles is the activation of materials and the consequent need to handle them and trigger data readouts remotely. Moreover, shielding materials such as lead are heavy and could hinder the alignment of diagnostics and optical lines. On the positive side, diagnostics relying on X-ray polarization will become much more helpful since a higher X-ray flux is expected. The community could benefit from research and development of these types of diagnostics.

C-3.2.2 Charged-Particle Diagnostics

As was previously mentioned, the high EMP levels expected will make these NGFs very large, allowing diagnostics to be located far away from the interaction point. Charged-particle diagnostics working in single particle counting modes will need to be carefully adapted to the high background signal levels.

C-3.2.3 Optical and Laser Diagnostics

The NGFs will also challenge modern optical and laser technology. The expected signal-to-noise ratios are unknown. Therefore, it would be important to understand whether measurements performed in current lasers can be scaled or extrapolated.

C-3.2.4 Neutron Diagnostics

Finally, as with x-rays and charged particles, neutron detection will also be hindered by the large EMPs expected in the NGFs. Standard elements used in neutron detection diagnostics, such as neutron time-of-flight detectors (nTOFs), involve photomultipliers to enhance the signal level and CCDs. Both electronic devices are highly sensitive to EMP, especially when located close to the interaction point. The interference from the gamma flash or photopeak can be handled by stand-off distance.

C-3.2.5 Electromagnetic Pulses (EMPs)

EMPs are already an important issue in modern laser facilities. The strength of these EMPs and their detrimental effects will increase in the NGFs. Therefore, X-ray, optical, neutron, and charged particle detectors must be located at a greater distance from the interaction point, and larger vacuum chambers will be needed. Target chamber design should carefully consider possible GHz chamber modes that could resonate in the EMP range. The diagnostics of the NGFs will need higher collection capabilities since the signal level will decrease when the distance between the detector and the interaction point is increased.

Strategies to deal with EMP involve mitigation at the source using techniques such as shaping the target stalks (e.g., zigzag) [2]. EMPs can also be dealt with from the diagnostic side, making them more resilient by, for example, replacing CCDs with a fiber bundle coupled to a scintillator. All diagnostics are biased, which requires understanding how the EMP affects active detectors, their output stability over time, and the differential effect in high-voltage- and low-voltage-biased detectors.

Section C-4: Diagnostics Needed for Upcoming Facilities

New facilities will bring new capabilities to users in response to their needs, opening uncharted avenues for research. Upcoming facilities should consider requirements from a wide variety of users. The requirements must support scientific needs related to spatial and temporal resolution, signal/noise ratio optimization, and component performance and survival in harsh environments. In addition to user feedback regarding diagnostic needs, upcoming NGFs should consider best practices from current facilities and the experimental platforms within to guide their design and operation. Moreover, it is imperative that these facilities plan for sustainability.

C-4.1 Diagnostic Requirements

Improved time resolution will enable better characterization of transient phenomena of short-lived HED states. For imaging diagnostics, better time resolution would help overcome motion-blurring challenges, for example. This need may be addressed through probing beam-pulse duration and/or through gated detection. Pulsed neutron sources can provide natural gating. In most laser facilities, X-ray backlighter sources and charged particle beams are generated by laser-irradiating solid and gaseous targets. Hence, time resolution is dictated by laser-target interaction dynamics.

Notably, accurate X-ray pulse measurements could lead to 3 MeV monoenergetic probing. On the other hand, detectors such as ultrafast streak cameras (optical and x-ray) and scintillators can provide 500 fs resolution with <300 fs desired for some applications. It should be noted that gated detectors and framing cameras are not readily available to smaller facilities within the LaserNetUS network.

Each NGF will have additional detection requirements, such as larger target chamber designs that can address EMP challenges, although diagnostic/detector systems with higher collection capabilities will be needed. In IFE-relevant research, detector systems must support higher repetition rates. Moreover, detecting methods that allow for higher flux and enable remote detection (e.g., activation and decay, neutrons' secondary reactions) may present a viable solution.

The primary neutron diagnostics used at current LaserNetUS facilities are neutron time-of-flight (nTOF) detectors, measuring directional neutron energy spectra and yields with scintillators coupled to PMTs. nTOFs intrinsically provide the capability to operate at a high-repetition-rate, but some components may need to be improved for faster data transfer and turn-around. The stability of diagnostics output over time must be explored as well. This pitcher-catcher scheme will present issues as the catcher degrades very quickly. More research is needed to find a strategy to carry out these measurements efficiently while keeping neutron numbers up. Also, increased EMP issues may present challenges for PMTs (which operate at bias) that will require mitigation. This might be worse for SiPM, which are biased at lower voltages than PMT.

In addition, enhanced neutron output at NGFs means more information will be obtainable from neutrons, requiring the development of new diagnostics capable of measuring not only directional neutron yields and spectra but also spatial emission profiles and time-resolved emission. These needs will only grow as neutron yields grow and more exciting new experiments are enabled.

X-ray lens technology must be developed to improve spatial resolution and component survival. Concerted efforts to support these developments may result in lower manufacturing costs, which will benefit users. Note that resolution improvements may be achieved through optics manufacturing, which should leverage technological needs and advances from other facilities–such as synchrotrons and XFELS–as these facilities often lead in X-ray diagnostic development.

A major manufacturing gap has been identified. This directly impacts component availability for laser systems and optical and X-ray diagnostics. For example, good-quality crystals for spectroscopy diagnostics are scarce. Note that this manufacturing gap may also prevent the development of novel instruments and new diagnostic techniques. This urgent need must be addressed through partnerships with industry, U.S. national laboratories, and international collaborations.

C-4.2 Facility Capabilities

Integrating standard capabilities in NGF will better support current and future diagnostics. Details will be provided in the context of specific diagnostic platforms and experimental research applications.

C-4.2.1 Laser Diagnostics: “Full Sensor Package” and Optics Damage Assessment

Users will benefit from a “full sensor package” for on-shot laser pulse characterization. Currently, few laser facilities offer this capability, although “full sensor package” characterization has been a common request from laser facility users at large. A “full sensor package” includes measurements of Energy and/or Intensity as well as on-shot Contrast (>ns and <ns), nearfield and fairfield pointing, and pulse front tilt through inverted field autocorrelator. Transmitted and reflected optical measurements are desirable, and wavefront sensors such as Grenouille Striped Fish [3] or another spatiotemporal phase sensor would be beneficial. It is imperative to co-time the full sensor package system for laser control and diagnostics.

Continued development in spatio-temporal pulse and pulse contrast measurements should be encouraged. Further improvements should be supported for higher repetition rate and multiple source systems with particularly robust long-pulse diagnostics able to withstand the harsh radiation and EMP environment. These requirements include timing diagnostics to co-time: 1) short pulses to one another and 2) short pulses to long pulses. It is necessary to implement diagnostic pairs that span fs/ps and ps/ns ranges, noting that these pairs must have the same clock. Oscilloscopes with high temporal resolution and long record lengths will be required.

Post-target diagnostics may be a valuable tool to evaluate laser system performance. In addition, constant imaging of laser optics can assess component condition and potential laser system damage. Note that a quick and prompt response may lead to reduced optics replacement downstream. Moreover, failure to identify damaged components can propagate to other optics, which may compromise the entire laser system. This must be a priority for NGF and the design of upcoming facilities considering increased laser output, and it will be even more relevant to high-repetition-rate systems.

C-4.2.2 Standard X-ray Imaging Platforms:

The development of X-ray radiography diagnostic techniques has broad applications across HED/IFE [4]. In particular, X-ray phase-contrast imaging may offer higher resolution and sensitivity [5]. X-ray imaging techniques have been underexploited, and their continued use and development may benefit the community broadly by pushing technological advancements in X-ray optics, which will benefit the community and beyond. The development of X-ray imaging platforms at each laser facility will also enable in-situ target metrology and other advanced imaging techniques, such as small-angle X-ray scattering measurements through dark-field radiography, which can be helpful in the characterization of porous materials (e.g., 2PP foams), for example.

Implementing standard X-ray imaging platforms for most HED facilities will require the development of suitable X-ray sources. Although a wide variety of X-ray imaging diagnostics have been implemented in laser facilities, the potential contributions from these methods have been limited by brightness, size, pulse width, bandwidth, and coherence. The LCLS-MEC leverages its XFEL beam and microscope X-ray imager (MXI) to offer X-ray propagation-based phase-contrast imaging. Recently, 2D Talbot X-ray imaging was used to probe laser-irradiated shocked-foams, delivering simultaneous retrieval of attenuation, phase, and darkfield maps with unprecedented resolution of <1 μm and ~300 fs.

Since XFEL beam integration is not feasible to most NGF, current X-ray backlighters must be improved. X-ray sources generated through solid target irradiation are widely used in High Energy Density Laboratory Plasmas (HEDLP) and ICF experiments (e.g., NIF's ARC [6]). Common problems to be solved with picosecond laser systems involve laser (hot spot) imprinting with subsequent high-energy emission from hot electron recirculation hindering monochromaticity. Nanosecond backlighting is an alternative in combination with ultra-fast time-gated detector schemes [7, 8]. Nevertheless, implementing consistent X-ray imaging diagnostics warrants additional research and development.

Alternative X-ray backlighting schemes should be considered. X-pinch X-ray sources [9] generate sub-micron nanosecond sources in a portable configuration, independent of laser availability. These sources may be adapted to high-repetition-rate systems with additional targetry development in the Hybrid or Laser-cut configurations [10]. Notably, betatron X-ray sources [11] are an attractive alternative. They offer bandwidth advantages over "standard" X-ray sources generated from laser-target interactions and could support high-repetition-rate systems.

Note that establishing standard X-ray imaging platforms will be attractive to the semiconductor industry and other fields with high investment potential. For example, refraction-based X-ray imaging techniques may offer non-destructive testing (NDT) for advanced manufacturing technology.

C-4.2.3 Standardized Particle Diagnostics:

HEDLP experiments will benefit from electron and ion diagnostics to characterize their interaction between these and with plasma. For this, diagnostics must be built to select the desired energy ranges for ions and electrons (10 keV- 100s keV and 100keV- 10 MeV) [12, 13]. Note that in IFE, the dynamic range will play a key role as increased flux is expected, which may lead to signal saturation. In petawatt laser systems, a high energy portion of the electron up to ~10 GeV and 3 - 100s MeV of ion spectrum may be encountered. Moreover, considering transport at low energies, filtering may become an issue (heavy ions), and thus, alternative solutions should be explored.

C-4.2.4 External Magnetic Fields:

Generating large magnetic fields through the Magneto-Inertial Fusion Electrical Discharge System (MIFEDS) is helpful when studying HED systems and their behavior under external magnetic fields. For example, an experimental platform uses the OMEGA laser to explore scaled MagLIF schemes [14], where OMEGA delivers 1/1000th of the energy of Z, compressing a scaled cylinder (1-10). Magnetic fields of <30 T were generated with MIFEDS, leading to enhanced neutron yield [15].

C-4.3 General Guidelines for Upcoming Facilities

It is vital to properly characterize, measure, and scale the conditions expected at the new facilities to extrapolate in an unknown territory.

C-4.3.1 Design:

Vacuum chamber design should optimize diagnostic collection and consider EMP issues, for example. The latter may be addressed through the careful design of resonant chambers. NGF must be robust to increased radiation levels, especially for IFE experiments requiring kJ lasers. Neutrons flux and consequent material degradation must be properly estimated. As larger/faster lasers will have compounded debris problems on all equipment with a direct line of sight to TCC, diagnostic operation in harsh environments must be tested along with damage thresholds, which can build on best practices from IFE communities. NGF design must also provide sufficient lab space for users and facility staff to enable additional experimental tasks such as target mounting and metrology, and film and data processing, etc.

C-4.3.2 Facility Operation:

Different approaches should be evaluated according to the needs of each specific diagnostic and the operation mode (i.e., single-shot, high-repetition-rate). NGF must minimize downtime and specify an acceptable maintenance schedule (e.g., 2 weeks at LCLS). Maintenance within a campaign can be assisted by reentrant mounting, which is currently used at Omega. It is crucial to establish the threshold for designating a harsh environment, including the criteria for deferring personnel.

Additionally, details should be provided on how operations in harsh environments will impact data collection and processing. NGF will need more diagnostics automation due to radiation activation as a response to limited personnel access. Remote detections, handling, and recording will become mandatory, considering long cool-down times and limited access to diagnostics. Note that remote operation will depend on motor resilience to EMP; thus, the associated technology must be optimized.

C-4.3.3 Experimental Operations Related to User Data Acquisition:

Damage-identification algorithms must be adapted to these new facilities. Further, NGF should take advantage of high-repetition-rate capabilities to improve data analysis methods. Current and future diagnostic techniques must be adapted to process data quickly for “real-time control”. This will lead to increased bulk data, informing codes and models, which can, in turn, propel new diagnostic techniques.

C-4.4 Research Needs

Diagnostic needs for upcoming facilities and NGF call for further research on specific topics requiring expertise from other fields. This highlights the need for cross-collaboration and/or leveraging state-of-the-art and common knowledge from diverse science and technology endeavors.

C-4.4.1 Materials Science:

Material degradation due to radiation from various beam and particle sources must be investigated. These studies must evaluate the impact of pulsed vs. single-shot operation and the associated challenges and solutions for each operation mode. The lifetime of the laser system and diagnostic components must be tested (e.g., optics coatings). Further, this opens up an opportunity to use NGF for materials science experiments at new facilities.

C-4.4.2 Radiation:

In general, the harsh yet controlled radiation environment may serve as a unique platform for performing activation studies in single-shot mode, high-repetition-rate, and/or burst modes.

C-4.4.3 Particles:

Particle energy deposition and scattering must be investigated along with single particle counting schemes within the background.

C-4.4.4 Neutrons:

Damage limits must be explored to assess whether those can be reached at NGFs. For example, neutron levels at OMEGA and NIF reach 1e14 and 1e18 neutrons per shot, respectively. Considering scaling, midscale facilities may not encounter this limit, but additional studies must be carried out to determine neutron damage limitations. Interesting research avenues are enabled by neutron probing:

1. Provided enough neutrons are available, can the LaserNetUS network be leveraged to study tritium breeding? This must be assessed along with nuclear reactor platforms. Is there any value in looking at this at repetition rate?
2. Considering areal densities achieved with >100 J lasers: Is there anything that can be probed with neutrons? Are the thermal/epi-thermal neutrons at mid-scale facilities useful in this regard? Since this is a different regime, boron-doped detectors should be explored (e.g., MCPs). Can neutrons be used as diagnostic for plasma conditions with deuterated targets?
3. Is it worth measuring thermal and fast neutrons concurrently to learn about thermal contributions in the pitcher/catcher scheme (thought to be low)? Using a thin detector, where the highest energy neutrons fly right through, may provide a solution.

C-4.5 Upcoming Facilities:

The challenges discussed in the previous sections will be encountered by most upcoming facilities. Potential solutions have been provided in the above based on best practices from current facilities. General descriptions of specific facilities are given below, along with user requests for their planned designs and upgrades.

C-4.5.1 MEC-U

The Matter in Extreme Conditions (MEC) instrument at LCLS co-locates high intensity lasers with the LCLS hard X-ray free electron laser ultrafast precision measurements of dynamic high energy density states. Dynamic compression experiments to >4 Mbar are driven by the variable pulse shaped 100 J nanosecond long pulse laser, and relativistic laser-matter interactions at up to > $4x10^{19}$ W/cm^2, as well as high-repetition-rate shock compression and isochoric heating are driven by the 1 J, 40 fs chirped pulse amplified short pulse laser. The LCLS hard X-rays, which are ultrabright, ultrafast , energy tunable, spatially coherent, and tightly focusable, are used for elastic and inelastic resonant and non-resonant scattering, photo-pumping, and sub-500 nm imaging. Applying a hard X-ray FEL to these measurements enables time-resolved first-principles measurement of temperature, viscosity, thermal diffusivity, sound speed, lattice structure, ionization, atomic structure and density as well as microstructural dynamics at unprecedented accuracies and precisions.

MEC is available through open-access proposals, primarily serving the areas of high energy density laboratory plasmas and dynamic compression. Facility diagnostics include VISAR, ultrafast high-resolution X-ray diffraction, resonant and non-resonant X-ray scattering and absorption spectroscopy, and a variety of high resolution X-ray imaging modalities. User diagnostics are routinely supported. Starting in 2024, inertial fusion energy priority research opportunities will be added as a sub-topic within this area, with up to 50% of MEC beamtime expected to be aligned to it. LaserNetUS supports the development of capabilities to support this area and funds expert scientists to advise and support experimental teams and develop relevant scientific techniques.

User needs: 1 PW, 10 Hz, 150 J, 150 fs; 1 kilojoule pulse shaped nanosecond laser; all lasers coupled to the LCLS hard X-rays with a full diagnostic suite emphasizing the unique capabilities of the XFEL. MEC-U is an active 413.3b project with the above specifications.

The planned laser upgrades will dramatically expand the range of plasma and compressed material conditions that can be probed with high precision by the XFEL. Diagnostic developments will be needed to adapt existing and developing XFEL probing capabilities to the more extreme target environment and to a target chamber that requires reduced personnel access to the interior (e.g. reentrant diagnostics) for operational and radiation safety reasons, all while supporting the high repetition rates of the PW laser and LCLS. Advancement of multi-GHz framing camera capabilities will be critical to take advantage of the unique pulse train capabilities of LCLS, providing multiple full energy pulses with spacing of nx350 ps. Mesoscale physics accessible with the kJ laser upgrade will benefit from developing single-shot ultrafast tomography techniques envisioned for the facility. New X-ray pulse formats, such as attosecond pulses and cavity based XFEL modes, will lead to new diagnostic opportunities as well.

C-4.5.2 JLF Upgrade

JLF supports multiple laser platforms: Titan, Janus, and COMET. Titan's two-beam system comprises a nanosecond, kilojoule long-pulse beam, and a short-pulse beam with 1-to-10 ps pulses and energies up to 300 J, depending on pulse duration. These beams can be used together or independently. JLF's Janus system has two independent beams, each of which can produce 1 kJ at 1.053 μm with pulse lengths from 1-to 20 ns. The system fires approximately every 30 minutes and offers frequency doubling, as well as a variety of pulse shapes. COMET's flexible configuration, designed primarily to generate laboratory x-rays, offers uncompressed pulse lengths from 500 ps to 6 ns, compressed pulses down to 0.5 ps, and beam energies up to 10 J.

JLF has a suite of diagnostics available for LaserNetUS users through collaborations with LLNL scientists. These include: Electron-positron-proton spectrometers, Thomson parabolas, Neutron time-of-flight spectrometers, RCF packs, Image plates, X-ray imaging systems, X-ray spectrometers (filter- and crystal-based), Optical diagnostics (interferometers, spectrometers, VISAR) and Visible and X-ray streak cameras.

C-4.5.3 CSU Upgrade

The ALEPH laser at Colorado State University is a 0.85 PW 800 nm wavelength Ti:Sa laser that can operate at up to 3.3 Hz repetition rate in burst mode. The laser can also operate in the second harmonic at 400 nm with ultra-high contrast. ALEPH will be upgraded to operate at a peak power of up to 2 PW at up to 10 Hz repetition rate. A new target chamber ~ 2.2 meters diameter will be available for short (f/2) operation, and target chambers for operation with longer focal lengths will also be available.

The diagnostics capability at CSU includes Thomson parabola ion spectrometers (two) and electron spectrometers, high (10,000:1) and medium (1,000:1) resolution X-ray crystal spectrometers, filtered X-ray diode arrays, X-ray streak camera (on loan from LLNL), a set of eight scintillator/photomultiplier neutron detectors that were calibrated with a dense plasma focus, and image plate reader.

User needs: several lasers 1 PW, 10 Hz, 200 J, 100 fs (ALEPH laser upgrade) + 20 fs (from current 40 fs)

Section C-5: Innovative Solutions and Emerging Technologies

C-5.1 Cutting-Edge Technologies

Material Testing: Comprehensive testing protocols may need to be implemented at the LaserNetUS facilities. These protocols include rigorous examination of equipment not only within dedicated test facilities but also in the challenging environments of the actual laser facilities. Such protocols have already been implemented in facilities such as the Z-machine [14, 16].

EMPs: A multifaceted approach should be employed to address the technological and data acquisition challenges that EMPs pose. This includes the comprehensive study of EMP generation, detection, and mitigation strategies [2] to allow precise and adaptable measurements. Various techniques, such as optical mirrors with large F#, electron optics, and image-preserving fiber bundles, can enhance detector resilience. Motorized systems that place detectors in safe positions could also be helpful.

Shielding mechanisms such as mesh or solid conducting boxes require specialized electrical engineering expertise and thermal management. Moreover, materials like Be, Al, or Cu could be considered for shielding, along with implementing umbilical shielding flex conduits. Finally, the EMP-mitigation strategy should extend to replacing vulnerable components in electromechanical systems. Additionally, the use of fiber-based collection could be explored, though challenges with Fiber Fluorescence are acknowledged.

It's crucial to note that precautions, such as avoiding BNC cables as they can act as antennas, should be taken to hinder electronic damage or shot disruption. Finally, the focus should extend to the chamber design. Avoiding GHz chamber modes that resonate within the EMP range will be especially important. Since larger chambers will be used to locate detectors far from the interaction point, implementing diagnostics with higher collection capabilities becomes imperative.

Radiation: In the domain of radiation management, the approach involves both prompt and activation phases. For prompt radiation, a robust shielding strategy is employed, utilizing materials such as concrete bricks, boron, lead, or different polymers to mitigate the immediate effects. To further enhance protection, increasing standoffs should be implemented, aiming to attain a known survivable flux. Transitioning to the activation phase, the focus shifts towards automated remote handling within radiation environments. This approach should ensure that systems and components are efficiently handled even in potentially hazardous radiation conditions. Together, these strategies could underscore a comprehensive and forward-thinking approach to radiation mitigation, balancing immediate protection with long-term system resilience.

Debris and Damage: A vigilant approach could be adopted to manage debris and damage to optical systems. The latter should be based on continuously monitoring optics to promptly identify any signs of damage and effectively prevent its propagation. Innovative solutions, such as exploring replenishable optics like tape or liquid crystal, are promising and should be considered for further investigation, with notable examples like the Ohio liquid crystal [17]. High-value optics benefit from specialized protective measures, including deploying gas-puff systems for ballistic deflection, strategically positioned magnets, and rapid shutters.

Pioneering deflection techniques involving pulsed magnetic fields, exemplified by ASML's Company application in safeguarding the collector optic during EUV pulse generation, could contribute to the overall resilience of optical components. A strategic arrangement places passive systems closer to the target, with active defenses logistically positioned further back, creating a layered defense system. Finally, monitoring should be extended to multiple locations to ensure a comprehensive surveillance network, aiming at maintaining the integrity of optical systems across diverse operational scenarios.

Measurements in Extreme Environments: A high-collection efficiency X-ray Thomson scattering (XRTS) spectrometer [18] could be developed and used to diagnose high-Z warm dense matter (WDM) to validate ionization models for dense matter, which is critical for accurately inferring the plasma conditions in this regime. Such a diagnostic could be implemented at the MEC LaserNetUS facility, where the ns laser pulse is used to create WDM states, and the LCLS hard X-ray beamline can be implemented as an XRTS probe. The X-ray CCD detector attached to the spectrometer would need to withstand high-noise environments, and the spectral resolution of the spectrometer's curved crystal needs to be evaluated.

Moreover, the users of LaserNetUS facilities need advanced diagnostics that can be adapted to a range of experiments and shipped between facilities. One of these diagnostics could be an optical Thomson scattering diagnostic used to measure plasma densities between 5×10^{16} - 10^{19} cm $^{-3}$ and temperatures up to 3 keV [19]. Such a diagnostic would be suitable for small facilities, and its portable nature would allow it to be transported and mounted on diverse laboratories. However, the specific scattering geometry must be designed for each experiment and/or experimental facility, and the laser input, dump, and signal-collection vacuum port must be devised and manufactured to mount the diagnostic.

Section C-6: Conclusion

EMPs and damage due to high neutron flux and other radiation are generally expected to impact diagnostics at NGFs. Temperature will also be a factor for diagnostics placed close to an experiment, and stray light of multiple wavelengths will be a consideration for optical diagnostics. Environment cool-down times and limited access to diagnostics will necessitate remote handling and recording techniques. EMPs, in particular, become a challenge at kJ-class facilities and are a problem that diagnostics of all types must address or mitigate.

Suitability for diagnostics to operate in harsh conditions can be improved by increasing stand-off distances, using more passive components, finding ways to operate remotely, and improving EMP resilience and/or shielding against radiation (neutrons), for example, by using concrete bricks, boron, or polyethylene. Another option is using simple off-the-shelf components that can be directly replaced when they fail.

Identifying technological hurdles in developing diagnostics for the NGFs is crucial for their successful development and present resource allocation. In the context of X-ray diagnostics, challenges include improving spatial resolution through new solid target technologies or betatron sources, with a focus on characterizing betatron sources in NGFs. Charged-particle diagnostics present challenges in understanding material degradation and activation due to higher energies and shot repetition-rates. Optical and laser diagnostics face complications from increased debris in larger, higher-repetition-rate laser facilities, requiring advanced damage identification algorithms and adapted laser systems. Neutron diagnostics aim for spatially-resolved spectral information and face challenges in implementing pitcher-catcher schemes and mass-producing deuterated targets for high-repetition-rate applications. Strategic collaborations across disciplines are emphasized to address these challenges effectively.

Tackling technological obstacles regarding data acquisition and analysis within the harsh environments of the NGFs is of major importance. X-ray diagnostics will need to work in high background and noisy environments. Specific shielding and analysis of the entire vacuum chamber will be crucial for accurate signal detection. The activation of materials, remote data readouts, and challenges posed by heavy shieldings like lead are also highlighted. Charged particle diagnostics must also adapt to high-signal backgrounds. Optical and laser diagnostics encounter uncertainties in signal-to-noise ratios, requiring an understanding of measurement scalability from current facilities. Particle and neutron diagnostics will be strongly affected by EMPs, forcing detectors to be located at a more considerable distance from the interaction point. EMP-mitigation strategies include shaping target stalks and enhancing diagnostic resilience. The impact of EMPs on active detectors is emphasized, prompting a need to comprehend differential effects on high- and low-voltage biased detectors in order to ensure robust diagnostics in the NGFs.

NGFs can set the stage for discovering new physics in uncharted regimes. Both planned upgrades and new facilities must consider the needs and respective diagnostic requirements in their design, operation, and data acquisition plans. To guide these efforts, best practices from current LaserNetUS nodes and user facilities from the accelerator community can be leveraged.

It is also imperative that these facilities plan for sustainability. Diagnostic signal quality and resolution are among the top scientific needs, while optimal diagnostic performance will require critical technological advances to assure component survival in harsh environments. Moreover, manufacturing capabilities must be identified and the development of new technologies must be supported. Specific capabilities are requested at each LaserNetUS facility to provide users with a complete laser system sensor package, standard X-ray imaging and particle diagnostic platforms, and external magnetic fields.

General descriptions of new facilities and upgrades have been given for MEC-U, Titan, Colorado State University, and EP OPAL. As laser power and intensities increase, so do the challenges faced by the community. This presents an opportunity to engage with other fields to develop new technologies in materials science, particles, neutrons, and radiation physics. These collaborations will give way to emerging technologies that will benefit the field and beyond.

Throughout material testing, protocols may need to be implemented in the NGFs. Furthermore, a versatile approach should be employed to address the technological and data acquisition challenges EMPs pose. This includes the comprehensive study of EMP generation, detection, and mitigation strategies. The latter involves diagnostics shielding, motorization, and chamber designs that avoid GHz modes that resonate in the EMP range. Regarding radiation handling, a comprehensive strategy involves shielding using materials like concrete, lead, or polymers and increased standoffs to achieve a determined flux at a given distance.

Transitioning to the activation phase, emphasis is placed on automated remote handling to ensure efficient operation in hazardous radiation conditions, balancing immediate protection and long-term resilience. Managing debris and damage to optical systems requires a vigilant strategy involving continuous monitoring, fast identification, and prevention of damage propagation. Innovative solutions include replenishable optics and specialized protective measures like gas-puff systems, strategically positioned magnets, and rapid shutters.

The approach then transforms into a complete defense system incorporating pioneering techniques and a comprehensive surveillance network. Finally, to diagnose high-Z warm dense matter and validate ionization models in extreme environments, a specific high-collection efficiency X-ray Thomson scattering (XRTS) spectrometer, adaptable to the MEC LaserNetUS facility, could be developed. A portable optical Thomson scattering diagnostic suitable for smaller facilities could also be implemented with specific experimental geometries and laser input requirements in mind.

Section C-7: References

[1] S. Zahra et al., “Electromagnetic metasurfaces and reconfigurable metasurfaces: a review”, Frontiers in Physics, 8, p.593411 (2021).

[2] F. Consoli et al., ”Laser produced electromagnetic pulses: Generation, detection and mitigation”, High Power Laser Science and Engineering, 8, p.e22 (2020).

[3] E. Grace et al., “Single-shot complete spatiotemporal measurement of terawatt laser pulses”, Journal of Optics, **23** (7), p.075505 (2021).

[4] B. Kozioziemski et al., "X-ray imaging methods for high-energy density physics applications", Review of Scientific Instruments **94** (4), (2023).

[5] D.S. Montgomery, “X-ray phase contrast imaging in inertial confinement fusion and high energy density research”, Review of Scientific Instruments, 94 (2), (2023).

[6] M. Hohenberger et al., “A combined MeV-neutron and x-ray source for the National Ignition Facility”, Review of Scientific Instruments, 93 (10), (2022).

[7] C. M. Krauland et al., “An evaluation of high energy bremsstrahlung background in point-projection x-ray radiography experiments”, Review of Scientific Instruments, 83 (10), (2012).

[8] G. N. Hall et al., “The crystal backlighter imager: A spherically bent crystal imager for radiography on the National Ignition Facility”, Review of Scientific Instruments, 90 (1), (2019).

[9] V. L. Kantsyrev et al., “Powerful microfocus x-ray and hard x-ray 1 MA x-pinch plasma source for imaging, spectroscopy, and polarimetry”, SPIE Adv. Lab-based X-ray Sources and Optics II, 62-73 (2001).

[10] M. P. Valdivia et al., “Wire, hybrid, and laser-cut X-pinches as Talbot–Lau backlighters for electron density diagnostics”, Plasma Physics and Controlled Fusion, 64(3), 035011, (2022).

[11] F. Albert et al., “Observation of betatron x-ray radiation in a self-modulated laser wakefield accelerator driven with picosecond laser pulses”, Physical review letters, 118 (13), 134801 (2017).

[12] H. Chen et al. "A compact electron spectrometer for hot electron measurement in pulsed laser solid interaction", Review of Scientific Instruments **74**, 1553, (2003).

[13] J. I. Apiñaniz et al., "A quasi-monoenergetic short time duration compact proton source for probing high energy density states of matter", Scientific Reports 11, 6881 (2021).

[14] D. A. Yager-Elorriaga et al., “An overview of magneto-inertial fusion on the Z machine at Sandia National Laboratories”, Nuclear Fusion, 62 (4), p.042015. (2022).

[15] J. L. Peebles et al., “Demonstration of neutron-yield enhancement by laser preheating and magnetization of laser-driven cylindrical implosions”, Physics of Plasmas, 30 (8) (2023).

[16] S. Auluck et al., “Update on the scientific status of the plasma focus”, Plasma, 4 (3), pp.450-669 (2021).

[17] P. L. Poole et al., “Experiment and simulation of novel liquid crystal plasma mirrors for high contrast, intense laser pulses”, Scientific reports, 6(1), p.32041 (2016).

[18] K. Falk, “Experimental methods for warm dense matter research”, High Power Laser Science and Engineering, 6, e59 (2018).

[19] J. Banasek et al., “Probing local electron temperature and density inside a sheared flow stabilized Z-pinch using portable optical Thomson scattering”, Review of Scientific Instruments, 94 (2) (2023).

D: Data Collection and Processing Tools

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Section D-1: Introduction

The advancement of HRR laser capabilities has and will continue to usher in a new era of scientific exploration. As the previous chapters have discussed, these emerging facilities require new suites of sophisticated diagnostic tools that will generate an unprecedented volume of data. However, this abundance of information presents a formidable challenge: how can users efficiently handle and derive meaningful insights from the sheer magnitude of data generated? In every experimental campaign, the gathered data must be securely stored. However, as data volumes increase, efficient data analysis becomes equally critical. HRR experiments offer exciting possibilities, but to fully exploit them, the community must navigate the complexities of data management. This chapter aims to put forward balanced observations of best practices with sensitivity to the LaserNetUS node diversity, but it undoubtedly puts more focus on HRR systems as they pose greater challenges in data collection and processing.

Because the LaserNetUS program encompasses most laser facilities at the forefront of HRR research in North America, it is in a unique position. This community has the opportunity to establish standard practices for HRR data collection and processing to propel accelerated progress within the field through increased efficiency. Choices are most effectively implemented during the foundation of experimental acquisition systems. Given that the transition to robust HRR operations is still in its early stages for many facilities, employing the best methods now will likely be less disruptive compared to doing so later on. While standardizing practices across diverse facilities poses challenges, LaserNetUS's unique combination of distinct facilities makes it the most suitable organization to influence systematic approaches and processes on a broader scale. Ultimately, getting buy-in from all facilities will be the most progressive for the whole network, which is the continual aim.

This chapter discusses the requirements for efficient data gathering and processing. Section D-2 describes specific requirements for collecting data at high repetition rates. What techniques and protocols are optimal? How can seamless data flow be ensured? Data analysis and processing are also discussed. Methods for extracting meaningful insights from raw data are explored. Real-time processing, machine learning pipelines, and data-reduction techniques play pivotal roles. Section D-3 overviews some of the existing resources, tools, and infrastructure already available for data collection and processing in both low-repetition-rate and HRR facilities that have been identified as most beneficial and/or successful. Understanding these resources should inform LaserNetUS Users' approach to handling HRR data efficiently. Finally, in Section D-4, the proposal for a LaserNetUS-managed online resource center to address many of the challenges of the preceding sections is discussed. This centralized repository would securely store and access data, instrument calibration information, and peer-reviewed analysis tools.

Efficient data management is another crucial step to unlocking the potential of HRR experiments. By navigating and/or learning from existing resources, understanding specific needs, and fostering collaboration and cooperation, the LaserNetUS community will pave the way for accelerated progress in laser research.

Section D-2: HRR Data Collection, Analysis, and Processing Needs

High-repetition experiments fundamentally change the approach to data collection. This includes handling the amount of data, where it is stored, how it is processed, how experimentalists interact with it, and how conclusions are drawn from it. Until recently, ultra-high-power laser facilities have operated at rates that allow for developing, scanning, and/or processing data between each laser shot. This has even included thorough manual analysis between shots. When transitioning from one shot per hour, as roughly the previous fastest operational rate, to 1 Hz or greater, there has to be either a refinement of prior methods or a complete departure from them for any efficiency in scientific progress that these facilities can offer.

Here, the increasing use of artificial intelligence (AI) and machine learning (ML) to interpret diagnostic data and analyze experiments is one notable example that can significantly enhance the rate of learning. However, accessing the full potential of artificial intelligence (AI)/machine learning (ML) algorithms requires large datasets. Given that HRR experiments generate data at 10–10,000 times the current rate, this volume of data will enable the development of ML-based models for predicting new optima.

Additionally, integrating AI into these HRR platforms will enable unprecedented rates of progress in high-intensity laser-based experimental research. While AI/ML isn’t the primary focus of this section, it is unsurprisingly tied to or beneficial for many of the specific needs or requirements for HRR systems as it relates to data collection and processing.

D-2.1 Evolving Data Collection Requirements

By the simple definition of HRR experimentation, it becomes evident that the ability to collect data rapidly prompts the desire to gather more. This underscores the opportunity presented by high-shot-rate experimentation in advancing exploration across multidimensional parameter space at an accelerated pace. However, realizing this potential necessitates diagnostics capable of operating at HRR, as extensively detailed in Sections D-2 and D-3. With an increase in functioning diagnostics at HRR comes a surge in data, which poses significant challenges in data management. Even with conservative estimates, projecting approximately 200 shots per day and 5 GB per shot, HRR experiments could easily yield more than 1 TB of data daily.

Apart from the increased demand for storage space, managing the data entails tracking, indexing, and associating it with the correct laser shot. This is crucial, as misindexed data could lead to erroneous conclusions during analysis. Metadata, comprising additional information describing and contextualizing the primary data collected during experiments, becomes pivotal. Such information may include experimental conditions, equipment configurations, laser parameters, and timestamps for each data point.

Data transfer is likely to become a bottleneck, as data is typically gathered on a machine running the diagnostic and then transferred to another machine for analysis or a centralized system. This transfer process can pose limitations, particularly with larger file sizes or due to the sheer volume of data. Since experiments with significantly higher shot rates will generate orders-of-magnitude larger volumes of data at rates exceeding recording speeds, reducing data on the fly before storage becomes imperative.

Various data reduction techniques can occur between data acquisition and storage, including lossless compression, lossy compression, binning or averaging of large arrays, and fast data analysis methods. Incorporating low-power computing near data sources, or "edge computing," becomes essential. These processes inherently rely on or can be improved by AI/ML algorithms to reduce data in quasi-real time.

Regardless of data reduction efforts, the need for substantial data storage will inevitably grow alongside increased HRR research activity. As the LaserNetUS community expands and HRR facilities see heightened utilization of their capabilities, making these vast volumes of data accessible to researchers, including collaborators worldwide, even after experimental campaigns conclude, becomes imperative. This underscores the need for multi-access storage with appropriate security measures or privacy protocols, particularly in the near term, for researchers and their collaborators leading investigations. Moreover, there is currently little infrastructure to aggregate and sustainably archive such data, hindering the extraction of full value from experiments generating large datasets.

A similar challenge exists for extensive and costly simulations, such as particle-in-cell simulations. In the worst-case scenario, this could result in unnecessary duplication of experiments or simulations, significantly impeding research progress and straining allocated budgets. Conversely, easier and faster access to experiment-generated data via high-performance computing (HPC) servers would greatly facilitate remote collaboration for real-time and post-experiment data analysis while providing access to greater computing power, thereby minimizing the need for extensive data transfer.

D-2.2 Analysis and Processing Needs

Figure 5 depicts key data analysis and processing needs.

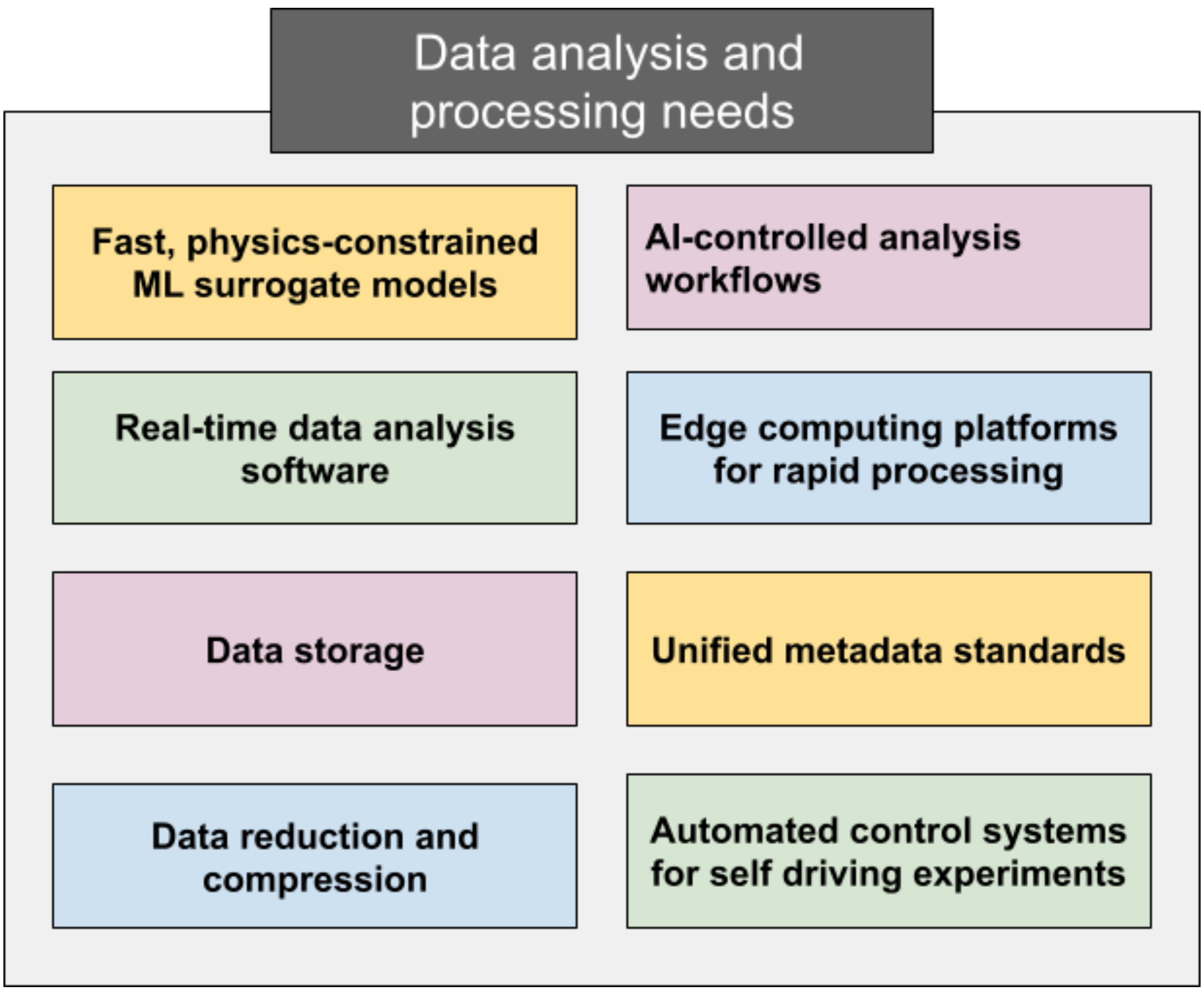

Figure 5. *Chart featuring the critical needs for data analysis and processing.*

In an HRR laser environment, data analysis and processing can exist in all stages of the experiment. Previously, almost all data processing occurred after the experiment was over. In the HRR environment, there is a need for more efficient tools for analyzing vastly larger datasets and analysis occurring “on the fly”. Unless the goal is merely to generate statistics from a single configuration or to blindly modify experimental input parameters without direction or bias, it is necessary to distill highly complex diagnostic data into key physics-relevant metrics. This enables active feedback to either the user or the driver and target input systems.

In other words, experimental measurements are rarely direct and often require inference to obtain quantities of interest. Human intervention in this process introduces both bias and delay. Fast, physics-constrained ML surrogate models for data inference and AI-controlled analysis workflow can address these new challenges. This brings up the concept of self-driving experiments [1, 2], where data collecting and processing are crucial at higher rates than the laser shot rate to inform the next experimental shot. In other words, having a control loop would allow for incorporating measurements from multiple diagnostic sources to make adjustments (e.g., correcting systematic target and/or laser misalignment based on inferred parameters from a given shot’s performance).

These self-correcting control systems will make HRR experiments more robust against shot-to-shot variability, increasing the quality and repeatability of measurements. Here, it becomes clear that there is a need to develop AI/ML techniques to automate and improve data processing and analysis. ML and AI become necessary to deal with the speed of information feedback, where identifying given metrics and/or conclusions (i.e., ML) leads to an action or control (i.e., AI) in the experiment.

Rapid and robust data analysis is a prerequisite for even a modest-repetition-rate facility, so the need for and associated impact of these capabilities could be immediate, even without getting to the self-driving state. Unified metadata standards will enable standard community analysis routines to work on different datasets. The same goes for the need for accessible diagnostic calibration information to be included in a given routine, which is discussed in later sections.

Each preceding topic will rely on advanced computational algorithm development and utilization of the best available hardware to eventually integrate experiments and simulations and fully realize autonomous discovery. Edge computing might further enhance experimental operation speed (analysis, targeting, data handling).

D-2.2.1 Near-term Considerations for Analysis Advancements at LaserNetUS Nodes

Given the abundant data-associated needs in the HRR experimental space, resource-based or financial support should be provided to the community to facilitate near-term to mid-term advancements in real-time analysis capabilities. With HRR and moving towards ML/AI tools, it behooves the experimental community to delve into data analysis for fielded diagnostics well before an experiment.

Some suggestions of dedicated data scientist(s) support for efficient code development and/or integration of user-specific analysis scripts were broadly requested for HRR facilities. It should be emphasized that any analysis code developed under LaserNetUS funds would be asked to become open access. Further suggestions have been made to include a section in proposals to capture the PI/experimental team's experience and plan for (live, when applicable) data analysis to ensure efficient use of facilities along another metric.

D-2.3 Common File Formats

In plasma physics, data are stored in idiosyncratic formats unique to the facility (or code) that created it. Prioritizing data standardization for experiments and simulations is essential to enhance our ability to share and collaborate between groups. Standardizing data protocols will streamline the tools that access the data. This, in turn, makes the shareability of data more accessible, which is vital to progress. Similarly, different teams and facilities often duplicate data analysis and processing tools.

Adopting a common file type/format with appropriate metadata could make these tools more easily shared or open source. This is especially important when thinking about a CDP that has either a single diagnostic moving to various facilities or a diagnostic more or less duplicated to be a fixture at many facilities. Having the data formatted the same regardless of the diagnostic location and system it runs on adds much value to data processing ease and reliability.

As mentioned, AI/ML algorithms are most powerful when applied to large datasets, such as databases of experimental measurements or simulation outputs. In practice, some standardization of the dataset format and contents is required to apply these algorithms. The FAIR (Findable, Accessible, Interoperable, Reusable) guiding principles for scientific data management and stewardship [3] provide a blueprint for addressing these problems. Developing open and shared data formats that conform to these principles will allow the LaserNetUS community to share data between institutions, improving cooperation between nodes or facilities and public-private partnerships, which is an ongoing goal.

Improvement and standardization of data formats with metadata will also enable more generalizable analysis codes, increasing scientists' effectiveness by reducing duplication of effort. It will also encourage the application of AI/ML techniques to large datasets. Investing early in developing these standards and updating existing data to conform with them is expected to yield compounding benefits.

Section D-3: Available Resources for Data Collection and Processing

Several scientific fields have already started to or have confronted and met the challenge of collecting big data. Particle physics experimentalists routinely create, store, and analyze petabytes of raw data [4-6]. Beamline accelerator experiments within the high-energy physics (HEP) community already incorporate edge computing techniques to allow data collection on 1 MHz experiments. High-shot-rate experimental drivers >1 kJ are now operating outside of the LaserNetUS facilities [7-10], and efforts are already underway to develop ML-based data-processing algorithms [11, 12] for IFE-relevant HRR experiments.

Since several experimental facilities have already efficiently streamlined data collection and storage processes, this offers a clear learning opportunity for the LaserNetUS community. Within the domain of LaserNetUS-scale laser facilities, a large variety of data collection and processing systems exists. The system choice often depends on factors such as the facility’s age and data rate. Here, the focus is on presenting the different existing methods and emphasizing the best practices that could inspire LaserNetUS standards.

D-3.1 Laser Facilities

Most laser facilities continue to rely on local computer data storage and manual data transfer methods, utilizing memory sticks and external hard drives. These systems typically operate on **a single-shot or low-repetition-rate basis**, allowing for the implementation of specific user-owned diagnostics and tailored data acquisition to meet individual needs. The preference for local detector operation and data collection stems from the simplicity of set-up, diagnostics operation, and bandwidth considerations.

Local data storage and manual transfer offer straightforward procedures. Facilities can quickly configure their systems without extensive complexity because each diagnostic is more or less isolated from any other system. Also, by keeping data local, facilities avoid potential bottlenecks related to network bandwidth. This would likely become a concern when dealing with large datasets generated during HRR experiments if part of the real-time data analysis or feedback from remote storage required network access.

Some facilities have embraced more modern practices, offering Secure Shell Protocol (SSH) access to data servers or leveraging cloud services. These approaches enhance accessibility and, therefore, make collaboration easier. Particularly larger laser facilities with an extensive, non-local user base have recognized the limitations of local storage and taken a different approach.

Notable examples include the OMEGA laser facilities at LLE and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), both of which employ account-based remotely accessible storage servers. This approach ensures accessibility for approved personnel and efficient management of experimental data on a reasonable timescale for experimental users and collaborators of the facility. For Omega, these servers are populated with data after each shot within minutes to tens of minutes.

The NIF data is uploaded minutes to days after the shots, depending on the type and accessibility or capability of the diagnostic itself. Although both facilities operate on a single-shot or low-repetition-rate (~ 1 shot per hour) basis, they also leverage the Hierarchical Data Format (HDF) for data files. HDF is specifically designed to address the challenges of managing large volumes of scientific data. From a Data Organization standpoint, HDF holds raw data and captures essential metadata associated with experiments and diagnostics. These files can be, and are, routinely produced through read-out automation from various diagnostic types and data profiles. Given the inclusion of metadata, which is crucial when the volume of shot data increases for verifiable indexing, HDF files are optimal input for analysis scripts or software.

Along with appropriate data storage, NIF employs some automated analysis tools for common diagnostics. This allows users to understand key experimental parameters quickly, on the order of hours post-shot, which is appropriate for NIF and allows for concentrated analysis elsewhere. Automated analyses are best suited for laser diagnostics and others that do not require extensive, unique pre-shot information for analysis to occur, such as detailed image or spectral analysis. Plotting raw data with appropriately calibrated axes can go a long way for first-look data inferences.

X-ray free electron laser (XFEL) user facilities, such as LCLS and European XFEL (EuXFEL), generate vast amounts of data owing to high-repetition-rate data acquisition, which is then acquired and stored on external servers. This user data includes facility metadata containing all experimental parameters and its shot indication system. In addition to accessing the data, EuXFEL users can post-process it using the Maxwell supercomputer in Germany.

For the diagnostic information that requires more detailed evaluation, user-developed processing tools often play a significant role in every scale facility. In some part, due to a lack of feasibly standardized solutions, sharing individually-generated software seems always to remain limited. This is revisited in Section D-4.

In Europe, laser facilities such as Laboratoire pour l'Utilisation des Lasers Intenses (LULI), Apollon Laser facility, and ELI Beamlines adhere to a data retention policy for public research. Research data is retained for five years but is embargoed for three years before becoming publicly available. This approach ensures transparency and preserves the integrity of research endeavors.

D-3.2 HHR Particle Accelerator Facilities

Beyond laser facilities, particle accelerators operate routinely at HRR, and, as such, they have already had to develop robust methods for efficiently collecting, organizing, and processing vast amounts of data. For example, the European X-Ray Free-Electron Laser (EU-XFEL) in Germany operates at rates exceeding ~10 Hz, and the Linac Coherent Light Source (LCLS) at SLAC achieves a 120 Hz repetition rate. As mentioned earlier, as part of LaserNetUS, the Matter in Extreme Conditions (MEC) instrument at LCLS combines the capabilities of the extremely bright HRR X-ray source from the Linac and a high-intensity laser to perform unique (or uniquely diagnosed) HED experiments.

When fielding the short-pulse laser, the system is operational at 5 Hz at 1J and 120 Hz at 5mJ. As such, it possesses a data collection system compatible with this repetition rate, as it has been operational for 12 years. Some of the needs and challenges discussed in the preceding sections have been or are currently being addressed at these facilities. The successful practices and solutions highlighted here provide ideal learning opportunities for the broader LaserNetUS community.

At LCLS, raw data is stored in facility-custom format files, residing in both "online" and "offline" storage clusters and on magnetic tape. Importantly, all these storage clusters are accessible online via SSH facilitating remote analysis. A popular approach at LCLS involves processing these large raw files to generate smaller HDF files suitable for distribution and thorough analysis. The proprietary graphical analysis tool (AMI) is utilized during experiments for immediate monitoring. This readily available tool, typically employed in the control room, enables ~ 1Hz data visualization and simple analyses such as peak finding, accumulation, and thresholding, utilizing the low-latency shared memory. Additionally, users can develop simple custom scripts in collaboration with the support team for more tailored real-time analysis.

LCLS provides Python-based software with user-friendly, optimized methods that can be executed with single-line commands. These methods, for instance, include applying detector calibration, generating HDF files, and implementing parallelization. It's important to note that these rely on industry-standard tools such as batch systems, SLURM, and MPI [13]. Tutorials with examples and test data are available to help the user familiarize themselves with them.

For more complex real-time analysis, users can access the slightly higher latency (~ one-minute delay in data access) online cluster using standard tools like Jupyter and batch processing. Organizing data into runs and events and having access to HPC enables large-scale automation for improved analysis speed. The analysis output is temporarily stored in a sizable scratch folder and deleted after a certain period (approximately one week). Following an experiment, users can continue their analysis using the same scripts, accessing the offline cluster with a lower response rate.

LCLS II, which came online in 2023, will operate at MHz, which opens up additional problems. Operating at this repetition rate requires further data reduction and clear computing and data management structures. It also introduces a requirement for an experimental timing system that extends the accelerator timing system to include bidirectional communication for feedback signals from the sensor readout pipelines. The advanced requirements have necessitated the development of a new data system, which is currently being deployed and tested [14, 15]. While MHz operation goes beyond what was envisioned for LasernetUS facilities today, and because the data collection system is still very young, this may present another opportunity to be very progressive and proactive.

Finally, it is worth noting that the EuXFEL approach is very similar to LCLS. However, a notable difference lies in users' ability to manually categorize the generated data into distinct categories such as calibration, test, and valuable measurements. This manual sorting reduces the overall size of the data stored on the offline cluster.

D-3.3 Common Control Systems

Regarding streamlining control systems for the various facilities, it is worth noting that LCLS, LLNL, and CSU all use the Experimental Physics and Industrial Control System (EPICS). EPICS is a set of software tools and applications used to develop and implement distributed control systems to operate devices such as particle accelerators, telescopes, and other large scientific facilities. In fact, EPICS is used at dozens of facilities of diverse sizes, focused on various disciplines and across many continents.

The tools are designed to help develop systems that often feature large numbers of networked computers delivering control and feedback. They also provide supervisory control and data acquisition (SCADA) capabilities. Since 2004, EPICS has been freely distributable after its release under the EPICS Open License [16]. EPICS uses client-server and publish-subscribe techniques to communicate between computers. Servers, the “input/output controllers” (IOCs), collect experiment and control data in real-time using the measurement instruments attached to them. This information is then provided to clients using the high-bandwidth Channel Access (CA) or the recently added pvAccess networking protocols designed to suit real-time applications such as scientific experiments.

Input/Output Controllers (IOCs) are the backbone of control systems, managing and interacting with a database of "records" that represent individual devices or various aspects of those devices requiring control. These IOCs can be hosted by standard servers or PCs and specialized processors like VME or MicroTCA, among other standard embedded system processors. In "hard real-time" applications, IOCs typically operate on RTEMS or VxWorks operating systems, while "soft real-time" applications commonly run on Linux or Microsoft Windows platforms.

Data is represented by unique identifiers called Process Variables (PVs) within the records held by IOCs. These PVs are accessible over network channels provided by the CA/pvAccess protocol, enabling seamless communication and control.

A wide range of record types is available to accommodate different types of input and output signals (e.g., analog or binary) and to provide various functional behaviors, such as calculations. Furthermore, custom record types can be created to suit specific needs. Each record comprises a set of fields containing the record's static and dynamic data and specifications for behavior when different functions are requested locally or remotely. Most record types are detailed in the EPICS record reference manual, offering comprehensive system configuration and operation guidance.

To provide users with intuitive control and monitoring capabilities, graphical user interface packages enable them to visualize and interact with PV data through familiar display widgets like dials and text boxes. Examples of such packages include EDM (Extensible Display Manager), MEDM (Motif/EDM), and CSS, which empower users to manage and monitor their control systems efficiently.

Any software implementing the CA/pvAccess protocol can read and write PV values. Extension packages are available to support MATLAB, LabVIEW, Perl, Python, Tcl, ActiveX, etc. These can be used to write scripts to interact with EPICS-controlled equipment.

D-3.4 Existing Resource Summary Highlights

Various facilities, especially particle accelerators, serve as valuable learning opportunities in the HRR space, paving the way for efficient data handling. As laser facilities are similarly navigating a dynamic landscape of data practices, the hope is that by adopting innovative approaches and standardized formats, the LaserNetUS facilities and community lay the groundwork for efficient, transparent, and impactful research endeavors by reducing the barriers to efficient HRR experimentation.

Adopting a unified approach is recommended.

- Graduate students at various facilities rely on LabVIEW for data acquisition. This platform offers flexibility and ease of use but is not free. EPICS is a good option as it is open source and can interface with many other proprietary and open-source software.
- Open source should be encouraged at every turn.

The Importance of Data Format Agreement

- Standardizing Image Formats: Facilities should agree on a common image format to enhance interoperability. Consistency simplifies data exchange and ensures seamless collaboration.
- Opting for standardized formats and accessible tools sets the stage for efficient data handling and impactful research.
- (OpenPMD could allow for easy implementation and use of these standards; the PIC simulation community can help with that.)

Section D-4: Online Shared Resource Center

D-4.1 Concept and Purpose

Collaboration and efficient data management are paramount in the dynamic landscape of experimental research and laser facilities. The concept of an **Online Shared Resource Center (OSRC)** emerges as a powerful solution—a hub where information, vetted solutions, and, potentially, data can converge. The concept for an OSRC is to serve as a virtual repository where researchers, experimental teams, and the broader community can collaboratively share material. The current vision discussed by the LaserNetUS community suggests something more than just storage but also an organized and managed space that provides resources for experimental preparation. Within it, guidelines, best practices, and insights on past uses and/or issues for diagnostics would be readily accessible.

Many of the suggestions in the previous sections could benefit from a virtual or cloud-based, shared resource hosted by LaserNetUS. An OSRC would be where knowledge can be readily accessed and shared; therefore, it must also be well-managed and organized. This repository should include but may not be limited to–

1. **Training Resources**:
    - The file system includes a resource of guidelines—best practices, protocols, and procedural recommendations—for experimental preparation for individual diagnostics.
    - Training related to use cases, manuals, and/or tutorials for specific diagnostics; new users benefit from standardized guidelines ensuring consistency and

efficiency.

2. **Diagnostic Inventory and Status/Availability**:
    - A current catalog of LaserNetUS node's diagnostics with basic information on measurement capability.
    - Up-to-date information on the status or availability of a given diagnostic at a specific facility and the responsible individuals (i.e., points-of-contact) for each diagnostic. This would also include information on currently damaged or inoperable instruments.
    - A repository for histories of particular diagnostics in common use within LaserNetUS experiments.

3. **Facility and Diagnostic-Specific Documentation**:
    - Facility-based information, such as CAD models of experimental chambers and engineering drawings that relate to diagnostic footprints in specific chambers and/or locations, to help with experimental planning.
    - Diagnostic drawings, layout, and configuration information that allow users to consider details relevant to evaluating deployment benefits.
    - Fielding procedures that provide information on successful operations and damage minimization.
    - Publications associated with LaserNetUS diagnostics.

4. **Analysis Code Sharing and Revision**:
    - Researchers can share analysis code for collaborative revision. Collective efforts improve efficiency, enhance analysis quality, and correct errors (double-checking).
    - Version information and/or legacy tools that have been adapted for comparison to older analyzed data.
    - Efficient Algorithms: The community benefits from faster data analysis by sharing optimized code.

5. **ML/AI Data Acquisition Tools**:
    - In the HRR environment, ML/AI tools can become necessary for data processing, analysis, and feedback controls, and the resource center could offer a repository for regulated or author-imposed access to share tools as needed.

6. **Standardization Information**:
    - The OSRC itself encourages the use of standards, whether data formats, naming conventions, or analysis methods, but it should also have standardization details to make the data protocols clear for use.

7. **Instrument Response and Calibration Information**:
    - Theoretical response and/or diagnostic calibration information (version annotated, as necessary) provides up-to-date knowledge for data analysis tools.

8. **Message Board**:
    - A forward-facing, discussion-friendly forum for user input and questions that encourage connectivity and collaboration, especially for solving individual issues.

9. **Well-Organized Data Storage with Controlled Access**:
    - The OSRC could ensure well-organized data storage where metadata-rich datasets are accessible, searchable, and retrievable.
    - Controlled Access: Security protocols regulate who can access specific data, maintaining confidentiality and integrity, at least for some time before it becomes open access.
    - Hierarchical/credential system so that PIs or software authors can set and assign privileges (read, write, etc.).
    - Researchers can access community data for training, experimental preparations, and comparative studies.

The intent of the OSRC is to elevate research through collaboration and information dissemination while maintaining sensitivity to privacy and ownership. It intends to further knowledge exchange, skill enhancement, and community empowerment in diagnostics. As the LaserNetUS community, including the laser facilities staff, embraces this concept, data collection can be improved through standardization practices and peer revision while training the next generation of researchers. The latter point is part of the primary LaserNetUS mission and is something many researchers express concern for, specifically when considering HRR experimentation.

As different aspects of laser-based research may become automated, knowledge must not disappear. An OSRC is the first attempt to collect and maintain necessary, valuable, current, and historical knowledge about diagnostics and data analysis techniques associated with them. There are other approaches outside the scope of this document that may be considered to further hands-on training and knowledge retention, but the consensus is that the OSRC is most broadly applied and, therefore, could have the most notable impact on the community. It would be expected that the information on the online resource center would be populated by the community but managed by the LaserNetUS administration.

Section D-5: Conclusion

This chapter provided an overview of the findings of key data collection and processing tools. Increased repetition rates pose numerous challenges in data collection. As laser systems operate at higher repetition rates, there is a surge in data generation, necessitating greater storage capacity and addressing potential data transfer constraints. Due to larger file sizes and the sheer volume of data, efficient data transfer mechanisms become crucial. Techniques such as pre-processing, data reduction, and averaging are likely to assist in managing data efficiently.

Furthermore, HRR experimentation requires real-time data collection and reduction to maximize the efficient use of these facilities. ML/AI algorithms can enable on-the-fly decision-making, whether it is user-imposed or becomes self-driving.

Standardizing file formats and common diagnostic analysis tools for automation significantly ease the barriers to sharing accessible, consistent, and reliable data or analysis among research collaborators, teams, facilities, and other partners.

Addressing the challenges associated with HRR data, it becomes evident that a shared resource center (OSRC) can play a meaningful role. The OSRC can be a virtual repository where researchers, teams, and the community can share data. It can provide guidelines, training resources, pertinent diagnostic information for appropriate fielding, and open-source community analysis software.

While acknowledging the burden of data storage that may not align with an OSRC, there is a desire for archived data that utilizes controlled access to ensure confidentiality, at least in the near term. Regardless of whether a full data repository is included, a shared resource center empowers researchers with knowledge, enhances collaboration, and streamlines information management, thereby facilitating scientific discovery through improved efficiency.

Section D-6: References

[1] T. Ma et al., "Accelerating the rate of discovery: toward high-repetition-rate HED science", Plasma Physics and Controlled Fusion, 2021. 63(10): p. 104003, 10.1088/1361-6587/ac1f67.

[2] G. G. Scott et al., High repetition rate diagnostics with integrated machine learning analysis for a new paradigm of actively controlled Inertial Fusion Energy experiments "[White Paper]", in NIF Workshop: IFE Science and Technology Community Strategic Planning Workshop, 2022 (See White Papers listed at https://lasers.llnl.gov/nif-workshops/ife-workshop-2022/white-papers).

[3] M. D. Wilkinson et al., "The FAIR Guiding Principles for scientific data management and stewardship", Scientific data, 2016. 3(1): p. 1-9, https://doi.org/10.1038/sdata.2016.18.

[4] P. Fokianos et al., "CERN Analysis Preservation and Reuse Framework: FAIR research data services for LHC experiments", in EPJ Web of Conferences, 2020, EDP Sciences, https://doi.org/10.1051/epjconf/202024506011.

[5] CERN, CERN-OpenData-Portal, available from: http://opendata.cern.ch/.

[6] L. Mascetti et al., "Cern disk storage services: report from last data taking, evolution and future outlook towards exabyte-scale storage", in EPJ Web of Conferences, 2020, EDP Sciences, https://doi.org/10.1051/epjconf/202024504038.

[7] A. Bayramian et al., "The Mercury project: A high average power, gas-cooled laser for inertial fusion energy development", Fusion Science and Technology, 2007, 52(3): p. 383-387, https://doi.org/10.13182/FST07-A1517.

[8] M. C. Myers et al., "Repetitively pulsed, high energy KrF lasers for inertial fusion energy. Nuclear fusion", 2004, 44(12): p. S247, https://doi.org/10.1088/0029-5515/44/12/S16.

[9] Jan Pilar et al., "Characterization of Bivoj/DiPOLE 100: HiLASE 100-J/10-Hz diode pumped solid state laser", in Solid State Lasers XXVII: Technology and Devices, 2018, SPIE, https://doi.org/10.1117/12.2290290.

[10] E. Sistrunk et al., "All diode-pumped, high-repetition-rate advanced petawatt laser system (HAPLS)", in CLEO: Science and Innovations, 2017, Optica Publishing Group, https://doi.org/10.1364/CLEO_SI.2017.STh1L.2.

[11] D. A. Mariscal et al., “Design of flexible proton beam imaging energy spectrometers (PROBIES)”, Plasma Physics and Controlled Fusion, 2021. 63(11): p. 114003, https://doi.org/10.1088/1361-6587/ac234a.

[12] R. A. Simpson et al., “Development of a deep learning based automated data analysis for step-filter x-ray spectrometers in support of high-repetition rate short-pulse laser-driven acceleration experiments”, Review of Scientific Instruments, 2021. 92(7): p. 075101, https://doi.org/10.1063/5.0043835.

[13] https://slurm.schedmd.com/documentation.html.

[14] https://indico.jlab.org/event/459/contributions/12502/attachments/9617/14255/Thayer-LCLS-CHEP%202023-nomovie.pdf.

[15] J. B. Thayer et al., "Building a Data System for LCLS-II," 2017 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), Atlanta, GA, USA, 2017, pp. 1-4, doi: 10.1109/NSSMIC.2017.8533033

[16] https://epics-controls.org/epics-open-license/.