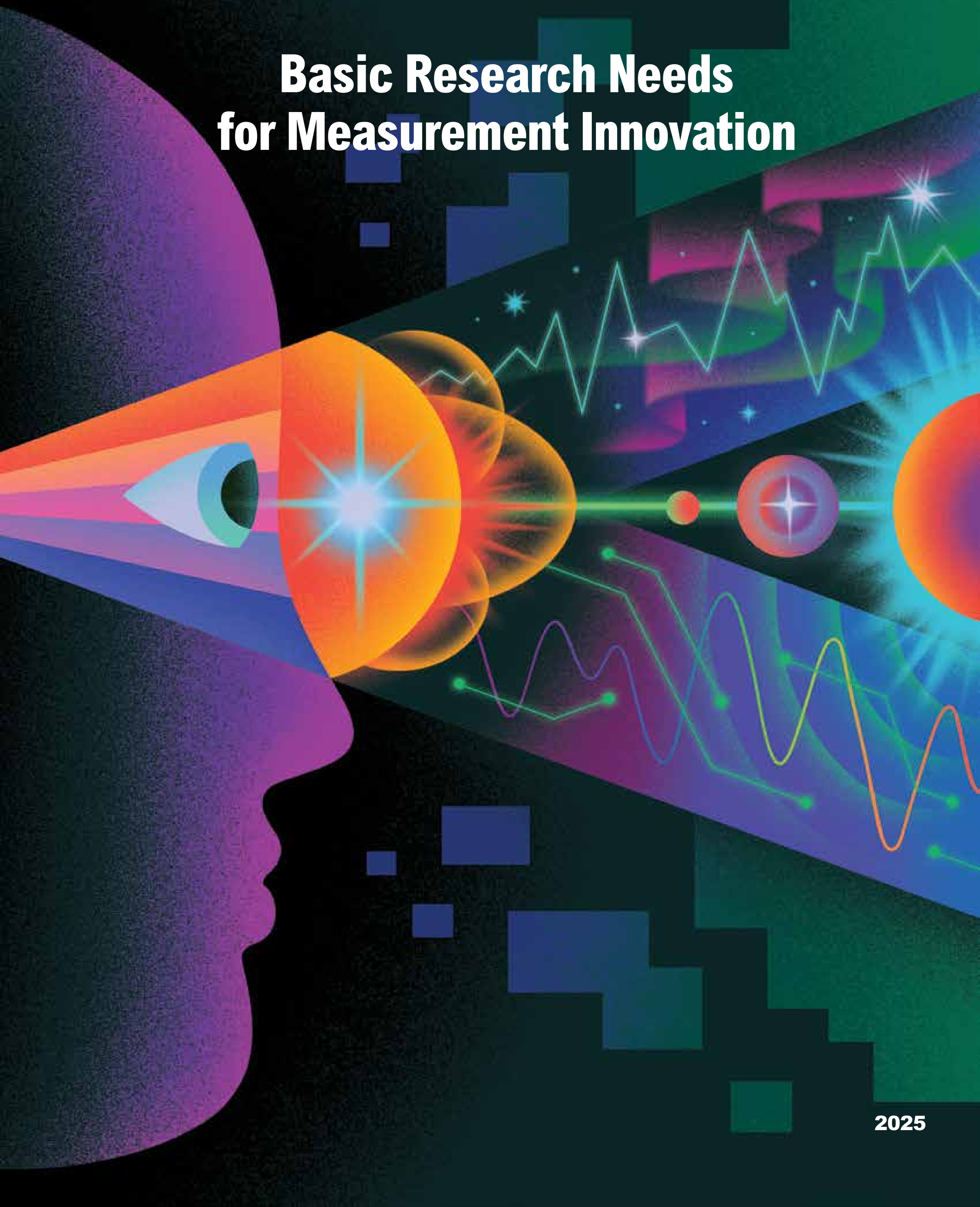
A REPORT OF THE FUSION ENERGY SCIENCES ADVISORY COMMITTEE

Basic Research Needs for Measurement Innovation



2025

Plasma…

A REPORT OF THE FUSION ENERGY SCIENCES ADVISORY COMMITTEE

the fourth state of matter

Background

The Basic Research Needs (BRN) Workshop on Measurement Innovation (MI), sponsored by the U.S. Department of Energy's (DOE) Offices of Science and Fusion Energy Sciences (FES), was held in Washington, D.C., on Jan. 9 – 11, 2024. Its organization mirrored the seven plasma physics research areas funded by the FES, namely: 1) low temperature plasma, 2) high energy density plasma, 3) plasma material interaction, 4) magnetic confinement fusion — burning plasma, 5) inertial confinement fusion — burning plasma, 6) magnetic fusion energy — fusion pilot plant (FPP), and 7) inertial fusion energy — fusion pilot plant.

The purpose of the workshop was to collect information on the basic research needs for advances in measurement innovations to enable progress toward fusion energy, to identify where diagnostics are needed to support the desired advances in burning plasma and fusion science, and to project what plasma measurements are needed to fully explore plasma science and technology activities supported by the DOE's FES.

Measurement innovation refers to the advancement of techniques, instruments, and methodologies for acquiring and analyzing data in ways that expand the scope of measurements, achieve required accuracy and resolution, and understand the fundamental plasma behavior. Unlike conventional diagnostic development, which focuses on implementing or optimizing known measurement techniques, measurement innovation introduces transformative capabilities. For example, the quest for a fusion pilot plant in the United States drives the measurement requirements and sets direction for the measurement innovations that are needed. For a magnetically confined fusion pilot plant, measurements will focus on plasma control and performance verification measurements during long-pulse operation with high levels of radiation. Offline testing of proposed diagnostics will require facilities to generate high-radiation fusion environmental conditions. For an inertially confined fusion pilot plant, measurements must be developed for monitoring the implosion, the health of the driver, and innovative target tracking and metrology schemes. These diagnostics will need to function at high repetition rates (i.e., ~10 Hz) and withstand high levels of radiation. Although some existing technologies used in research facilities like the National Ignition Facility (NIF), Omega Laser Facility, and the Z Pulsed Power Facility could be further developed and adapted to support progress toward fusion pilot plants, innovations beyond these existing techniques are expected to be required.

The BRN on MI included subject matter experts from academia, national laboratories, and industry. Each research area was assigned a 10-member working group. Eleven of the 70 working group members were from industry, including members from fusion startup companies. In the fall of 2023, a request for white papers on measurement innovation was announced to the plasma physics community, and a total of 257 white papers were received by the working groups. The working groups held parallel sessions at the workshop where the members discussed the white papers with the authors and began the process to outline a set of priority research opportunities (PROs) identifying measurement innovations needed over the next decade to support the fusion energy science research goals. In this report, the scientific challenges and measurement innovations associated with each PRO are presented and crosscutting areas (CCAs) are identified.

Findings

The main findings from the workshop are listed below.

- Measurement innovations have led and will continue to lead to scientific and engineering breakthroughs in plasma science and technology activities supported by the DOE's FES, especially fusion energy sciences.
- The majority of the fusion-related PROs concentrated on measurement innovations to monitor and control the fusion plasma, plasma facing components (PFCs), thermonuclear fuel preparation, and tritium breeding.
- The pace of progress for measurement innovations for the FES community, especially for the realization of nuclear fusion energy, could be accelerated by the use of validation and verification (V&V) of design modeling codes, artificial intelligence and machine learning (AI/ML), and the use of digital twins (i.e., as defined in a recent report from the mini-conference on digital twins for fusion research, a digital twin is a transformative approach for merging the digital and physical realms, turning complex, real-time data into actionable insights that enhance decision-making, mitigate risks, and drive rapid innovation).
- Measurement innovation offers a critical cross-thread in the FES community, as described in the appendices. FES has successfully supported similar activities through programs like LaserNetUS.
- A more systematic approach to diagnostic calibrations would benefit measurement innovations. The DOE supports a range of radiation source facilities that could be used for diagnostic calibrations. Developing a well-advertised network of radiation sources capable of supporting calibration efforts would empower FES diagnosticians while simultaneously improving the use of such facilities.
- The measurement innovations needed for FPPs are pushing the FES community into new scientific and engineering frontiers, and will require a momentous workforce development.
- Experience has shown that applying measurement innovation rapidly accelerates progress and that transferring diagnostics and operational expertise from the public sector to private facilities will offer synergistic benefits to the fusion energy science community.
- The working groups realize the value of forming national teams to transform ideas for measurement innovations into working diagnostics in an efficient and economical way. The National Diagnostics Working Group, supported by the DOE's National Nuclear Security Administration, is a good working example.
- The broad scope of the research and development identified in the PROs for all of the plasma physics research areas is significantly larger than the current FES MI program.
- Measurement innovations needed for remote operation and maintenance of fusion pilot plants (FPPs) (e.g., remote manipulation and robotics) should be the topic of future workshops.

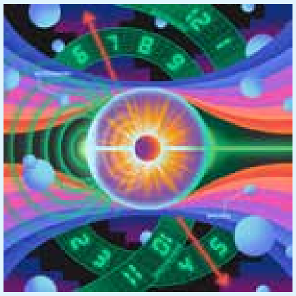
Priority Research Opportunities

A summary of the main PROs within each of the seven research areas is listed below. These PROs were generated by the working group members, where industry represented almost 15% of the membership. Many of these PROs align with the framework of the Community Planning Process of the American Physical Society's Division of Plasma Physics and the DOE's Fusion Energy Sciences Advisory Committee's Long-Range Planning drivers reports.

Low Temperature Plasma

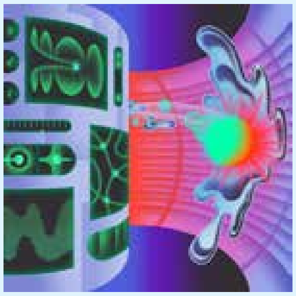
The PROs identified by the Low Temperature Plasma (LTP) working group cover these topics: surface and bulk interactions between plasma species and interface materials; high-spatial and temporal resolution measurements of plasma wave interactions resulting in particle velocity and energy distributions and interaction with electric and magnetic fields; forward modeling of diagnostics; community access for fundamental physical reference data; development of common diagnostic analysis methodology; nonequilibrium computational modeling; and an integrated framework for AI/ML.

High Energy Density Plasma



The PROs identified by the high energy density plasma (HEDP) working group cover these topics: measurement innovations in techniques, diagnostics, and sources to achieve full characterization of HEDP; electronic detectors for X-rays, gamma rays, charged particles, and neutrons; and high repetition rate lasers, targets, and diagnostics.

Plasma Material Interaction



The PROs identified by the plasma material interaction (PMI) working group cover these topics: monitoring evolution and flow of material from internal surfaces in fusion reactors; hydrogen retention and transport in plasma facing materials; evolving plasma material interactions in multispecies plasma; effects of device operation and dust accumulation on the lifetime of PFCs; neutron damage to surface and bulk material of reactor components; transient heat and particle loads on PFCs; and liquid metal PFCs.

Magnetic Confinement Fusion — Burning Plasma

The PROs identified by the magnetic confinement fusion — burning plasma (MCF-BP) working group cover these topics: measurement and control techniques and concepts; diagnostic technical demonstrations; atomic physics theory, simulation, and validation; and real-time acquisition and data analysis using machine learning and synthetic modeling.

Inertial Confinement Fusion — Burning Plasma

The PROs identified by the inertial confinement fusion — burning plasma (ICF-BP) working group cover these topics: X-ray, gamma ray, neutron, and charged particle diagnostics for high fusion energy gain; alpha-heating and burn-wave propagation; metrology and delivery of thermonuclear fuel; radiation hardening; and advanced data analysis techniques.

Magnetic Fusion Energy — Fusion Pilot Plant

The PROs identified by the magnetic fusion energy — fusion pilot plant (MFE-FPP) working group cover these topics: FPP control and measurements needs for operation; bridging the technological gaps between MCF-BP and MFE-FPP diagnostics; leveraging advanced MCF-BP diagnostics to prototype measurement innovations for MFE-FPP; integrated data analysis techniques; relativistic effects; robust calibration techniques; radiation shielding; and new supporting technologies.

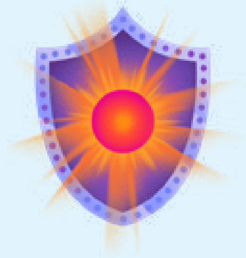
Inertial Fusion Energy — Fusion Pilot Plant

The PROs identified by the inertial fusion energy — fusion pilot plant (IFE-FPP) working group cover these topics: data infrastructure and software ecosystem; high-repetition-rate for high average power; radiation hardening; metrology and delivery of thermonuclear fuel; FPP requirements for infrastructure, controls, and diagnostics; and implosion diagnostics.

Crosscutting Areas

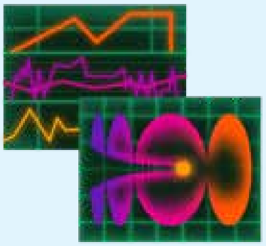
A summary of the four CCAs identified in the workshop is listed below.

CCA1 Diagnostic Radiation Hardening



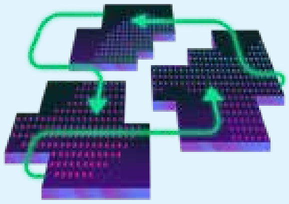
Diagnostic radiation hardening for FPPs is common to the HEDP, PMI, MCF-BP, ICF-BP, MFE-FPP, and IFE-FPP research areas.

CCA2 Requirements for Infrastructure, Controls, and Diagnostics



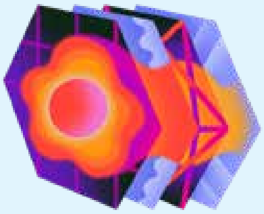
Requirements for infrastructure, controls, and diagnostics for FPPs are common to the MFE-FPP and IFE-FPP research areas.

CCA3 Real-Time Data Analysis



Real-time data analysis, including AI/ML, V&V, and digital twins is common to the LTP, HEDP, PMI, MCF-BP, ICF-BP, MFE-FPP, and IFE-FPP research areas.

CCA4 Tritium Retention, Neutron Damage, and Heat Loading



Tritium retention, neutron damage, and heat loading in PFCs, diagnostics, and materials in FPPs are common to PMI, MFE-FPP, and IFE-FPP research areas.

Acknowledgements

The chair and co-chair greatly appreciate the input from the plasma physics community; the insightful perspectives and dedicated efforts of the working groups; the guidance of the DOE, especially Curt Bolton from the FES; the organization of the workshop by the Oak Ridge Institute for Science and Education team; the support of the Princeton Plasma Physics Laboratory (PPPL) Communications Department, including B. Rose Huber, Raphael Rosen, and Kelly Lorraine Andrews, to deliver this report to the community; Michael Branigan of Sandbox Studio for art direction and design; and Ariel Davis for the illustrations.

Luis Felipe Delgado-Aparicio (PPPL, Chair)
Sean P. Regan (Laboratory for Laser Energetics at University of Rochester, Co-Chair)

A plan to accelerate fusion energy through transformative diagnostics and real-time measurement science.

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Introduction

Background

The U.S. Department of Energy (DOE) sponsors basic research needs (BRN) workshops for fields of research that are needed to achieve specific DOE missions. Selected subject matter experts for a particular research field are gathered and presented with a charter to identify critical research areas and identify priority research opportunities (PROs). The BRN workshop provides a forum for the experts to focus on fundamental, long-term knowledge advancement and to identify the foundational research that is required to advance that particular research field. The findings are summarized in a report.

The BRN Workshop on Measurement Innovation (MI), sponsored by the DOE's Offices of Science and Fusion Energy Sciences (FES), was held in Washington, D.C., Jan. 9 – 11, 2024. Its organization mirrored the seven plasma physics research areas funded by the FES, namely: 1) low temperature plasma, 2) high energy density plasma, 3) plasma material interaction, 4) magnetic confinement fusion — burning plasma, 5) inertial confinement fusion — burning plasma, 6) magnetic fusion energy — fusion pilot plant, and 7) inertial fusion energy — fusion pilot plant.

The purpose of the workshop was to collect information on opportunities for advances in diagnostics to enable progress toward fusion energy, to identify where diagnostics are needed to support the desired advances in burning plasma and fusion science, and to project what plasma measurements are needed to fully explore plasma science and technology activities supported by the DOE's FES.

The BRN Workshop on MI included subject matter experts from academia, national laboratories, and industry. Each research area was assigned a 10-member working group. In the fall of 2023, a request for white papers on measurement innovation was announced to the plasma physics community, and a total of 257 white papers were received by the working groups. Community webinars were held to organize a workshop and to have Joseph Kilkenny of General Atomics and Robert Kaita of the Princeton Plasma Physics Laboratory present invited talks on the multi-decadal diagnostic developments in inertial confinement fusion (ICF) and magnetic confinement fusion (MCF), respectively. These talks highlighted the crucial role of measurement innovations leading to scientific breakthroughs in fusion research. The workshop had a hybrid format where the working group members, invited speakers, and federal program managers attended the workshop in person and the rest of the research community participated remotely. During the workshop, additional invited talks were presented on the research status of plasma material interactions by Jean Paul Allain of FES and Robert Kolasinski of Sandia National Laboratories, on low temperature plasma by David Graves of Princeton University, and on the lessons learned with diagnostics at Conseil Européen pour la Recherche Nucléaire (CERN) by Giulio Pellegrini of the Institute of Microelectronics in Barcelona, Spain.

The working groups held parallel sessions at the workshop where the members discussed the white papers with the authors and began the process of outlining a set of PROs identifying measurement innovations needed over the next decade to support the fusion energy science research goals. In this report, the scientific challenges of measurement innovations associated with each PRO are presented and crosscutting areas (CCAs) are identified.

Measurement Innovation

Measurement innovation refers to the advancement of techniques, instruments, and methodologies for acquiring and analyzing data in ways that expand the scope of measurements, achieve required accuracy and resolution, and understand the fundamental behavior of plasma. Unlike conventional diagnostic development, which focuses on implementing or optimizing known measurement techniques, measurement innovation introduces transformative capabilities. For example, the quest for a fusion pilot plant in the United States drives the measurement requirements and sets direction for the measurement innovations that are needed. For a magnetically confined fusion pilot plant, measurements will focus on plasma control and performance verification measurements during long-pulse operation with high levels of radiation. Offline testing of proposed diagnostics will require facilities to generate high-radiation fusion environmental conditions. For an inertially confined fusion pilot plant, measurements must be developed for monitoring the implosion, the health of the driver, and innovative target tracking and metrology schemes. These diagnostics will need to function at high repetition rates (i.e., ~10 Hz) and withstand high levels of radiation. Although some existing technologies used in research facilities like the National Ignition Facility (NIF), Omega Laser Facility, and Z Pulsed Power Facility could be further developed and adapted to support progress toward fusion pilot plants, innovations beyond these existing techniques are expected to be required.

Example areas of measurement innovation are listed below.

New sensing paradigms are needed to develop novel sensing approaches that surpass existing limitations, such as:

- Alternative detection principles that can be exploited (e.g., quantum sensors, ultrafast photonics, AI-assisted inference, radiation-hardened detectors).
- Miniaturized or embedded sensors that function in extreme fusion environments.
- In situ, real-time, or remote measurement techniques that were previously impractical.

Enhanced data acquisition and processing are needed to innovate how measurement signals are captured, processed, and analyzed, such as:

- Advanced ML and AI-driven real-time processing to improve signal extraction and reduce noise.
- High-bandwidth, multiplexed acquisition systems to handle massive data streams from multiple diagnostics.
- Multiple diagnostics compressive sensing and fusion to extract higher-order insights with reduced hardware complexity.

- Bayesian probabilistic frameworks (e.g., integrated data analysis (IDA)) to infer key plasma parameters from a reduced set of observables, enabling self-consistent, uncertainty-quantified reconstructions of plasma conditions.

Breakthrough temporal and spatial resolution are needed to develop measurement techniques that push the limits of what can be resolved in time and space, such as:

- Ultrafast, high-sensitivity detectors for capturing rapid plasma dynamics.
- Multiscale measurements linking global plasma behavior with micro-instabilities.
- Non-perturbative or minimally invasive techniques for confined plasmas.

Cross-disciplinary adaptation is needed to leverage advancements for other fields (e.g., astrophysics, high energy physics, materials science, quantum information science (QIS) metrology). This includes:

- Novel diagnostic principles repurposed for fusion applications.
- New approaches to uncertainty quantification and predictive modeling.
- Synergies between fusion diagnostics and high energy physics (HEP), including industrial or biomedical imaging technologies.

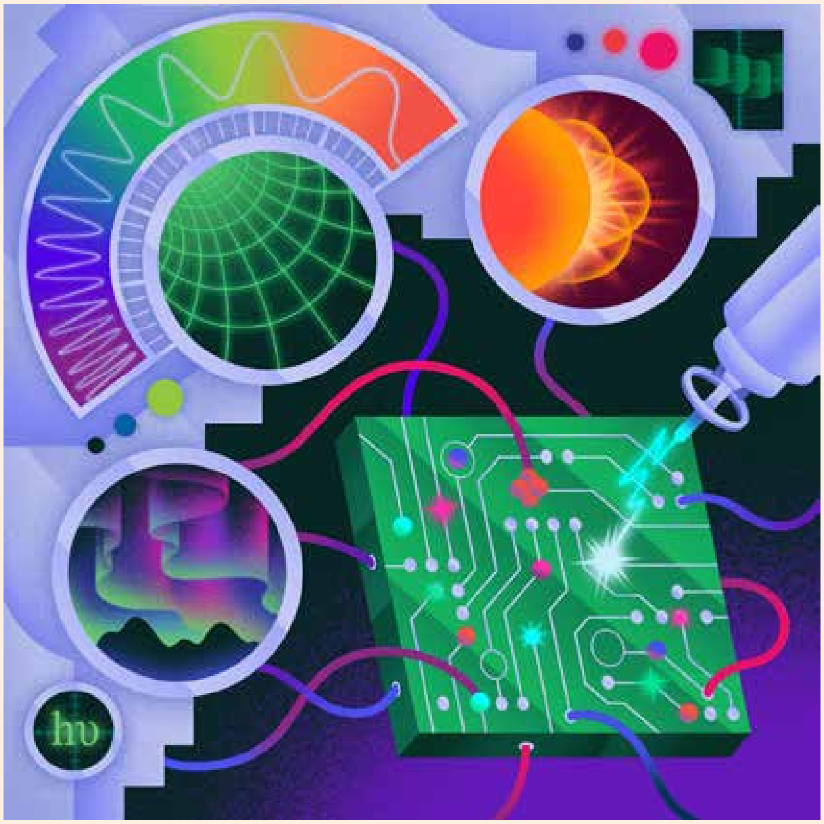
Advanced reduced modeling and validation through measurement is needed to bridge measurement innovation with plasma theory and computational modeling. This can be done by:

- Developing and refining reduced models based on advances in plasma theory (e.g., magnetohydrodynamics (MHD), transport, and turbulence).
- Verifying and validating reduced models using synthetic diagnostic tools to ensure consistency between simulations and experimental data.
- Benchmarking reduced models by designing measurement strategies that directly test theoretical predictions, improving predictive capability for fusion performance.

Main Topical Research Areas

A major objective of the BRN Workshop on MI was to provide the DOE's FES with the main PROs to inform future research efforts and funding opportunities in the specific areas constituting the building blocks for advances in measurement innovation and diagnostics. Many of these PROs align with the framework the American Physical Society's Division of Plasma Physics' Community Planning Process (APS-DPP-CPP) and the DOE's Fusion Energy Sciences Advisory Committee's (FESAC) Long-Range Planning (LRP) drivers reports. These PROs will enable progress toward fusion energy and help identify where diagnostics are needed to support the desired advances in burning plasma and fusion science and will help to project what plasma measurements are needed to fully explore plasma science and technology.

The following seven topical research areas were considered.

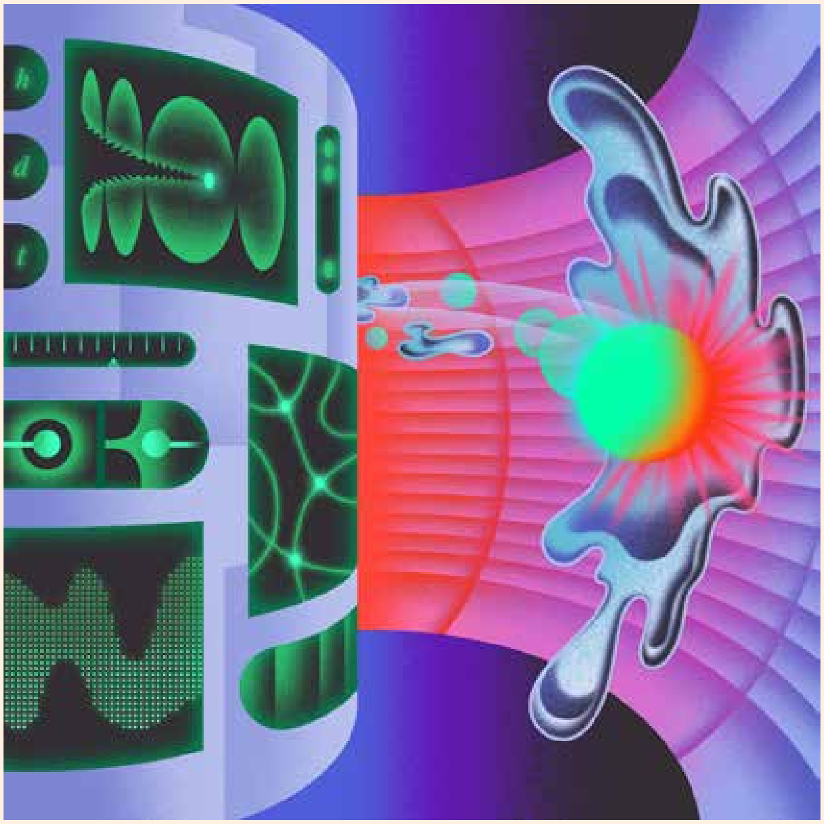


Low Temperature Plasma

Low temperature plasmas (LTPs) are relatively cool, partially ionized gasses that enable investigations into fundamental plasma physics phenomena that are otherwise hard to study. Scientists can use LTPs in laboratories to understand the cool plasmas that exist throughout the universe. LTPs are at the heart of multiple fields, including semiconductor manufacturing, the production of various materials and chemicals, biotechnology, agriculture, and lasers. LTPs support the study of critical processes in other areas of plasma science and technology, including fusion experiments and antimatter confinement. There typically have been three ways to improve LTP diagnostics. The first involves developing completely new techniques. The second involves enhancing existing diagnostic methods to make them easier to use. The third involves modifying diagnostics so they can measure new fundamental physical quantities leading to innovative diagnostic techniques and data analysis. While these three methods are important for all areas of plasma diagnostic research, the bond between the fundamental research community and industry means that LTP diagnostic innovations move relatively quickly into widespread use.

High Energy Density Plasma

High energy density plasma (HEDP) involves plasma characterized by energy densities exceeding 10^{11} joules per cubic meter (J/m^3) or equivalently, with pressures exceeding 1 megabar (Mbar). HEDP is a unique discipline encompassing plasma physics, astrophysics, condensed matter, materials science, high-pressure research, planetary science, and fusion science. Recent advances in HEDP have significant potential impacts on society. One aspect limiting science and technology breakthroughs is the ability to accurately diagnose both focused (unit physics) and integrated (i.e., ICF implosions) experiments at today's high energy density science facilities. The lack of accurate data with focused experiments limits theoretical development. With integral experiments, the lack of accurate data limits its applications. A major challenge with high energy density diagnostics is that the phase space is large, with the number densities ranging from 10^{15} to $10^{27}/cm^3$ and temperatures from kelvin to hundreds of millions of kelvins (<milli-eV to 10s of KeV and 10–100s MeV, including probe beams). The plasmas often evolve dynamically over approximately one billionth of a second, are embedded with large electrical and magnetic fields, and have substantial spatial gradients in the approximate millimeter-scale plasmas volume. Moreover, in many cases, subsystems are not in equilibrium with each other, so each subsystem may need to be characterized independently for HEDP.



Plasma Material Interaction

Plasma material interaction (PMI) concentrates on plasma-facing components (PFCs), including liquid walls and the interaction of tritium and neutrons with reactor materials in general. Current research concentrates on innovative, active-laser diagnostics to probe the material composition, chemical nature and erosion products in the plasma. These diagnostics are used on linear plasma devices simulating plasma conditions in a fusion reactor, where optical access is easier than in actual fusion reactors. However, many of these diagnostics have not been developed to the capability needed for delivering reliable data under fusion-relevant plasma exposure conditions. Thus, the goal of PMI measurement innovations is to advance the in situ and in operando diagnostics by 1) adapting existing ex situ diagnostics to have new deployment capability, and 2) innovating and developing new disruptive diagnostics with high temporal and spatial resolution.

Magnetic Confinement Fusion — Burning Plasma

Diagnostics are critical to operating magnetic confinement fusion (MCF) devices safely and efficiently, as well as for determining which experimental conditions could help scientists design, construct, and operate an MCF power plant. While diagnostic coverage and expansiveness may be limited for future magnetic fusion energy reactors due to radiation issues, limited access, and cost considerations, plasma scientists are committed to developing the required diagnostics for a full range of MCF machines. Optimization of plasma operating scenarios for the core, edge, and divertor regions of the MCF plasma will continue as new challenges are encountered with greater power and with the transition to deuterium-tritium operation, which is necessary for MCF-burning plasma (BP) and MCF-fusion pilot plant. Current research concentrates on closing significant measurement gaps by continuously developing and adapting diagnostic techniques with an aim of achieving MCF-BP conditions, which drives the MCF-BP measurement innovations.

Inertial Confinement Fusion — Burning Plasma

Inertial fusion energy (IFE) has greatly benefited by the proof-of-principle laboratory demonstration of achieving ignition and energy gain with inertial confinement fusion (ICF) at the NIF. This historic achievement relied on well-calibrated, shielded diagnostics and precise experimental techniques to make innovative measurements of the plasma conditions. These measurements captured small scales (smaller than one-millionth of a meter) of phenomena occurring on the picosecond to nanosecond timescales, all while sustaining extreme levels of background radiation from X-rays, gamma rays, charged particles, electromagnetic interference, and neutron flux. To forge ahead to higher fusion yields in ICF, several advancements are required in measurement innovation for diagnostics and radiation hardening, targets, data management and analysis, and infrastructure.

Magnetic Fusion Energy — Fusion Pilot Plant

First-generation fusion pilot plants (FPPs) generating magnetic fusion energy (MFE) will require comprehensive measurements focusing on plasma control, performance verification, and plant operation monitoring. These requirements differ from those stipulated for present-day devices, where diagnostics are used primarily for detailed physics studies. However, because contemporary diagnostics may not be able to operate in the unprecedented environmental conditions of a MFE-FPP, the community must research and develop alternate or improved methods. New diagnostics require measurement innovations with a range of properties, including the ability to withstand high levels of radiation, neutron and gamma fluences, as well as induced noise; the ability to feed data into an integrated analysis process; adaptability; and long-pulse compatibility; among others. Eventually, the community must determine a minimal set of required measurements that can satisfactorily maintain safe and efficient plant operation. Supporting infrastructure will need to be developed and built to test and validate new diagnostics for MFE-FPP deployment. These considerations are largely independent of the magnetic configuration of the fusion device, but specific aspects will matter at the design stage and will need to be considered, especially for relative priority and needed resources.

Inertial Fusion Energy — Fusion Pilot Plant

The recent accomplishments of ignition and energy gain on the NIF compel the scientific community to work toward an IFE-FPP. Measurement innovations are required to build and operate an FPP. Significant infrastructure diagnostics have to be developed for monitoring the health of the plant and driver, accountancy in the fuel cycle, including tritium breeding, and innovative target tracking and metrology schemes. All these innovations need to function at possibly high repetition rates of up to 10 hertz and survive in harsh radiation environments under continuous operation. These FPP requirements mean that in addition to new developments, existing technologies used in research facilities like NIF, Omega Laser Facility, and Z Pulsed Power Facility will need to be further developed and adapted with a focus on simplicity and economy.

Priority Research Opportunities

The PROs of each of the seven research areas are listed below.

Low Temperature Plasma

LTP PRO 1	Develop LTP diagnostics to probe the interactions between plasma species and interface materials above the interface, on the interface, and below the interface.
LTP PRO 2	Develop diagnostic methods to measure particle energy distributions, electric fields, and magnetic fields, with high spatial and temporal resolution in low temperature plasmas.
LTP PRO 3	Develop forward models of diagnostic systems to facilitate the interpretation of measurements.
LTP PRO 4	Develop the infrastructure to identify and address the needs of the plasma community for long-term access to fundamental physical reference data, the sharing and improvement of analysis methodology for commonly employed diagnostics, and the creation of nonequilibrium computational models.
LTP PRO 5	Develop an integrated framework that uses data collected by diagnostics to train AI/ML models.

High Energy Density Plasma

HEDP PRO 1	Invest in advanced techniques, diagnostics, sources, and all of their combinations to achieve full characterization and understanding of HEDP for basic science and IFE.
HEDP PRO 2	Design and validate electronic detectors capable of observing >10 keV X-rays, gammas, charged particles, and neutrons.
HEDP PRO 3	Develop state-of-the-art lasers, targets, and diagnostics for high-repetition-rate (HRR) HEDP facilities.

Plasma Material Interaction

PMI PRO 1	Characterize the evolution and steady state of the surface composition in all fusion reactor internal surfaces and enable understanding of material flows within the plasma-wall interface.
PMI PRO 2	Understand and enable prediction of hydrogen retention and transport in plasma-facing materials.
PMI PRO 3	Advance the understanding of evolving PMI surfaces in multispecies plasma.
PMI PRO 4	Assess the long-term evolution and degradation of PFCs due to device operations and the impact on whole-device operation by dust accumulation and PFC degradation and failure.
PMI PRO 5	Increase understanding of how neutrons affect the surfaces of components and the underlying bulk material structure.
PMI PRO 6	Determine the maximum tolerable transient heat and particle loads on PFCs.
PMI PRO 7	Develop material diagnostics that help accelerate the technological maturity of liquid metal (LM) PFCs so that they can be deployed within a 10-year time frame in a large confinement device.

Magnetic Confinement Fusion — Burning Plasma

MCF-BP PRO 1	Develop innovative measurement and control techniques/concepts for MCF-BP.
MCF-BP PRO 2	Perform research and development to support measurement innovations for MCF-BP devices.
MCF-BP PRO 3	Support diagnostic technical demonstrations for MCF-BP.
MCF-BP PRO 4	Support atomic physics theory, simulation, and validation for MCF-BP experiments.
MCF-BP PRO 5	Support real-time acquisition, data analysis, ML, and synthetic modeling for MCF-BP.
MCF-BP PRO 6	Support diagnostic testing and characterization to evaluate measurement innovations for MCF-BP operation.

Inertial Confinement Fusion — Burning Plasma

ICF-BP PRO 1 Accelerate X-ray, gamma ray, neutron, and charged-particle measurement innovations critical to reaching high gain.
ICF-BP PRO 2 Develop alpha-heating and burn-wave propagation diagnostics to understand and control the fusion yield.
ICF-BP PRO 3 Enhance capabilities for target metrology, including in-flight target imaging to deliver the critical target conditions needed for an ignition and energy gain.
ICF-BP PRO 4 Develop diagnostics that can withstand high levels of radiation.
ICF-BP PRO 5 Employ advanced data analysis techniques to accelerate physics understanding.

Magnetic Fusion Energy — Fusion Pilot Plant

MFE-FPP PRO 1 Define control and measurement needs for MFE-FPP operation.
MFE-FPP PRO 2 Utilize existing and develop new measurement techniques, diagnostics, and facilities to address technological gaps and anticipate MFE-FPP environmental conditions.
MFE-FPP PRO 3 Validate diagnostics and control schemes in an integrated test environment for a MFE-FPP.
MFE-FPP PRO 4 Use advanced MCF-BP diagnostics in current DOE and international facilities to support implementation, utilization, and operation for MFE-FPP measurement innovations.
MFE-FPP PRO 5 Develop IDA techniques to address measurement gaps, drifts, and failures for MFE-FPP.
MFE-FPP PRO 6 Investigate relativistic effects on plasma measurements anticipated for MFE-FPP.
MFE-FPP PRO 7 Develop rugged, reliable calibration techniques that can ensure diagnostic accuracy required for MFE-FPP.
MFE-FPP PRO 8 Develop and validate mitigation techniques to protect in-vessel diagnostic components, such as mirrors, cables, and shutters in a MFE-FPP.
MFE-FPP PRO 9 Develop new supporting technologies, such as X-ray optics, high-frequency microwave components, and quantum sensors for MFE-FPP devices.

Inertial Fusion Energy — Fusion Pilot Plant

IFE-FPP PRO 1 Develop a diagnostic data infrastructure and the software ecosystem that meets IFE requirements.

IFE-FPP PRO 2 Develop real-time, high-repetition-rate diagnostics to accelerate physics understanding and enable stable, long-term, high-average, fusion power output.

IFE-FPP PRO 3 Develop diagnostics that are radiation hardened to prompt dose from ignited plasmas, including single-event disruption mechanisms and cumulative damage and diagnostic lifetime studies.

IFE-FPP PRO 4 Develop systems to rapidly measure the dimensions and defects of IFE targets.

IFE-FPP PRO 5 Develop critical infrastructure and diagnostic requirements for Initial Operation of an an IFE-FPP.

IFE-FPP PRO 6 Develop implosion diagnostics for an an IFE-FPP.

Crosscutting Areas

While conducting the BRN Workhshop on MI, researchers across our communities found several PROs that appeared across multiple research areas and are of high importance to the fusion energy science mission space. Some of the themes discussed in the forum were:

- Measurement innovations are needed for next-generation measurement techniques to provide real-time, high-fidelity insights into fusion-relevant parameters, enabling precise control of core performance, stability, and fusion energy gain.
- Measurement innovations are needed for primary diagnostics to operate in extreme conditions and withstand high neutron flux, intense thermal loads, and complex plasma-wall material interactions, requiring advances in remote sensing and handling, robotic deployment, and automated inspection systems aligned with reliability, availability, maintainability, and inspectability (RAMI) principles.
- Measurement innovations are needed to harness fusion energy, requiring diagnostics to evolve beyond laboratory-scale experimentation toward integrated, reactor-ready measurement solutions that support sustained plasma operation, inform fusion power extraction strategies, and validate predictive models for next-generation reactor designs.
- Measurement innovations should be embedded in the fusion research and development ecosystem to ensure that diagnostic capabilities remain at the forefront of scientific discovery, bridging foundational plasma physics with the engineering requirements of a viable fusion energy system.

The PROs from each working group associated with each CCA are listed below.

CCA1	**FPP Diagnostic Radiation Hardening**
HEDP PRO 2	Design and validate electronic detectors capable of observing >10 keV X-rays, gammas, charged particles, and neutrons.
PMI PRO 5	Increase understanding of how neutrons affect the surfaces of components and the underlying bulk material structure.
ICF-BP PRO 4	Develop diagnostics that can withstand high levels of radiation.
MFE-FPP PRO 2	Utilize existing and develop new measurement techniques, diagnostics, and facilities to address technological gaps and anticipated MFE-FPP environmental conditions.
IFE-FPP PRO 3	Develop diagnostics that are radiation hardened to prompt dose from ignited plasmas, including single-event disruption mechanisms and cumulative damage and diagnostic lifetime studies.
MFE-FPP PRO 3	Validate diagnostics and control schemes in an integrated test environment for a MFE-FPP.

CCA2	FPP Requirements for Infrastructure, Controls, and Diagnostics
HEDP PRO 1	Invest in advanced techniques, diagnostics, sources, and all of their combinations to achieve full characterization and understanding of HEDP for basic science and IFE.
HEDP PRO 3	Develop state-of-the-art lasers, targets, and diagnostics for high-repetition-rate (HRR) HEDP facilities.
PMI PRO 2	Understand and enable prediction of hydrogen retention and transport in plasma-facing materials.
MCF-BP PRO 1	Develop innovative measurement and control techniques and concepts for MCF-BP.
ICF-BP PRO 1	Accelerate X-ray, gamma ray, neutron, and charged-particle measurement innovations critical to reaching high gain.
MFE-FPP PRO 1	Define control and measurement needs for MFE-FPP operation.
MFE-FPP PRO 4	Use advanced MCF-BP diagnostics as much as possible to support implementation, utilization, and operation for MFE-FPP measurement innovations.
MFE-FPP PRO 6	Investigate relativistic effects on plasma measurements anticipated for MFE-FPP.
MFE-FPP PRO 7	Develop rugged, reliable calibration techniques that can ensure diagnostic accuracy required for MFE-FPP.
MFE-FPP PRO 9	Develop new supporting technologies, such as X-ray optics, high-frequency microwave components, and quantum sensors for MFE-FPP devices.
IFE-FPP PRO 2	Develop real-time, high-repetition-rate diagnostics to accelerate physics understanding and enable stable, long-term, high-average, fusion power output.
IFE-FPP PRO 5	Develop critical infrastructure and diagnostic requirements for initial operation of an IFE-FPP.
IFE-FPP PRO 6	Develop implosion diagnostics for an IFE-FPP.

CCA3	**FPP Real-Time Data Analysis, Including AI/ML**
LTP PRO 3	Develop forward models of diagnostic systems to facilitate the interpretation of measurements.
LTP PRO 5	Develop an integrated framework that uses data collected by diagnostics to train AI/ML models.
MCF-BP PRO 5	Support real-time acquisition, data analysis, ML, and synthetic modeling for MCF-BP.
MCF-BP PRO 7	Explore crosscutting opportunities with the other research areas in radiation hardening, CalibrationNetUS, HRR measurement innovations, DiagnosticNetUS, standardized data techniques using AI/ML, and workforce development.
ICF-BP PRO 5	Employ advanced data analysis techniques to accelerate physics understanding.
MFE-FPP PRO 5	Develop IDA techniques to address measurement gaps, drifts, and failures for MFE-FPP.

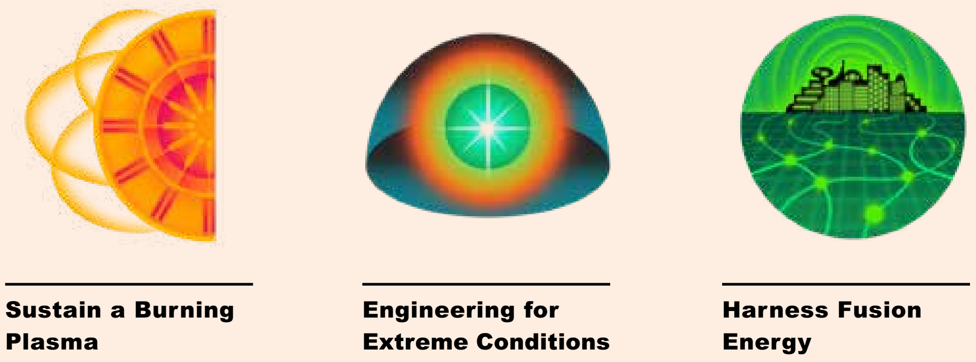
CCA4	**FPP Tritium Retention, Neutron Damage, Heat Loading in PFCs, Diagnostics, and Reactor Materials**
PMI PRO 6	Determine the maximum tolerable transient heat and particle loads on PFCs.
MFE-FPP PRO 8	Develop and validate mitigation techniques to protect in-vessel diagnostic components, such as mirrors, cables, and shutters in a MFE-FPP.
IFE-FPP PRO 5	Develop critical infrastructure and diagnostic requirements for initial operation of an IFE-FPP.

Alignment

To align with the APS-DPP-CPP and the DOE's FESAC LRP Drivers, measurement innovations are needed.

The advancement of diagnostic development and measurement innovation is fundamental to achieving the scientific and technological milestones outlined in the APS-DPP-CPP and the FESAC LRP drivers. These reports emphasize three critical drivers for fusion science: (a) sustaining a burning plasma, (b) engineering for extreme conditions, and (c) harnessing fusion energy — each of which relies on transformative measurement capabilities to close critical knowledge gaps and accelerate fusion's path to realization (see Figure 1 below). Measurement innovation thus extends beyond conventional diagnostic development, integrating cutting-edge approaches, such as Bayesian inference frameworks, AI-driven data analysis, synthetic diagnostics for model validation, and radiation-hardened semiconductor technology, and ensuring robust and self-consistent plasma characterization under increasingly demanding reactor conditions.

Figure 1. Alignment with fusion APS-DPP-CPP and FESAC LRP drivers



APS-DPP-CPP and LRP Drivers

Sustain a Burning Plasma

Engineering for Extreme Conditions

Harness Fusion Energy

Artwork by Ariel Davis for FESAC

To sustain a burning plasma, next-generation measurement techniques must provide real-time, high-fidelity insights into fusion-relevant parameters, enabling precise control of core performance, stability, and fusion gain. Engineering for extreme conditions requires diagnostics that can withstand high neutron flux, intense thermal loads, and complex plasma-wall-material interactions — necessitating advances in remote sensing and handling, robotic deployment, and automated inspection systems aligned with RAMI principles. Finally, to harness fusion energy, diagnostics must evolve beyond laboratory-scale experimentation toward integrated, reactor-ready measurement solutions that support sustained plasma operation, inform fusion power extraction strategies, and validate predictive models for next-generation reactor designs. By embedding measurement innovation into the fusion research and development ecosystem, diagnostic capabilities would remain at the forefront of discovery, bridging foundational plasma physics with the engineering requirements of a viable fusion energy system.

Additionally, a natural crosscutting synergy exists between MCF and ICF research, offering a unique opportunity for shared advancements in measurement science. While the physical conditions and confinement methods differ — MCF sustains long-duration plasmas in toroidal magnetic fields (e.g., tokamaks and stellarators), while ICF compresses fuel to ignition using high-energy lasers — both approaches face common challenges in plasma diagnostics, extreme environment engineering, and integrated data analysis. Techniques such as X-ray and neutron imaging and their calibration, high-speed optical diagnostics, and synthetic modeling for validation are crucial to both fields, providing a natural avenue for collaborative innovation. Advances in HEDP measurements from ICF research at facilities like NIF and the Omega Laser Facility can inform diagnostic strategies for high-temperature magnetically confined plasmas, just as MCF's expertise in long-pulse measurement stability, ML-based data fusion, and magnetic probe development can enhance ICF's ability to diagnose transient, high-energy plasmas with greater precision. By fostering a strong cross-disciplinary collaboration between MCF and ICF communities, measurement innovation can accelerate progress in both fields, enhancing our ability to control and sustain fusion conditions across diverse confinement approaches. These synergies not only improve fundamental plasma understanding but also strengthen the collective effort to realize fusion energy as a practical power source.

Realizing Net Power From Fusion Plasma

As fusion energy research advances toward sustained burning plasma conditions in MCF plasmas and to high energy gain in ICF plasmas, the role of innovative in vacuo, in situ, and in operando diagnostics is still increasingly critical for characterizing plasma behavior, monitoring PFCs, and ensuring stable reactor operation. Current fusion experiments benefit from a diverse suite of diagnostics that can be retracted, repositioned, or recalibrated between “shots” to optimize data acquisition. However, as the research community transitions to HRR and long-pulse steady-state devices, traditional diagnostic access will become increasingly limited. This shift necessitates the development of embedded, radiation-hardened, and self-calibrating measurement systems capable of withstanding the harsh fusion environment while providing continuous, high-fidelity data. Table 1 (see page 24) summarizes measurement innovations that are common to MCF-BP, MFE-FPP, ICF-BP, and IFE-FPP.

For future burning plasma facilities, where neutron flux, gamma radiation, and limited access pose significant barriers to traditional diagnostic deployment, a natural reduction of the diagnostic set will occur, prioritizing only the most essential, resilient, and self-sustaining measurement techniques (see options listed in tables below). Many conventional diagnostics that rely on direct plasma interaction or fragile optical components will require replacement with remote, synthetic, or inferential measurement techniques that can extract key plasma parameters from a reduced set of robust observables. Advances in microwave and X-ray technology, wide-bandgap semiconductor-based sensors, AI-driven data reconstruction, and integrated multi-diagnostic approaches (e.g., Bayesian IDA) will be crucial to overcoming these challenges. Additionally, the fusion community must explore alternative measurement paradigms, such as distributed fiber-optic sensing, microwave and THz-based techniques, and neutron-resilient imaging systems, to ensure real-time feedback and control remain viable under BP conditions. The long-term success of fusion as a power source will depend on the community’s ability to innovate in this space by designing diagnostics that survive in the extreme fusion environment. Table 2 (see page 25) highlights measurement innovations needed to engineer at extreme conditions, while Table 3 (see page 26) highlights measurement innovations needed to harness fusion energy in the fusion energy cycle.

Table 1. Measurement innovations common to MCF-BP, MFE-FPP, ICF-BP, and IFE-FPP.

Measurement Innovation	MCF-BP / MFE-FPP	ICF-BP / IFE-FPP
Radiation-hardened neutron diagnostics	▬	▬
—DD and DT flux and spectra —Si_3D, SiC, Diamond, GaN and AlN —Scintillators with Li^6 and B^1		
Radiation-hardened gamma ray diagnostics	▬	▬
Radiation-hardened microwave technology	▬	▬
—From GHz→THz using GaN and AlN		
Radiation-hardened and heat-resistant radiated power (P_{rad}) and photon monitors (including ultraviolet (UV), soft X-ray (SXR) and hard X-ray (HXR))	▬	▬
—Multi-energy systems —Metal vacuum photodiodes —Spectrometers with reflectors		
Real-time data analysis of multiple data streams using Bayesian integrated data analysis (IDA) and ML/AI models	▬	▬
Complementary tools:	▬	▬
—V&V of high-Z spectroscopy models —Radiation-hardened and temperature-resistant QIS sensors —Synthetic modeling —New calibration schemes		
Nonthermal and/or relativistic effects in microwave (downshift) and SXR/HXR (non-isotropic) technology	▬	
—Heating and current drive —Slide-away and runaway electrons (REs)		
First Wall PMIs	▬	▬
Tritium Fuel Cycle	▬	▬
Tritium Breeding Blanket	▬	▬

Table 2. Measurement innovations needed for PMI and specific engineering needed for extreme conditions as discussed in the APS-DPP-CPP and FESAC LRP drivers. Many of these measurement innovations are needed for MCF-BP / MFE-FPP and ICF-BP / IFE-FPP.

Engineering for Extreme Conditions

Measurement innovations needed for solid plasma-facing materials

- Near-surface detection of nucleation and growth
- Detection of changes in surface composition (%)
- Retention of tritium
- Erosion and redeposition (e.g., basis of high-Z unidentified flying objects in MCF/MFE)

Measurement innovations needed for liquid plasma-facing materials

- Flow rate and MHD effects (both liquid Li and molten salts)
- Stability of liquid surfaces and H, D, and T pumping
- Surface wetting and evaporation rate during high-heat flux
- Diagnostics for liquid metal vapor boxes

Measurement innovations needed for FPP structural materials

- In situ effects of neutron irradiation of vacuum vessel
- Corrosion, tritium permeation, irradiation creep and thermal shock

Measurement innovation for FPP functional materials

- Effects of n irradiation of high-temperature superconductor coils (performance and lifetimes)
- Effects of plasma on diagnostic mirrors and windows when absolutely necessary
- Effects of n and γ on neutron multiplier, breeder materials and Fusion Energy Cycle (FEC) (e.g., Li, PbLi, and FLiBe)

Table 3. Measurement innovations needed for harnessing fusion energy as discussed in the APS-DPP-CPP and FESAC LRP drivers. Many of these measurement innovations are needed for MCF-BP / MFE-FPP and ICF-BP / IFE-FPP.

Harnessing Fusion Energy

Measurement innovations needed for the fusion fuel cycle

- Tritium concentration in blankets
- Impurity concentration (including Li, Pb, F, Be, etc.)

Measurement innovations needed for isotopic separation and breeding

- Li^6 vs. Li^7
- Liquid metal and/or molten salts flow without MHD drag
- Hydrogenic concentrations

Measurement innovations needed for functional materials

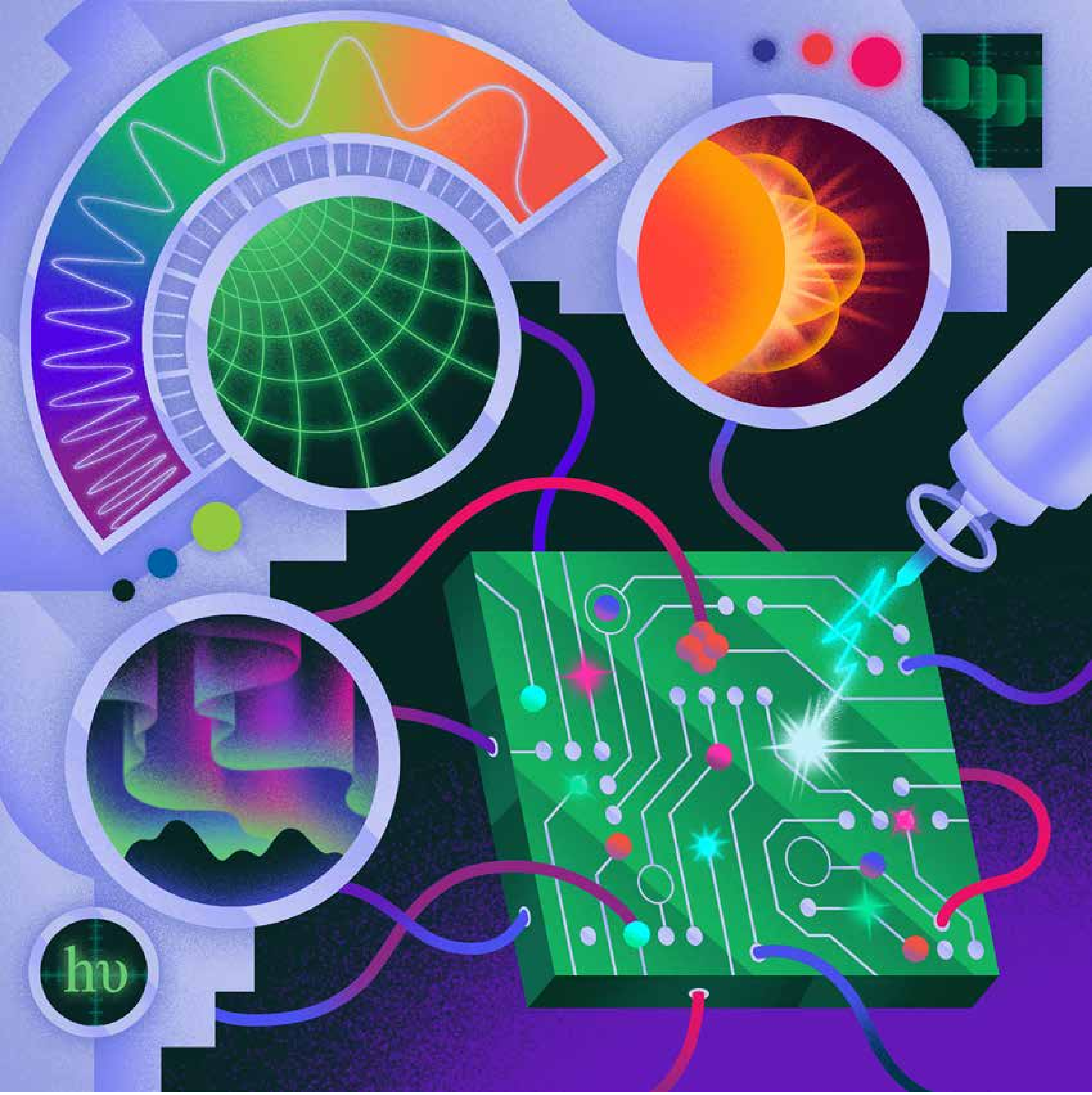
- Radiation-hardened and temperature-resistant sensors and electronics (e.g., SiC, diamond, GaN, AlN)
- Adopt lessons learned at HEP accelerators (e.g., CERN)
- In-pile fission irradiation at relevant conditions (10^{14}–10^{18} n/cm2/MeV)

Measurement innovations needed for FPPs (other)

- Balance of plant technology (e.g., monitors for RAMI)
- Remote handling for maintenance and safety
- Robotics (e.g., test cell and beyond biological shield)
- Monitors to suffice licensing framework/procedures (e.g., neutrons, T, Pb, Bi, and Po)
- Passive monitors embedded in FEC to address nonproliferation concerns (e.g., U, Th, and Pu)

Organization of the BRN Workshop on MI Report

The report is arranged with a chapter for each research area as follows: Chapter 1: Low Temperature Plasma, Chapter 2: High Energy Density Plasma, Chapter 3: Plasma Material Interaction, Chapter 4: Magnetic Confinement Fusion — Burning Plasma, Chapter 5: Inertial Confinement Fusion — Burning Plasma, Chapter 6: Magnetic Fusion Energy — Fusion Pilot Plant, and Chapter 7: Inertial Fusion Energy — Fusion Pilot Plant. Each chapter introduces the research area, presents a retrospective and current status of the research, and highlights the scientific challenges and measurement innovations for each PRO. The charge to the community, the membership of the working groups, and the list of white papers submitted by the community are presented in Appendices A, B, and C, respectively. Measurement innovation offers a critical cross-thread in the FES community, which is described in Appendices E, F, and G for community diagnostic development, community diagnostic calibration, and community workforce development, respectively. FES has successfully supported similar activities through programs like LaserNetUS.



CHAPTER 1

Low Temperature Plasma

Introduction

Low temperature plasmas (LTPs) are relatively cool, partially ionized gasses that enable investigations into fundamental plasma physics phenomena that are otherwise hard to study. For example, scientists can use LTPs in laboratories to understand the cool plasmas that exist throughout the universe, far from the laboratory.

LTPs are at the heart of multiple fields, including semiconductor manufacturing, the production of various materials and chemicals, biotechnology, agriculture, and lasers. LTPs also aid the study of critical processes in other areas of plasma science and technology, including fusion experiments and antimatter confinement.

There typically have been three ways to improve LTP diagnostics. The first involves developing completely new techniques. The second involves enhancing existing diagnostic methods to make them easier to use. The third involves modifying diagnostics so they can measure new fundamental physical quantities leading to innovative diagnostic techniques and data analysis. While these three methods are important for all areas of plasma diagnostic research, the bond between the fundamental research community and industry means that LTP diagnostic innovations move relatively quickly into widespread use.

Unfortunately, investment in improving LTP diagnostics has been sporadic. In the case of measuring and calculating fundamental physical quantities, support in the United States has diminished so much that the knowledge needed to generate the data is in danger of being lost. Therefore, the community needs an investment plan for LTP diagnostic development to expand upon the efforts of LTP researchers who have contributed to the knowledge of fundamental physics and helped develop plasma-based technologies that have enabled a range of advancements, from space missions to asteroids to our entire information technology infrastructure.

One of the more pressing needs in the LTP field is developing standardized data formats. Standardizing data would allow researchers to build large diagnostic datasets that could aid the creation of large-scale learning models, like those used in artificial intelligence (AI) and machine learning (ML). LTP-focused industries like semiconductor fabrication are rapidly adopting AI and ML to design future generations of plasma processes; training these models requires data from diagnostics. Researchers also need large sets of *imprecise* data to help confirm the accuracy of complex models that simulate plasma chemistry. When planning to build new diagnostics, researchers should consider these two needs — large datasets and varying degrees of precision.

The LTP working group generated the following six priority research opportunities (PROs), which both address fundamental science and how to translate this fundamental research into technology that can benefit society. The scientific challenges and measurement innovations for each PRO are presented.

Retrospective

The ideas for the PROs in this chapter came from 25 white papers submitted by the LTP community, which focused on six topics: (1) plasma-surface interactions, (2) plasma-surface interactions and the semiconductor industry, (3) new diagnostics and methods, (4) maximizing yields from diagnostics, (5) inferring additional information from diagnostics, and (6) numerical modeling and ML.

One theme in the working group discussions was the plasma community's need for diagnostics to produce more data, which would help improve current diagnostics and aid the advanced computations and the development of computer models that could help design future fusion reactors. Two common themes were the emerging role of advanced computations (whether directly modeling physical systems or synthesizing large datasets derived from measurements or models) in both industry and basic research. A crosscutting priority that was identified in the LTP and other working groups was the need to gather more physical reference data. Progress in diagnosing many of the plasmas of industrial and scientific interest is hampered by a lack of physical reference data, e.g., electron impact cross sections, ion mobilities, cross sections for entangled photon absorption, and emission spectra of negative ions. As codes become more sophisticated and more representative of, for example, industrial reactors, measurements that can specifically test the key predictions of these codes are critically important to the code development process.

There was considerable discussion about the definition of "diagnostic innovation." Participants agreed that innovation could include new diagnostic methods that provide increased sensitivity levels or that enable measurements of, heretofore, unmeasurable quantities. Innovation could also include improving the apparatus or analysis methods used for existing diagnostics that make particular diagnostic techniques more accessible, easier to operate, and less expensive to implement. For example, open-source tools that make analysis of plasma measurements more accessible to a wider range of users, e.g., industry, can potentially improve the adoption and use of existing or new diagnostic methods.

Participants noted that coupled models of diagnostics and plasma systems could significantly impact the accuracy of future measurements. For example, high-fidelity models of diagnostics placed into a model of a plasma system could quantify the perturbations introduced by inserting physical probes into a plasma. With high-fidelity plasma models, researchers could determine if large numbers of measurements with modest accuracy are sufficient to validate models that are then used in a predictive manner instead of requiring extensive high-accuracy measurements. In other words, high-fidelity plasma models could help determine the optimal "cost" of measurements and models that could result in an accurate, predictive model.

The plasma material interaction (PMI) working group has considerable overlap on many of the issues of interest to the LTP working group. The PMI working group focuses on measuring plasma materials interactions under extremely harsh, burning plasma conditions involving neutron irradiation and large plasma and thermal fluxes. These conditions are far harsher in terms of their destructive capabilities than those encountered in LTPs. In many LTP systems, controlled plasma materials interactions are a desired outcome for materials fabrication, leading to, for example, the production of biocompatible thin films, tailored properties of materials, or nanoscale devices. Some LTP systems share the same concern for negative outcomes, such as the erosion of insulators in electric propulsion systems due to energetic electron and ion bombardment. Similar needs in LTP and PMI applications were identified, such as in situ and in operando measurement, improved spatial and temporal resolution, and monitoring of materials' conditions (erosion, deposition, defect propagation) and species (identity, dynamics) at interfaces. Many PMI white papers identified diagnostic techniques already broadly used in LTPs, which allows them to expand their applications to PMIs. These diagnostics include laser-induced breakdown spectroscopy and Raman spectroscopy. There are opportunities to provide LTP expertise to assist PMI investigations involving such diagnostics. The interactions of plasma species close to, at, and below the surface of plasma material interfaces remain a challenging area to diagnose effectively. Many target species or fields (electric and magnetic) of interest still lack effective, accurate diagnostic methods across a wide range of plasma conditions.

A specific area of considerable overlapping interest with the PMI working group is the need for in situ monitoring of plasma material interfaces. There are significant challenges facing PMI measurements in existing fusion machines, when ITER comes online, and in planned machines such as DEMO. The radiation and thermal environments of those systems may require ex situ measurements using many of the techniques developed by LTP researchers to characterize materials after interactions with plasma. One example of a possible approach to in situ PMI measurements from the PMI working group is the development of micro-electromechanical systems (MEMS) devices (as embedded wall sensors) specially adapted to the harsh PMI environment. For LTPs, the broader use of multiple types of commercially available MEMS devices for embedded, in situ measurements is a potential development area. Another example from PMI relevant to LTP surface interaction monitoring would involve the use of very high-resolution echelle-type spectrometers (now more accessible for laboratory experiments) for the measurement of particle kinetics and erosion.

The community also agreed that improved laser systems were needed. Unlike other areas of plasma science, LTP often needs measurements that use precise laser wavelengths. In most non-LTP areas, lasers are used for scattering experiments to measure, for example, electron density or temperature. These measurements are not highly sensitive to precise wavelengths. Many, if not most, LTP measurements are of specific species that require a precise wavelength for measurement (e.g., absorption, laser-induced fluorescence, Raman spectroscopy). These wavelength-sensitive measurements add challenges to laser-source development. Another theme across all working groups was the lack of available physical reference data, which is limiting the development of new diagnostic methods and full utilization of existing diagnostic methods and models of LTP systems.

Current Status

This review of the state of the field and future directions for the diagnostics of LTPs follows the publication of recent LTP reports derived from community contributions. One such review, issued in 2023, is the basic research needs report titled, “Science Challenges and Research Opportunities for Plasma Applications in Microelectronics.” There is a significant overlap between the more general LTP science discussed here and the plasma science required to advance semiconductor manufacturing. Important areas of overlap were the need for physical reference data, diagnostics for the plasma-surface interface, and the emerging importance of high-fidelity models, not just for modeling plasma systems but for the model of specific diagnostic systems. The 2021 decadal study of the National Academy of Sciences titled, “Plasma Science: Enabling Technology, Sustainability, Security, and Exploration,” also provided recommendations for broad research priorities for LTPs.

Priority Research Opportunities

PRO 1: Develop LTP diagnostics to probe the interactions between plasma species and interface materials above the interface, on the interface, and below the interface.

Scientific Challenges

One of the most critical areas of LTP science is the interaction between plasmas and materials. These interactions are crucial to processes like plasma etching, which is essential to manufacturing microelectronic devices or producing biocompatible coatings for medical uses. However, scientists today do not understand this critical area because there are not enough diagnostics that can provide the necessary measurements.

One specific challenge is determining how exposure to plasma affects surfaces, including which plasma particles remain on the surface and how the surface's physical structure might change. However, conventional diagnostic methods like X-ray photoelectron spectroscopy and low-energy electron diffraction cannot be used in plasma environments. Another technique known as Fourier-transform infrared absorption spectroscopy requires special conditions and long measurement times.

Scientists also need to know how plasma particles penetrate materials and modify them below the surface. This process is especially important for fabricating microelectronics, which requires detailed knowledge about how the energy and chemical compositions of both neutral and charged particles change deep within materials. Making these measurements is particularly challenging, though, because the width of the relevant features is much smaller than the wavelength of the visible and ultraviolet light that would be used in optical spectroscopic methods.

Measurement Innovations

Developing LTP measurement innovations is necessary to determine the absolute density of atoms and molecules with high spatiotemporal resolution, gas temperatures, and the distribution of reactive species below the interface with the following objectives:

- To probe plasma species in close proximity to, on, or below the surface. Within distances comparable to the plasma sheath width, conventional techniques such as optical emission spectroscopy, optical absorption spectroscopy and laser-induced fluorescence can be used for a limited number of neutral species. Measuring properties of positive ions is a particular challenge in the sheath because of the low-number densities relative to the bulk plasma. Without information on which neutral and charged species impact surfaces with what energy and angular distributions, it is not possible to obtain a thorough understanding of plasma-surface interactions.

- –To characterize the outcome of plasma exposure on the surfaces facing the plasma. Fundamental research challenges include which species are present on the surface and what is the physical structure at the surface (e.g., ordered crystalline or amorphous surface).
- –To determine the transport and reactivity of the species generated by the plasma in the surface and subsurface environments. For example, fluorine atoms generated by the plasma will diffuse deep into silicon and disrupt the crystalline lattice. In plasma etching of high-aspect ratio (~100:1) features for microelectronics fabrication, it is particularly important to quantify the chemical composition and translational energy of neutral reactants and ions deep within the structured surface (i.e., ~1 mm).

PRO 2: Develop diagnostic methods to measure particle energy distributions, electric fields, and magnetic fields, with high spatial and temporal resolution in low temperature plasmas.

Scientific Challenges

To synthesize nanomaterials like nanoparticles, nanotubes, and nanoflakes (i.e., structures that have a wide range of applications, including aiding the production of space suits and military vehicles), plasma scientists need diagnostics that can measure the speeds, temperatures, and sizes of plasma particles more precisely than is currently possible. That information would increase scientists' understanding of the processes that help form nanomaterials, leading to better control and higher efficiency.

Along with the above capabilities, researchers need diagnostics that can measure how plasma particles interact with electromagnetic waves. That information can increase understanding of how power and energy flow through LTPs, among other properties. However, to gather this information in plasma environments with high temperatures and low pressures, researchers must be able to measure electric and magnetic fields very precisely. Measurements in extreme environments, particularly in low-pressure systems, need highly sensitive diagnostics capable of measuring small electric and magnetic fields changing in billionths of a second across distances measuring less than a millionth of a meter. This capability does not exist yet.

Measurement Innovations

The development of nonintrusive, in situ diagnostics to provide measurements in extreme conditions and in low pressure environments is a high priority in the LTP field. These diagnostics have uses beyond the typical small-scale LTP reactors. The edge regions of large-scale, high-temperature plasma facilities are within the LTP realm. LTP diagnostics developed and applied to these regions would better characterize the important edges of these plasmas. To improve the capabilities of existing diagnostics, efforts should be made to exploit the new technologies, including detector sensitivity for improved noise discrimination, the recent availability of new types of optical components, e.g., narrow-band filters, and the improved accessibility of very high-resolution spectrometers. Developing these LTP diagnostics should be performed in concert with model development and validation. Doing so would allow researchers to confirm that the data produced by the new diagnostics was correct while identifying additional physical quantities or phenomena requiring measurement and avenues for future diagnostic innovation.

PRO 3: Develop forward models of diagnostic systems to facilitate the interpretation of measurements.

Scientific Challenges

Forward models play pivotal roles in the interpretation of diagnostic system measurements in fusion research and are equally critical to LTP systems. Forward models are computational tools that predict outcomes and interpret measurements of plasma diagnostic systems. They provide a framework for understanding measurement outcomes, specifically, how a plasma-probe system should operate under ideal or specific conditions. To some degree, forward models are solving the inverse problem. As an example, a model of a Langmuir probe is inserted into a comprehensive plasma model or in a computational environment having specified plasma properties. The Langmuir probe model then predicts the current-voltage (I-V) characteristic that would be produced in an experiment. Comparing the predicted I-V characteristic with an experimental measurement then determines the plasma conditions. This method reduces reliance on generic interpretations of diagnostics output.

In the context of tokamak plasmas, forward models are routinely used to gauge the viability of a diagnostic system given specific plasma parameters (e.g., forward models that simulate the behavior of a diagnostic tool, such as Doppler backscattering or radial correlation doppler reflectometry). A simplified model is used to understand the scattering amplitudes in different plasma conditions of a tokamak to measure the turbulence wavenumber spectrum and the radial correlation length. This approach is particularly important because the turbulence naturally exhibits a non-separable power law spectrum in wavenumber space, which, in turn, affects the radial correlation length’s dependence on the binormal wavenumber.

Measurement Innovations

Encouraging the development of forward models that simulate the expected output of diagnostic systems based on known input parameters is necessary. Ideally, forward models should be embedded in comprehensive plasma transport and reactor models to account for the diagnostic’s effect on the plasma and to determine how precisely a diagnostic measures phenomena occurring across very short distances and in extremely short periods of time. Such models could also generate synthetic signals, allowing scientists to test diagnostics without running physical experiments. In addition, forward models could improve existing models by letting scientists compare predictions made using synthetic data to observations obtained by analyzing actual data. The improved models could then anticipate system behavior under untested conditions, benchmark system performance, and optimize design and operation parameters for better outcomes. Forward models could also identify potential diagnostic failures or maintenance needs before they manifest and establish best practices for interpreting diagnostic measurements across different LTP systems.

PRO 4: Develop the infrastructure to identify and address the needs of the plasma community for long-term access to fundamental physical reference data, the sharing and improvement of analysis methodology for commonly employed diagnostics, and the creation of nonequilibrium computational models.

Scientific Challenges

The entire LTP community benefits from acquiring, preserving, and accessing fundamental physical reference data that is critical to developing new diagnostics. These datasets make possible detailed models that simulate a range of LTP systems by calculating the behavior of plasma particles and the plasma's overall chemical composition. However, for most plasma systems, these datasets are incomplete (e.g., negative ions and interactions between atoms and nanoclusters) with the exception of pristine, rare gasses. These datasets serve essential roles in enabling high-fidelity models of a wide range of LTP systems that incorporate full particle kinetics and/or plasma chemistry, specifically enabling computation and comparison of energy distributions of species not in local thermodynamic equilibrium with experimental measurements. While it is important to expand the databases to new species, it is equally important to extend existing databases of physical reference data to be able to accurately model interactions between species at suprathermal energies (i.e., toward energies where inelastic collisions participate in reactive collisions involving high-energy thresholds).

Measurement Innovations

The support of research projects focusing on measuring and sharing critical fundamental physical reference data is needed. The LTP community should also develop a set of standardized plasma sources that aid measurement standardization and, thereby, accelerate the generation of physical reference data. That new data should include information about different types of plasma particles and interactions happening at high energies. To aid these efforts, there should be incentives to encourage scientists to share data and analysis techniques.

PRO 5: Develop an integrated framework that uses data collected by diagnostics to train AI and ML models.

Scientific Challenges

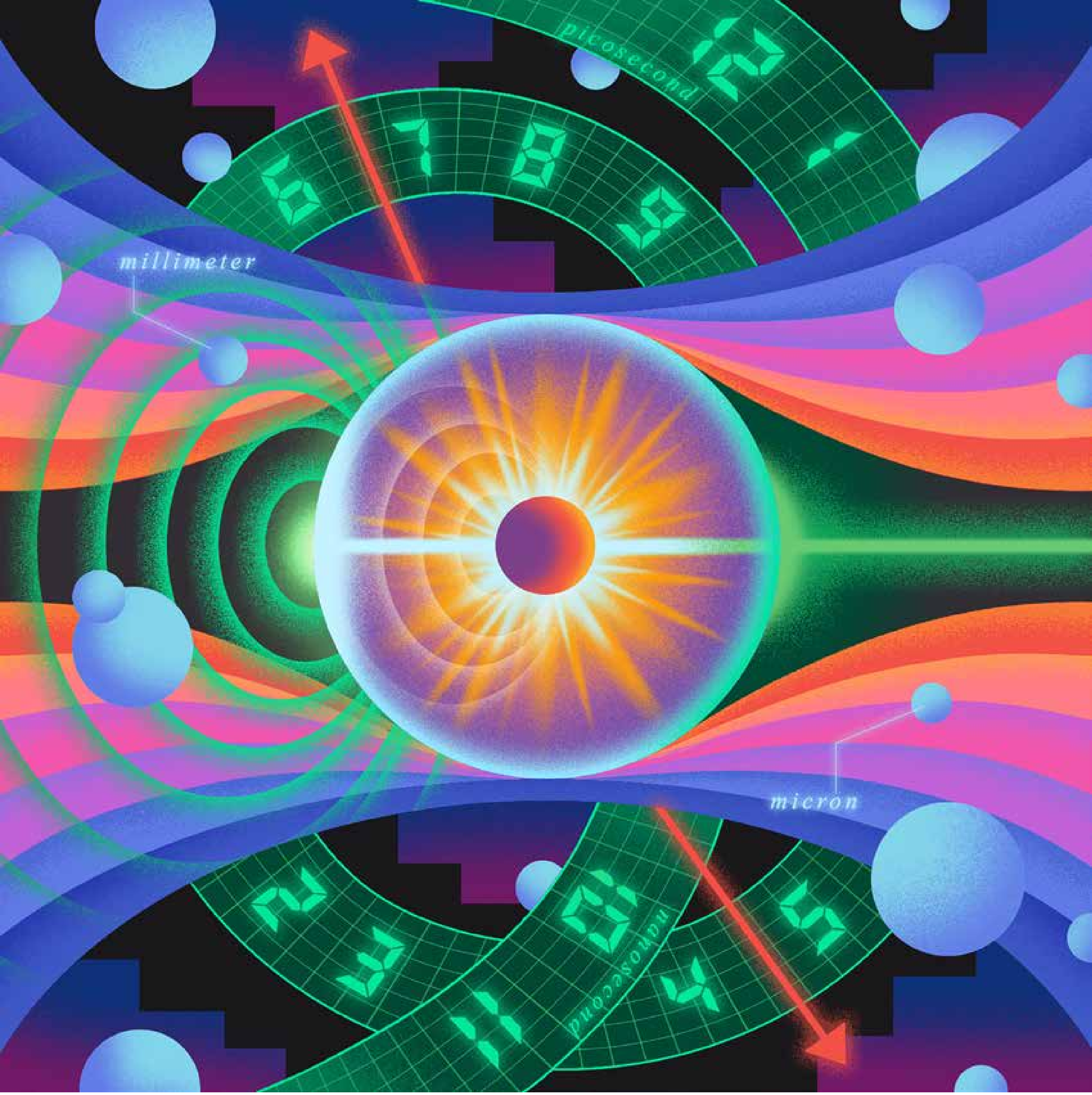
While the interaction between AI, ML, and the physical sciences is in its infancy, AI and ML, have already facilitated significant advancements in the analysis and interpretation of diagnostic data for LTP science problems. For example, the ability of ML to identify correlations has allowed scientists to determine the electron energy distribution function from optical emission spectroscopy data, control an atmospheric pressure plasma jet for plasma medicine, and develop a semiconductor fabrication process at a reduced cost.

The continued development of AI and ML for LTP faces the following challenges:

- Researchers need to develop diagnostic methods that can better identify critical processes in LTP systems. This information should be used to develop a first-principles understanding of how AI and ML models can help focus measurement efforts on the most important processes and reduce the computational time of simulations.
- Researchers need to use AI and ML to increase the speed of plasma models. With increased speed, these models could simulate plasma behavior across extremely small distances and take extremely small amounts of time — smaller than can be simulated today — as well as chemical complexity that provides access to temporal and spatial scales and chemical complexity not previously accessible due to computational constraints that could be used to guide real-time feedback control of the plasma state.
- Researchers need to develop diagnostic methods that can measure large collections in LTP particles. Such measurements would help validate and develop models that help interpret future measurements.
- Researchers need to develop digital twins (i.e., as defined in a recent report from the mini-conference on Digital Twins for Fusion Research, a digital twin is a transformative approach for merging the digital and physical realms, turning complex, real-time data into actionable insights that enhance decision-making, mitigate risks, and drive rapid innovation) of LTP systems that would then be validated with precision measurement. The digital twins could help scientists estimate how different diagnostic methods perturb the plasma. That information, in turn, could help scientists determine the precision that diagnostics need to best validate models of LTP systems. Using digital twins would also help determine the relative costs and effectiveness of different diagnostic methods.
- Researchers need to develop methods to reduce and store measurement data to facilitate standardized sharing and cross-benchmarking of the AI and ML training data. An open and well-maintained LTP data economy could increase the impact of diagnostic measurements and expedite scientific discovery.

Measurement Innovations

The plasma community should continue to develop ML and AI techniques to better understand how to use diagnostic measurements, along with computer simulations to manage plasma systems better. The community should develop surrogate models, or digital twins, of plasma systems. Researchers should also develop and disseminate standards for measurement data formats that would facilitate data mining and the development of predictive models.



CHAPTER 2

High Energy Density Plasma

Introduction

High energy density plasma (HEDP) involves plasma characterized by energy densities exceeding 10^{11} joules per cubic meter (J/m^3) or equivalently, with pressures exceeding 1 megabar (Mbar). HEDP is a unique discipline at the confluence of plasma physics, astrophysics, condensed matter, materials science, high-pressure research, planetary science, and fusion science. Recent advances in HEDP have significant potential impacts on society. One aspect limiting science and technology breakthroughs is the ability to accurately diagnose both focused (unit physics) and integrated (i.e., inertially confined fusion (ICF) implosions) experiments at today's high energy density systems (HEDS) facilities. The lack of accurate data with focused experiments limits theoretical development and, with integral experiments, limits its applications. A major challenge with HED diagnostics is that the phase space is large, with number densities ranging from 10^{15} to 10^{27} /cm^3 and temperatures from kelvin to hundreds of millions of kelvins (<milli-eV to 10s of KeV and 10–100s MeV, including probe beams). The plasmas often evolve dynamically over ~one billionth of a second, are embedded with large electrical and magnetic fields, and have substantial spatial gradients in the ~mm-scale plasmas volume. Moreover, in many cases, subsystems are not in equilibrium with each other, so each subsystem may need to be characterized independently in HEDS.

Many of the grand challenges for HEDS have been discussed in the 2023 National Academies of Science, Engineering, and Medicine's report on "Fundamental Research in High Energy Density Science. They include the following:

- How can burning fusion plasmas be controlled and harnessed for society's energy, security, and technology needs?
- Can extreme astrophysical phenomena evident from observations or predicted by theory be reproduced in the laboratory?
- What are the HED quantum states of matter that could lead to new classes of materials for energy transport, storage, and quantum information science?
- Will the discovery of exotic atomic and electronic structures of matter and materials at HED conditions lead to a new chemistry of elements at conditions that occur throughout much of the cosmos?
- Can we understand the conditions under which life forms and the signatures of planets on which life could emerge?
- How can multi-scale theory, simulations, and experiments predict the behavior of macroscale objects and processes?

The HEDP working group aims at making significant progress in the grand challenges identified above. The working group received a total of 42 white papers, ranging from transformational upgrades from existing diagnostics to preliminary diagnostic proposals, general proposals with questions raised for community awareness and help, and innovative revolutionary ideas. The panel sorted the white papers into five categories, including improved measurement needs, high repetition rate (HRR) diagnostic needs, advanced analysis, innovative proposals, and crosscutting connections for general and cultural changes. All the white papers were presented at the workshop and discussed in detail. The key findings are:

- Measurement innovations are needed to fully characterize the HEDP conditions with high enough resolutions and simultaneous probing and to diagnose physical properties that are difficult to probe directly (e.g., viscosity, thermal conductivity, electrical conductivity).
- Principal investigators (PIs) have have pent-up demand for facilities to calibrate diagnostics and components of diagnostics (e.g., crystals, zone plates, X-ray mirrors, detectors, etc.) to allow for faster/better diagnostic development, fielding, interoperability (multi-user, multi-facility) and portability (traveling diagnostics).
- There is a need for new sources, X-ray and particle, to enable higher-fidelity measurements. This is especially true at today's major compression facilities, where, for example, the most used source of X-rays is a heated foil or implosion, both of which are limited in photon energy (~10 keV and below), bandwidth, collimation, coherence, etc.
- HEDP experiments require continued advances in analysis techniques to optimize data return and understanding from diagnostics and rep-rated systems for current and future measurement innovations.
- The HEDP/ICF community would make faster progress and foster more innovation from improved data handling (rep rate) and data sharing (common framework) by facilitating shared data analysis, improved data visualization, and community sourcing of innovative methods of data extraction and machine learning (ML)/ artificial intelligence (AI) analysis for novel data mining and combined analysis.
- New detectors are almost certainly required for several of these advances. The need for electronic detection of new sources with sub-nanosecond time resolution may align with leading edge advances in the semiconductor industry.

Retrospective

The impressive achievement of ignition at the Department of Energy's (DOE) National Nuclear Security Administration's National Ignition Facility (NIF) relied on its powerful laser, precisely fabricated targets, modeling and simulation efforts, and advanced diagnostics. Experimental measurements provided researchers with important insights to understand the physics of ignition. The ignition result at the NIF required a national strategy (i.e., the National Diagnostics Working Group) that coordinated the diagnostic efforts of diverse groups at academic institutions and national labs. This coordination enabled the development of the diagnostics by providing focus and prioritization. A similar coordination also enabled the development of bespoke detectors needed to confirm and understand the Higgs boson with the Large Hadron Collider at the European Organization for Nuclear Research.

These exciting scientific achievements would not have been possible without decades of research and development on measurement innovations. Moreover, these advanced measurement capabilities were achieved via community-wide collaborations; in fact, distributing work among many groups pursuing ideas in parallel has been an effective way to identify paths forward and determine which ideas are viable.

Experimental studies of HEDP are currently undergoing an exciting transformation driven by the technical advancement in high-energy and HRR lasers, as well as the success of ICF. Indeed, North America's 13 (and counting) laser facilities have coalesced into a network, LaserNetUS, to collectively pursue laser upgrades and allocate laser time.

Innovation in the lasers used to create HEDP will require associated innovation in measurement capabilities and diagnostic probe beams to take advantage of newly available conditions. With laser facilities and users scattered throughout the country, the HEDP community anticipates that it will need a national strategy to prioritize research directions and foster calibration. LaserNetUS would also need an associated "DiagnosticsNet" and "CalibrationNet" to perform optimal experiments.

Current Status

In recent journal articles and white papers, plasma scientists at universities, national laboratories, and the private sector have pointed out the need to apply current diagnostics to HRR laser facilities — those that can fire lasers at targets in quick succession — and upgrade those diagnostics with advanced detectors; data collection, acquisition, and management capabilities; online analysis systems; and data visualization capabilities to aid the gathering and interpretation of information. Specific upgrades could include enhancing current techniques that employ X-ray light, making laser sources brighter, and giving detectors capabilities to register signals more quickly. If completed, these upgrades would greatly increase how quickly researchers deepen their understanding of HEDP.

Most HEDP diagnostics rely on X-rays, high-energy light that can penetrate dense plasma. The broad spectrum of X-ray diagnostics also highlights the need for common ways and facilities for testing and maintaining the calibration of these diagnostics. X-rays contain much more information than can be extracted from the present generation of diagnostics. Generally, HEDP scientists use X-rays as probes to produce contrast images or spectroscopic analyses. Contrast images yield information about relative and absolute densities and can even be used to aid the use of other optical imaging techniques.

Recently, scientists have explored using phase information in X-rays to either enhance imaging or collect information about materials. These techniques can give detailed information about a material’s density and composition. In addition, the phase information can contain even more details about the plasma conditions, an area ripe for more study.

Another untapped area for HEDP diagnostics is the use of X-ray polarization. Measuring this property lets scientists detect magnetic fields and scattering centers, but the technique is limited by available optics and laser brightness. To address this deficiency, the HEDP community should develop new coherent or bright sources scattered off electron beams, which will allow high-resolution X-ray diagnostics to measure plasma parameters such as temperature, density, viscosity, thermal diffusivity, sound speed, coherent structures, degree of ionization, and atomic shell structures to an unprecedented degree of accuracy.

HEDP diagnostic techniques employ a higher photon energy light known as gamma rays, which can provide information about nuclear reactions or secondary reactions in a fusion plasma. Gamma rays can be used to infer quantities like fuel or ablator areal density, compression quality, and reaction history. Scientists also probe HEDPs using lower-energy radiation, including terahertz, optical, infrared, and ultraviolet light.

HEDP diagnostics use a variety of subatomic particles. Diagnostics employing protons can measure electromagnetic fields and turbulent fluctuations. Those using neutrons measure yields of ICF implosions and could one day measure the debris of melted ICF fuel and the amount of alpha particle heating. Electrons are not yet commonly used in HEDP diagnostics, but when used, they can help obtain information about the plasma particles' electromagnetic spectra.

In general, current diagnostics and data analysis techniques help scientists probe single-shot HEDP experiments to obtain plasma density, temperature, magnetic fields, and shock velocity. However, very few of these diagnostics can give all this information at all points in the target, and certain quantities like plasma viscosity, thermal conductivity, electron heat transport, transient flows, turbulent energy, and electron and ion distribution functions cannot yet be measured reliably. In addition, the novel linking of diagnostics using advanced data analysis could help each diagnostic by providing information about plasma parameters that neither diagnostic could yield alone. Measurement innovations are needed to find novel combinations of diagnostics and sources to improve our ability to fully understand these systems rapidly. The scientific challenges and measurement innovations for each priority research opportunity (PRO) are presented below.

Priority Research Opportunities

PRO 1: Invest in advanced techniques, diagnostics, sources, and all of their combinations to achieve full characterization and understanding of HEDP for basic science and inertial fusion energy (IFE).

Scientific Challenges

HED plasmas have a range of densities and temperatures, exist for billionths of a second, are embedded with large electrical and magnetic fields, and have volumes with spatial gradients in the millimeter scale. These unique conditions mean that using diagnostics to measure HEDP is challenging. Over the past decades, many diagnostics have been developed for small-scale HEDP experiments and for large-scale experiments like the Omega Laser Facility and NIF. Nevertheless, there is a need to obtain better HEDP measurements, especially for properties like viscosity and thermal conductivity that are not easily observed. Specifically, the community needs new diagnostic techniques, better optics, and ways to combine data from different diagnostics to infer new quantities and make progress more quickly.

Measurement Innovations

To meet the above challenges, the HEDP community should pursue the following strategies:

- Develop techniques to better measure fundamental HEDP properties. These properties include temperature, density, viscosity, thermal conductivity, electromagnetic fields, instabilities and growth rates, radiative effects, and stopping power, among others. Scientists traditionally measure a range of plasma properties using techniques employing X-ray spectroscopy or X-ray Thomson scattering, but the community needs new techniques to measure these properties with greater accuracy and precision and higher spatial and temporal resolutions. The resulting information could help researchers test theories and create more accurate simulations.
- Develop advanced sources of radiation and particles (X-rays, protons, ions, and electrons) to create new probe diagnostics and improve existing techniques (e.g., spectroscopy, diffraction, imaging, radiography). Scientists have used charged-particle radiography to measure the electromagnetic fields and characterize the turbulent properties of HEDP. Laser-driven protons have been integrated into warm dense matter to study proton focusing and stopping power. Innovative proton probes operating at HRR are needed. The development of ion sources, such as alpha particles, is very important for studying alpha particle transport in HEDP, especially alpha stopping in deuterium-tritium fuel, which is important data for IFE plans. MeV-scale electron sources are needed to probe near-solid-density

materials (e.g., an implosion core), as well as measure extremely large fields and rapidly evolving phenomena. Measurement innovations are needed to diagnose these probe signals in HEDP.

– Develop measurement innovations to probe a plasma simultaneously with a combination of particle and photon probes. Simultaneous probing of plasmas using a combination of particle and photon probes has several benefits, including the following: 1) allows the comparison of measurements of the same plasma parameters gathered by different diagnostics, 2) clarifies which properties best aid plasma simulations, and 3) allows for the discovery of new physics. Different particles, energies, and wavelengths reveal different aspects of a system, and the combination of these could lead to the direct measurements of emergent properties or inferred quantities.

– Improve our understanding of ICF and IFE by fostering the study of fundamental HEDP physics. Understanding the fundamental behavior of HEDP is key to developing IFE because it allows scientists to test various IFE concepts and create new laser and diagnostic technology. Studying fundamental phenomena also stimulates interest in graduate students and scientists from other fields and helps train the next generation of plasma scientists.

– Develop new diagnostic techniques for ICF and IFE by enhancing HEDP facilities: Small- and medium-scale facilities have an advantage. They can develop new diagnostics using methods that would be too costly for larger facilities. Therefore, the DOE should develop a plan to help larger facilities build and test diagnostics. One option might be developing a common framework for these diagnostics, which would help reduce the risk and cost of having many teams and facilities duplicating efforts to build, test, and field diagnostics that should be common to all facilities.

– Use public-private partnerships to advance detector technology to improve measurement fidelity for operations in challenging experimental environments associated with burning plasma and HRR lasers. HEDP detectors have included film, image plates, Columbia Resin #39 (CR-39), and charge-coupled device (CCD) sensors. When used with spectrometers, scintillators, imagers, or electron optics, these detectors produce a single dataset with each experiment. Because film is always integrating and even a one-microsecond CCD exposure is orders of magnitude longer than an HEDP experiment, information may be integrated over the entire time of the experiment into a single image, spectrum, or measurement unless coupled to a framing camera, which trades high temporal resolution for lower dynamic range. These detectors are incompatible with HRR lasers and advanced analysis methods to optimize the experiment in real time. Fortunately, gated electronic detection, which is well aligned with ongoing developments in the semiconductor industry, offers a more viable sensor for burning plasma and

HRR experiments compared to time-integrated sensors. Specifically, smaller and faster circuits can be used to create smaller and faster pixels. There are already several examples of private companies, spun out from academia and national laboratories, that design detectors, including Sydor Technologies, Kentech, Advanced hCMOS Systems, and Nalu Scientific. As electronic detection becomes more widely used and the number of laser facilities increases, the opportunities for more partnerships will grow.

– Improve the temporal resolution and spatial resolution of detectors to increase the frequency of recording data in a single experiment. A single HEDP experiment can last for as little as one-billionth of a second, and during this time, significant changes occur. Scientists must create instruments that can make multiple measurements in such extremely short periods of time.

– Develop fast readout diagnostics that are radiation hardened for X-ray, gamma, and neutron background signals in preparation of using an ICF implosion as a probe for HEDP. Researchers need hardened diagnostics to utilize the radiation produced by ICF implosions as a HEDP diagnostic probe. The hardening can be accomplished with solid-state detectors, which can replace insensitive detectors like solid-state nuclear track detectors, film, or image plates.

– Increase the frequency of measurements for HRR experiments. Measurement innovations are needed for HRR experiments to record data from HEDP facilities that have a 10-Hz firing rate. Each data acquisition needs to have the ability to record many sets of data within the experimental time frame (100 ps to 10s of ns) along a single diagnostic line of sight. High signal dynamic range detectors similar to the hybrid complementary metal-oxide semiconductor sensors should be developed with the ability to acquire data at a GHz rate or more. Such a capability would increase the data rate and the ability to understand the evolution of these HEDP systems in a much more efficient manner and allow for novel measurements like particle and feature tracking in hydrodynamic experiments and implosions, as well as real-time analysis of HEDP.

PRO 2: Design and validate electronic detectors capable of observing >10 keV X-rays, gammas, charged particles, and neutrons.

Scientific Challenges

Currently, most measurements of particles and high-energy X-rays involve either removable media like film, image plates, and CR-39 detectors or scintillators — devices that detect flashes of light — connected to optical imagers. In both cases, important information is lost. Moreover, these detection mechanisms are not compatible with HRR laser experiments.

Measurement Innovations

To meet these challenges, the HEDP community needs to make a range of advancements, including inventing diagnostics with detectors incorporating electronic sensors for high-energy X-rays, gamma rays, charged particles, and neutrons that can make measurements in time periods as short as one-trillionth of a second and over distances as small as one-millionth of a meter, as well as withstand greater levels of radiation than they can today.

PRO 3: Develop state-of-the-art lasers, targets, and diagnostics for HRR HEDP facilities.

Scientific Challenges

HEDP would be revolutionized by the ability to survey the vast range of plasma temperatures, densities, and ionization states in HRR laser experiments. HRR facilities will be the majority of small- and mid-scale facilities built in the coming years; to take full advantage of these facilities, the community needs to invest now in diagnostics that can operate at the same rate as the laser. The community also needs advanced systems to analyze, digest, and display this data in a fashion that best uses the facilities' infrastructure. This is important for several reasons: Matching the diagnostic rate to the facility allows for much more data to be obtained during the available beam time, maximizing facility productivity in a time of decreasing availability. Additionally, having rep-rated diagnostics increases the statistics for all experiments. Rep-rated diagnostics will also allow much faster alignment and testing, maximizing the gathering of data during a given beam time. Finally, having experimenters getting used to the idea of collecting more data on a single beam time leads to increased awareness about that data as to how to use it in the moment, how to store it for later, and how to analyze it efficiently offline, creating a pipeline for faster scientific progress.

A significant portion of the currently available diagnostic suite for HEDP- and ICF-relevant plasmas are intrinsically low repetition due to the use of analog detectors such as X-rays or optical film, radiochromic film, image plates, and CR-39. All require some time to either develop, scan, or both. While these detectors offer a high-dynamic range, are robust to electrical noise and background radiation, and some can differentiate between heavy particles (ions/neutrons) and photons, their data return can take tens of minutes to weeks, depending on chamber access requirements and handling. This precludes any type of rep-rated experiments unless these detectors are used to integrate many shots, which has value on small-energy systems but loses value as the energy of the driver goes above about 1 to 5 joules. Any high-power system that can fire more than once every few minutes will likely need new electronic detectors to replace these current workhorses. Development is needed in robust detector technology that can read out at up to 10 Hz, handle large bandwidth data pipelines and possibly on-chip processing, which can allow rapid analysis tools capable of extracting meaningful information from diagnostics, as well as summarize the output of multiple diagnostics to provide deeper insight.

Measurement Innovations

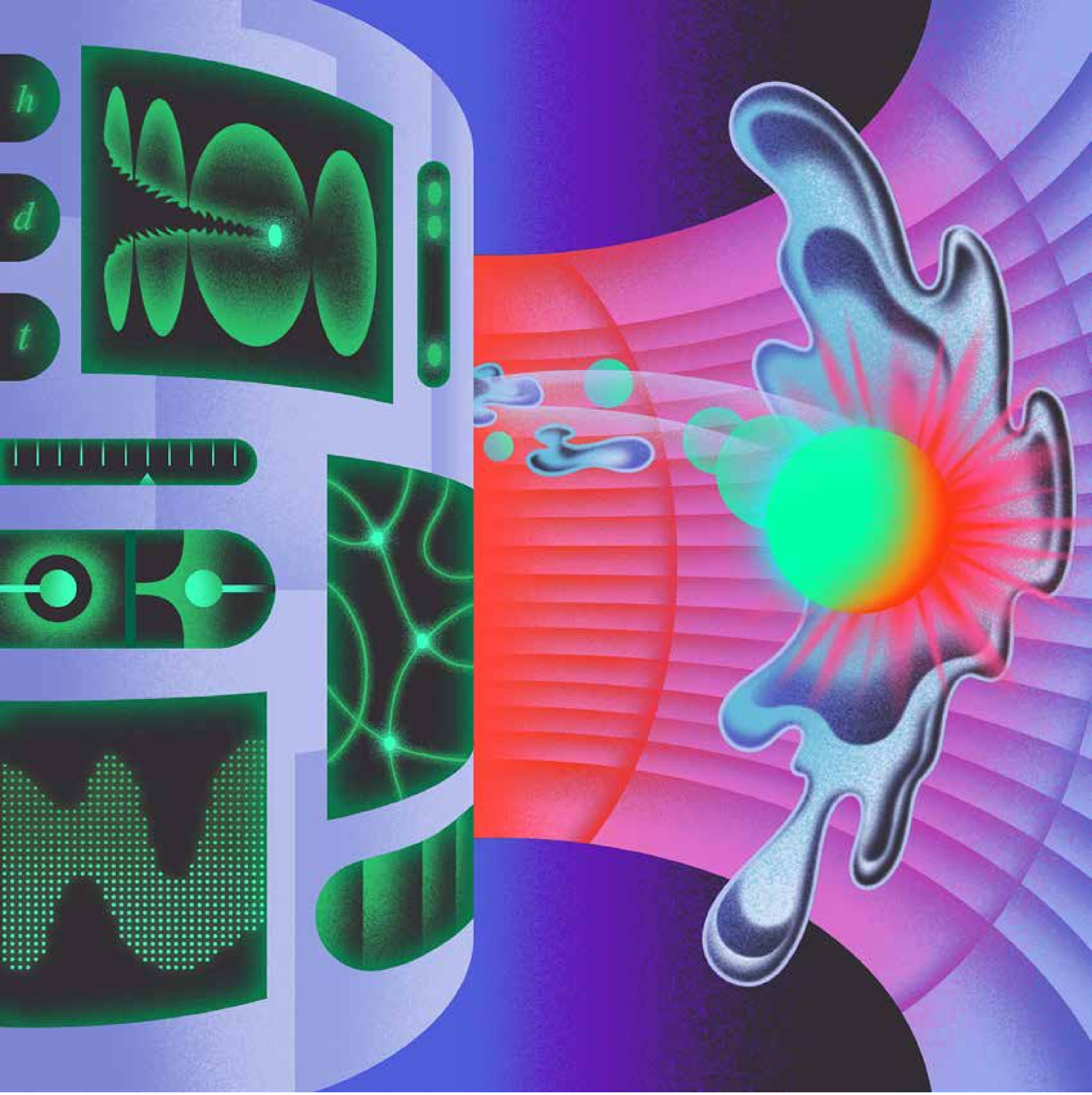
To meet the above challenges, the HEDP community should pursue the following strategies:

- Synthesize diagnostic systems with HRR-compatible detectors that meet or exceed the performance of current low-rep-rate HEDP measurements. Many available and reliable detectors currently being used take from tens of minutes to weeks to develop and/or analyze; thus, these detectors need to be faster and also highly reliable to maximize facility and experimenter time efficiencies.
- Develop repeatable, well-characterized source probes (X-ray and charged particles) that satisfy the needs of HEDP measurements at HRR. These sources must have HRR and be reliable in terms of availability, well characterized, and stable for maximum usefulness. X-ray, electron, ion and neutron sources, as well as inverse Compton scattering sources (photons scattered off an electron beam) would increase the ability to more fully and accurately characterize the plasma conditions produced at these facilities.
- Reimagine data acquisition systems, data stream management, and data visualization to allow real-time analysis and decision-making to optimize experimental and facility time. Develop systems that can analyze data in real time and display it in a way that can allow researchers to decide how to configure the next round of experiments.
- Examine and refine automation and target delivery to meet the challenging demands of HRR operations. Opportunities exist in this space to demonstrate the technology that will be used in next-generation laser facilities. Feedback loops and improved control systems could enable auto-alignment of diagnostics and targets. Taking advantage of these opportunities will require the ability to semi-autonomously vary diagnostic configurations across safe ranges of operating parameters during sequences of experiments.
- Use modern data science methods (including AI/ML) to optimize data return, diagnostic utilization, and scientific discovery for both large-single shot and small, HRR facilities. Improving data analysis using modern techniques, including AI/ML, to understand the large amounts of information that will be gathered from future experiments is needed.
- Develop new methods and leverage existing methods from other fields to maximize the use of data-rich diagnostics. Increasing the number of diagnostics and the amount of information they can gather is not useful until data analysis can synthesize that information. The community must develop methods that promote a consensus of physics interpretations that are compatible with multiple, simultaneous measurements. The community must develop and optimize methods for data-stream synthesis, such as Bayesian statistics, forward modeling, multi-objective optimization, and digital twins coupled with synthetic diagnostics.

– Use AI/ML to increase our understanding and extract more information from these naturally complex systems. AI can already recognize complex patterns, outperforming humans as datasets increase in dimensionality and complexity. As a result, the HED field should deploy new ML methods and stay abreast of developments in other fields so researchers can find trends in data, even when low signal-to-noise or spatiotemporal blurring complicate data analysis.

– Develop new methods that incorporate ML to accelerate knowledge gains. As facilities adapt to HRR operations, scientists no longer have the luxury of spending months analyzing each experimental data point. The turnaround from measurement to interpretation must be dramatically shortened. ML and data-reduction techniques may be pivotal in rapidly isolating important aspects of the data, as is on-shot, preprogrammed data visualization that allows experimentalists to understand their data as it is generated.

– Develop and support common data archiving, shared systems such as databases, and common formats to increase community access to valuable data to realize the dividends of communal data analysis and innovation. Data archiving, labeling, and storage in the era of HRR is a necessity. Scientists cannot fully utilize data that is not well organized; facilities and scientists must together adopt the best practices already in use in other fields. Better data storage and formatting improves multi-institution collaborations, simulation-data comparisons, and the capabilities of scientists to fully leverage their physics-rich measurements.



CHAPTER 3

Plasma Material Interaction

Introduction

Plasma material interaction (PMI) diagnostics have evolved tremendously over the last century. Ernst Ruska, a German electrical engineer, invented the electron microscope in 1931, the most widely used diagnostic in PMIs and surface science. Since then, innovations in the technology of X-ray photoelectron microscopy and Auger electron spectroscopy, along with ion-beam techniques (e.g., secondary-ion mass spectrometry, low-energy ion scattering), Rutherford backscattering spectrometry, and nuclear reaction analysis (NRA), have led to today's state-of-the-art materials diagnostics. Most of these ex situ diagnostics are used to investigate changes to materials and surfaces after exposure to plasmas at a location away from the plasma facility conducting the experiment. While ex situ diagnostics are very powerful in combination with single-effects plasma exposure experiments, interpreting ex situ data is difficult for material exposures in actual fusion experiments. Here, data are often integrated over an entire campaign or at least over a plasma pulse with significant temporal variations in the exposure conditions (e.g., heat flux, temperature, and impinging ion energy). Also, transporting the material sample from the exposure location to the off-site diagnostic facility typically takes time, exposing the sample to ambient air and altering the surface's chemical composition. With the exception of those surface diagnostics used for investigating activated materials for which normal user facilities are unavailable, measurement innovations are not needed for these ex situ diagnostics.

Using in vacuo diagnostics, where the material sample is transferred from the exposure location in a vacuum to a surface diagnostic instrument, is a great improvement for characterizing the chemical nature of the surface and characterizing hydrogenic uptake and retention in materials. In situ, or even better, in operando diagnostics can be used in laboratory experiments with multiple surface diagnostics during the exposure of materials with ion beams or low-intensity plasmas. This approach is not often realized during fusion plasma exposures due to the presence of very high magnetic fields, heat fluxes, and radiation fields. In situ and in operando diagnostics are usually based on optical emission spectroscopy passively tracing erosion products in the plasma.

Innovative, active-laser diagnostics are being developed and tested today to probe: 1) material composition (e.g., laser-induced breakdown spectroscopy (LIBS), laser-induced ablation spectroscopy (LIAS), laser-induced desorption spectroscopy (LIDS), 2) chemical nature (e.g., near-infrared and Raman spectroscopy and sum frequency generation spectroscopy), and 3) erosion products in the plasma (e.g., two-photon absorption laser-induced fluorescence (TALIF), laser-induced fluorescence, and cavity ring-down spectroscopy). These diagnostics are used on linear plasma devices simulating plasma conditions in a fusion reactor, where optical access is easier than in actual fusion reactors. However, many of these diagnostics have not been developed to the capability needed for delivering reliable data under fusion-relevant plasma exposure conditions. Thus, the goal of PMI measurement innovations is to advance the in situ and in operando diagnostics by 1) adapting existing ex situ diagnostics to have new deployment capability, and 2) innovating and developing new disruptive diagnostics with high-temporal and spatial resolution.

Retrospective

The plasma community has published two reports about the state of PMI diagnostics: "Report on Science Challenges and Research Opportunities in Plasma Materials Interactions" (Maingi 2015) and "Powering the Future: Fusion & Plasmas" (Carter 2020). The main findings of these reports are summarized below.

The Maingi report contains a comprehensive discussion about facilities, which is briefly summarized in the following paragraphs. Determining the maximum steady-state heat and transient fluxes, along with operating temperature windows for actively cooled plasma-facing components (PFCs), requires the use of high-heat-flux facilities (i.e., e-beams, plasma-arc lamps, or high-repetition dense plasma foci). The community would benefit by upgrading these devices so they can test neutron-irradiated materials and components. High-temperature, liquid metal (LM) facilities being used for closed-channel blanket magnetohydrodynamic (MHD) experiments (e.g., MHD toroidal research and magnetized plasma linear experimental) can also be upgraded to accommodate free surface-flow and heat-transfer experiments. Instrumentation upgrades for measuring flow that are compatible with high-temperature LM alloys are an essential element. Upgrades and applications of existing accelerator-driven neutron sources (e.g., the Spallation Neutron Source and the Moderator Test Station) with suitable material test stations (i.e., temperature-controlled irradiation conditions) would give more prototypical high-energy neutron damage data (i.e., high-helium concentration and displacement per atom ratio).

The community would also benefit from upgrading existing linear plasma facilities like the Plasma Interaction with Surface Component Experiment and the Tritium Plasma Experiment (TPE) to enhance one or more features to be more prototypical of next-step devices. Enhancements could include heat flux, particle flux, transient loading capability, actively cooled samples, ion-energy improvements, and improved diagnostics. Upgrades to existing toroidal facilities could test a broader range of LM concepts and provide more reactor-relevant plasma environments.

Such upgrades are particularly important for improved testing of transient events such as edge-localized modes (ELMs) and disruptions. Experiments with plasma guns are of limited interest since those guns have plasma pressures that are orders of magnitude higher than those expected in a fusion device; in contrast, the stored energy in current tokamaks is too low. To progress in this area, it's crucial to develop new, dedicated facilities combining pulsed energy and particle sources with relevant plasma conditions in terms of particle flux and energy (i.e., high, stored energy) while having low gas pressures. For a non-melted solid surface, particles might be ejected during transient events, especially when surface cracking occurs, for example, because of the repetitive thermal shock during ELMs. While negligible today, in future devices that operate with high-duty cycles, this effect might become important for the lifetime of the divertor material. A facility capable of operating at high fluence with combined quiescent and transient plasma conditions would enable one to study and understand these effects under relevant timescales.

Simulating ELM-like transient events similar to those occurring in a fusion reactor is challenging. Existing toroidal devices cannot deliver the anticipated power loads; however, dedicated pulsed power test stands (e.g., e-beams, lasers, plasma guns) can access the relevant energy flux density. Linear plasma devices have proven capable of providing useful information in testing materials exposed to steady-state plasmas and transient heat and plasma loads simultaneously (e.g., Magnum-PSI (plasma-surface interaction) in the Netherlands). Simultaneous testing of periodic ELM-like heat flux in conjunction with steady-state, reactor-relevant plasma and heat flux on neutron-irradiated material samples requires a new linear plasma facility.

This report also discussed material limits. Scientists in the PMI field try to determine the peak transient heat flux that a component can survive, given the armor properties and cooling capabilities of the heat sink and the duration and footprint of the transient event. Melting and thermal fatigue leading to cracking and erosion are critical issues, especially for the armor material, and this sets the threshold for the number of such survivable events. Simulations using transient computational fluid dynamics solvers, dynamic thermomechanical solvers, and kinetic Monte Carlo codes like the HEIGHTS package are necessary for design analysis and optimization.

These experimental activities to understand material limits would be similar to steady-state loading for solid and liquid PFCs. They would utilize the same facilities, albeit with loading durations and magnitudes that simulate the range from those typical of the component thermal response time, from slower speeds, measured in seconds, to higher speeds, measured in milliseconds. LM experiments have an additional challenge in this area: the capability to simulate transient magnetic field and halo current impacts on liquid surfaces, which needs more assessment. Extremely high-heat-flux, pulsed, high-duty-cycle and high-availability test beds are required for these studies. Fast-response diagnostics like fast-response infrared and laser diagnostics and spectrometers using fast focal-plane array detectors are critical components of this research. Real-time evaporation monitors are required for LMs. In addition, the transient and steady-state loading perturbations on the components must be superimposed to investigate the true environment. This requires a high level of integration between the low-duty cycle test apparatus and the pulsed device. Plasma surface heating is one example of synergistic testing required for a PFC qualification program. Others may include simultaneous neutron irradiation, neutral beam particle or radio frequency (RF) heating effects, or simultaneous, short-duration electromagnetic-induced mechanical loading.

The report also noted that repeated thermal transients can lead to surface cracking, which can increase outgassing, influence recycling properties, and lead to material ejection. To address these issues, it is essential to determine how cracking depends on neutron embrittlement and the magnitude of transients. Even refractory metals, the leading solid PFC candidates, might melt during transients. Consequently, melt-layer movement and droplet formation are important research topics to study for solid and liquid PFCs during transients. Data on the material response to transients of up to 108 ELMs needs to be examined to minimize the impact on confinement and stability.

The Carter report reflects the priorities of the national fusion and plasma communities and provides a distillation of the community's discussions regarding, among other topics, PFC management (Fusion Science and Technology (FST) Strategic Objective A) and diagnostic development (FST Program Recommendation E). The greatest concerns for PFC management relate to finding ways to protect PFC solutions from the extreme heat flux and particle loads expected in a fusion pilot plant (FPP). There is a need to better understand the conditions experienced by first-wall materials in currently operating experiments to effectively design PFC solutions for an FPP first wall. The conditions at the first wall that need to be better assessed include charge-exchange neutral flux, composition, and energy spectrum; ion flux to the first wall; and the resulting first-wall erosion rates and redeposition/co-deposition elsewhere. Improved diagnoses of these properties will enable more effective comparisons and validation with impurity transport modeling of the plasma at the scrape-off layer (SOL), which could enable more accurate predictions of long-term particle migration, the evolution of the fuel inventory stored in PFC materials, and the operational lifetime of divertor targets.

The report identified the need to continue developing and improving the deployment of in situ and ex situ material characterization tools. When used in confinement experiments and plasma-exposure platforms, these new tools could evaluate PFC performance more rapidly than current tools. The community should also focus on giving in situ diagnostics the ability to monitor the dynamic evolution of the surface composition and structure. The information gained from these diagnostics must then be linked to conditions in the SOL plasma as measured by edge-plasma diagnostics. The continued advancement of SOL plasma modeling tools should enhance the ability to link the edge-plasma conditions to the changes observed in the PFCs.

After the publication of the Carter report, researchers identified areas in which diagnostic development is most needed. Developing in situ measurements to monitor the dynamic evolution of the PFC surface and bulk under the combined effects of heat flux, plasma flux, and neutrons represents possibly the largest challenge. Another concern is hydrogen retention and permeation, which could affect operation and licensing of the FPP. In addition, the community needs more accurate measurements of tritium transport parameters, tritium trapping energies, and recombination rates. There is also a need for new measurement approaches to track surface composition and surface morphology changes in situ to rapidly evaluate PFC evolution.

In cases where in situ diagnostics may not be possible, plasma exposure stages located off-site may offer the opportunity to study more limited combined effects. In fact, there has been extensive development of sophisticated ex situ diagnostics capable of observing changes in material structure down to the atomic scale. Researchers should continue advancing these techniques to determine if they can be made available for in situ or in vacuo measurement capabilities. Moreover, researchers must continuously improve SOL diagnostics to increase the accuracy and precision with which the incident particle fluxes and heat loading can be measured under the intense conditions of a reactor scenario.

Current Status

Since the publication of the Maingi and Carter reports, there have been new developments to consider for defining the priorities of PMI diagnostics. These developments include the following:

- The explosive development of the private fusion industry.
- The ITER rebaselining and the associated change of the ITER first wall from Be to W.
- The construction of the Material Plasma Exposure eXperiment (MPEX).
- The emerging international program, in particular, the Spherical Tokamak for Energy Production and the Burning Plasma Experimental Superconducting Tokamak (under design/construction), JT60-SA's first plasma, and the more mature operation of the Wendelstein 7-X (W7-X) and the Tungsten (W) Environment in Steady-state Tokamak.
- The explosive development of machine learning and AI.

A 2023 workshop organized by the Electrical Power Research Institute on fusion materials road mapping held in Charlotte, North Carolina, provided fresh insights into PMI studies. Participants discussed the readiness of tungsten-based PFCs, silicon carbide, and ultrahigh temperature ceramics for solid PFCs. Participants stressed the need to study surface evolution over a long time and felt that researchers should examine realistic surface compositions in a fusion reactor, including dust formation due to long-range migration from other areas in the fusion reactor. The participants agreed that to advance the science of PMI, they should look at the physical and chemical processes both in situ and in operando. In addition, to allow for reliable extrapolations to conditions in a fusion reactor, the operational domain of current experimental devices needs to be extended to higher ion and heat fluxes, higher ambient temperatures (hence, higher surface temperatures), and a higher level of integration of physics effects.

The facilities to exploit PMI science of the above-mentioned materials in the next 10 years are as follows.

National Facilities

- Hybrid Illinois Device for Research and Applications, currently operating — liquid lithium plasma exposures
- PISCES-RF (University of California, San Diego), currently operating — ion irradiation and plasma exposure
- National Spherical Torus Experiment-Upgrade (NSTX-U) (Princeton Plasma Physics Laboratory (PPPL), operation schedule to be determined — LM PFCs in a confinement device

- MPEX (Oak Ridge National Laboratory (ORNL)), operating after 2028 — high fluxes, high fluence, and high levels of integration
- Divertor Material Evaluation System (DiMES), currently operating in the DIII-D tokamak
- TPE, currently operating at the Idaho National Laboratory

International Facilities

- WEST (French Alternative Energies and Atomic Energy Commission), currently operating — tungsten migration and dust formation
- Upgraded Pilot PSI (Dutch Institute for Fundamental Energy Research), currently operating — in situ and in operando NRA and high-flux plasma for hydrogen retention
- JULE-PSI (under construction) plasma exposures of neutron-irradiated materials
- Experimental reactors in Asia and Europe with material probes, including the Experimental Advanced Superconducting Tokamak (EAST), Korea Superconducting Tokamak Advanced Research, JT-60SA, W-7X, and the Mega Amp Spherical Tokamak Upgrade
- Purposefully built PMI machines in support of ITER, including the Divertor Tokamak Test facility

Deploying in-vessel, in vacuo, in situ, and in operando diagnostics to these facilities should be a goal. In vessel denotes measurements made on materials while they are within the vacuum vessel of the fusion device. In vacuo is the analysis of materials, either those within the vacuum vessel of the fusion device (between plasma shots, without venting to air) or those that have been transported to a separate analysis chamber without ambient air exposure. In-vessel and in vacuo measurements are fairly clearly defined; however, in situ and in operando classifications are often used interchangeably. For clarity in this report, we distinguish between in situ and in operando measurements as follows.

- In situ refers to analyzing material within the reaction mixture or the environment relevant to the operating system. Examples are analyzing materials immersed within the liquid solution in an electrochemical cell, the high temperature and gas pressure in a catalytic reactor, or the plasma discharge in a fusion device.
- In operando refers to the analysis of material within the environment of an operating system, combined with simultaneous measurements of the system. Researchers use this information to correlate properties like structure or composition to the system's performance under working conditions, enabling structure-function

correlations for the system. An example is the characterization of an oxide film on an electrode in a water-splitting device that has an applied bias of 1.5 V such that it is actually evolving oxygen and hydrogen gas simultaneously. For fusion devices, an example would be an analysis of the wall-surface composition during a plasma shot in PPPL's Lithium Tokamak Experiment-*Beta* (LTX-β) while the electron temperature or number density in the plasma edge is being measured simultaneously.

Therefore, in operando diagnostic measurements are those performed on an "active" surface or device while it is being modified or is operating under realistic (working) conditions, in order to monitor real-time structural, chemical, or functional changes. Shetty and Allain (2017) use in operando to emphasize characterization of active surfaces during their actual modification by the environment (for example, during plasma exposure), rather than only before/after or in a static, ex situ state. In operando techniques also capture time-resolved surface and subsurface evolution under real operating conditions and, therefore, reveal dynamics (reaction intermediates, transient phases, real-time sputtering/adsorption, etc.) that ex situ or merely in situ (controlled environment but not necessarily under real operation) measurements can miss.

Priority Research Opportunities

The community submitted 18 PMI white papers. The proposed diagnostics were categorized by the operating conditions for PMI analysis (i.e., ex situ, in vacuo, in situ, and in operando). The white papers were then categorized based on topics, including photon-based diagnostics, miscellaneous diagnostics, measurement needs, and policy white papers. A general finding was that most diagnostics proposed were based on established techniques, and the proposed innovation was mostly incremental. Exceptions were related to new and more widespread deployments of established diagnostics into fusion systems for in situ and in operando measurements. Many of the proposed diagnostics have been used before, but they would benefit from the advancement of hardware capabilities (i.e., more intense and compact lasers, more sensitive detectors, advanced optics, etc.). Others are well established but have not been used in the context of fusion materials (i.e., Mössbauer), and others represent new ideas for MEMS-based sensors embedded on PFCs.

The community identified several opportunities for breakthroughs. Researchers agreed that there would be many benefits to improving in vacuo characterization of materials on a retractable material probe that measures the atomic composition and chemical nature of materials with the sensitivity and resolution of stand-alone, high-performance surface-analysis instrumentation. The community should also explore implementing advanced LIBS modes to measure the in operando surface composition of plasma-facing surfaces.

Breakthrough measurements for measuring hydrogen PMI are critical for assessing key parameters for the fusion plant fuel cycle, such as the tritium-breeding ratio requirement when designing blankets or the accumulated tritium activity in PFCs. The ability to quantify hydrogen retention and permeation in plasma-facing materials (PFMs) during plasma exposures is, therefore, a key measurement for tritium inventory management. For the investigation of evolving surfaces, developing existing diagnostics and new techniques that can be integrated into limited-access regions within fusion reactors is essential.

Rapid scanning of plasma-shadowed regions for dust accumulation using lasers, X-rays, and visible cameras could provide invaluable information. Pump ducts are a particularly large concern for dust buildup and tritium accumulation. Improved data processing workflows to more rapidly interpret the large amount of information coming from cameras, sensors, and detectors would amplify the progress in our scientific understanding significantly. Furthermore, in situ evaluation of changes in the thermal conductivity of PFCs over long periods of time is needed.

Fast diagnostics for in operando imaging of the time evolution of crack formations on PFCs during transients would advance the field significantly. This process would include in operando quantification of material redeposition (net erosion) in real time during transients. Developing test stand facilities with realistic transient pulses of plasma heat flux and particle flux/energies to study single and multi-processes effects would help in this research area. Finally, the community needs new diagnostics to monitor LM surfaces. These new instruments would include camera systems and perhaps also X-ray diagnostics.

This section presents the seven priority research opportunities (PROs) generated by the PMI working group, which highlight scientific challenges and measurement innovations in PMI.

PRO 1: Characterize the evolution and steady state of the surface composition in all the fusion reactor internal surfaces and enable understanding of material flows within the plasma-wall interface.

Scientific Challenges

The surface composition of materials that interact strongly with the plasma can profoundly impact operations. Impurity generation, formation of mixed material, and a fuel recycling regime are examples of the strong interrelationship between plasma performance and surface composition. The transport of eroded material may lead to plasma cooling if the impurities can cross the separatrix or redeposition of eroded material in remote areas. The risk of forming macroscopic impurities such as dust or flakes increases as this loosely bound, redeposited material is exposed to the plasma. Therefore, to avoid these unwanted occurrences, researchers must use diagnostics to monitor what is happening in this plasma-material-border region.

To use diagnostics in this way, scientists must answer the following questions:

- What techniques can scientists use to monitor material surfaces in small fractions of a second during a device’s operation?
- How can scientists use AI tools to predict plasma performance?
- Which measurements would help scientists monitor and control PMIs?
- How can scientists assess the performance of wall-conditioning treatments?

One notable diagnostic currently used in this field is LIBS, which can both measure and clean surfaces. This technique involves off-the-shelf components and has multiple variations; those variations could be part of future plasma-material monitoring efforts.

Other instruments that could aid future diagnostic efforts are so-called “material probes” enabling the placement of witness plates at specific locations in the vacuum vessel that are often accessible to complementary diagnostics. The plates can be removed and analyzed either ex situ or in vacuo utilizing a vacuum transfer system without the need to vent the entire device. These probes have even been upgraded with the capability of specific surface analysis techniques in a vacuum chamber connected to the main device. One drawback is that the sensitivity and resolution routinely available in ex situ surface analysis are very difficult to achieve on these analysis stations due to the space restrictions and high-magnetic fields in fusion machines.

Measurement Innovations

To meet the above challenges, the PMI community should pursue the following strategies:

- Improvements to in vacuo measurements of materials by building a retractable material probe that provides information about the atomic composition and chemical nature of materials. This probe would have the sensitivity and resolution of stand-alone, high-performance surface analysis instrumentation.
- Exploring the use of advanced LIBS techniques to measure the in operando surface composition of plasma-facing surfaces.
- Explore upgraded in vacuo systems in fusion devices by deploying various state-of-the-art surface diagnostics.
- Develop in situ and in operando diagnostics for assessing the chemical status of internal surfaces.
- Develop in situ and in operando diagnostics for quantifying incoming (implantation, redeposition) and outgoing (erosion, evaporation) particle fluxes.

PRO 2: Understand and enable prediction of hydrogen retention and transport in plasma-facing materials.

Scientific Challenges

Hydrogen isotope management in a fusion reactor or an FPP is integral to fuel cycle performance as well as safety considerations. While numerous PMI phenomena must be considered within this area, they largely stem from concerns related to tritium retention. A fusion reactor will likely be regulated for a total site inventory. Ideally, all tritium would be used as fusion fuel, but over time, tritium will accumulate in PFCs and other systems. This retention and the movement of dust contaminated with tritium counts toward the total amount of tritium on a FPP site's inventory and, therefore, must be assessed and mitigated. Migration of dust and hydrogen co-deposition must be considered. Tritium retained in PFCs may stay within the material, permeate through the material, or desorb from the first wall or the backside of the PFC. Therefore, the important physics for understanding tritium behavior in PFCs include retention, permeation, and extraction. It is noteworthy that much about these phenomena has been known and investigated for many decades. Future research is required to enable in situ characterization of hydrogen in PFCs and to determine the extent to which these measurements are required for FPP operation.

These challenges raise the following research questions: 1) How much tritium is retained in PFCs under FPP conditions and fusion reactor conditions? 2) What is the effect of coating the PFCs with boron (i.e., boronization) on tritium retention? Other relevant, but lower priority elements to study are lithium and silicon. 3) What is the dependence of PFC tritium retention, under FPP and reactor-relevant conditions, when dust and hydrogen co-deposit on its surface? 4) How much tritium permeates into blanket structural materials and coolants under reactor-relevant conditions?

The primary diagnostics that are commonly used for measuring retention in PFCs include thermal desorption spectroscopy (TDS) and NRA. These techniques are not compatible for in situ or in-vessel reactor measurements. LIBS and LIDS have been developed to investigate retention and have significant potential for in-vessel reactor measurements. MEMS may someday be designed to provide indirect measurements that could potentially elucidate retention behavior. Hydrogen permeation measurements are performed in offline laboratory experiments and are not well suited for in-vessel reactor use. PMI retention behavior in solid and liquid metals must also be studied using offline experiments like the TPE at the Idaho National Laboratory and, by the end of the decade, the MPEX at ORNL.

Breakthrough measurement innovations for the interaction between hydrogen and PFCs would include:

- The ability to quantify real-time hydrogen retention in PFMs during plasma operations.
- The ability to quantify hydrogen permeation in PFMs during plasma exposure.

Measurement Innovations

The PMI community should develop diagnostics that can measure how tritium permeates PFCs and is retained in them under FPP and reactor-relevant conditions in real time.

PRO 3: Advance the understanding of evolving PMI surfaces in multispecies plasma.

Scientific Challenges

Another challenge in the PMI realm is monitoring the composition of PFC surfaces, a crucial factor in operating fusion devices. The surfaces can constantly change as a result of several effects. First, the implantation of hydrogen isotopes and helium into the surfaces of PFCs causes surface stresses that can lead to dislocation loops and other defects that then trap the implanted atoms further. These defects and stresses, in turn, lead to further stress-induced vacancies, which then migrate deeper into the surface and act as further trap sites. This sequence of events can change the surface's structure by forming nanobubbles, supersaturated layers, fuzzy nanostructures, and blisters, among others, leading to the surface having new properties that could interfere with the fusion reactions. The morphology developed will almost certainly exhibit different material properties to the original engineered surface (e.g., thermal and diffusive transport, erosion, etc.). Likewise, multispecies plasma interactions (deuterium/tritium), helium, conditioning species (boron), radiative admixture species (argon, neon) and impurities (oxygen, nitrogen, etc.) can implant within a surface and lead to different rates of erosion. These phenomena result in a surface composition that is constantly changing and different from the original design specifications. Therefore, to predict the performance of surface materials, scientists must measure the structure and composition of those surfaces, especially while the fusion device is operating.

These measurements are difficult to make, however, because there is limited access to these surfaces and the environmental conditions are extreme. The measurements are also hindered by specific confinement geometries and conditions and because the PMI effects that cause the surface changes happen on a variety of timescales.

These scientific challenges raise the following questions:

–Under which conditions do surface structure changes lead to changes in the properties of the surfaces that exceed design specifications and cause macroscopic erosion or deposition?

–Could scientists measure erosion and deposition in plasmas with many kinds of atoms and ions, and then use that information to confirm the erosion and transport properties of existing materials?

Current diagnostic techniques for measuring PMIs include the following:

–Ion-Beam analysis (IBA): Surface compositional changes in operando.

–Digital Holography: Surface morphology change in real time.

–LIBS: Surface composition in operando.

–LIDS: Hydrogen retention in situ.

–Mössbauer Spectroscopy: Isotopically monitor bonding changes in specific materials (e.g., tungsten) ex situ.

Current facilities that allow PMIs include the following:

–MPEX: divertor relevant PMI on activated materials with good diagnostic access.

–POSEIDON: PMI platform with good diagnostic access and ability to simultaneously damage material targets with high-energy ions.

–TPE: PMI with tritium.

–Dynamics of ION Sputtering and Implantation On Surfaces: PMI linear plasma testing with good diagnostic access and in-operando IBA.

–DIMES: material evaluation in tokamak plasma environment.

Opportunities for breakthrough in understanding include:

- Adapting existing diagnostics to operate in high-performance confinement experiments or their proxies.
- Building dedicated platforms or mounts within magnetic confinement fusion devices to hold PMI diagnostics.
- Integrating diagnostics within limited-access regions inside fusion reactors.

Measurement Innovations

To meet the above challenges, the PMI community should pursue the following strategies:

- Develop in operando measurement techniques that monitor the surface composition and morphology of PFCs under high temperatures and magnetic fields as plasma devices are operating.
- Develop in situ and in operando diagnostics to study the erosion of surfaces of PFCs as plasma devices are operating.
- Adapt existing diagnostics so they can operate in high-performance experiments or their proxies.
- Build dedicated platforms or mounts within magnetic confinement fusion devices to hold PMI diagnostics.
- Place diagnostics in limited-access areas within plasma devices.

PRO 4: Assess the long-term evolution and degradation of PFCs due to device operations and the impact on whole-device operation by dust accumulation and PFC degradation and failure.

Scientific Challenges

Long-pulse and steady-state operation of fusion devices will degrade PFCs through neutron damage and plasma-induced erosion. The net erosion of PFCs will create debris composed of micron-scale particulates, or dust, that can accumulate into piles in particular regions within the device. These piles will threaten operations because they can retain tritium and be easily liberated and swept into the plasma, interfering with fusion reactions. Moreover, extended periods of PFC plasma exposure, thermal cycling and neutron damage will change the structure of PFC surfaces, cause swelling, produce voids, cause microcracks, and change how well the material conducts heat.

Therefore, the community needs new diagnostics to monitor impurity accumulation in plasma-exposed and plasma-shadowed regions of fusion reactors. The amount and distribution of dust in the device will let scientists know how frequently cleaning cycles should occur and help them produce more accurate estimates of the amount of tritium on-site by accounting for the tritium in mobile dust particles. And though researchers can use current tools like visible cameras and laser alignment instruments to look for large surface changes, they will need new techniques to analyze all of the data gathered by these instruments.

Also, scientists have typically only been able to measure subsurface changes to PFCs using techniques that must be performed off-site. But future diagnostics will increasingly need to be able to evaluate the severity of subsurface damage in situ and possibly in operando. Current diagnostics include quartz crystal microbalances and digital holography.

Opportunities for breakthroughs in understanding include the following:

- Finding ways to rapidly scan plasma-shadowed regions for dust accumulation using lasers, X-rays, and visible cameras. Pump ducts are a particularly large concern for dust buildup and tritium accumulation.
- Improve data processing workflows to more rapidly interpret the large amount of information coming from cameras, sensors, and detectors.
- In situ evaluation of changes in thermal conductivity of PFCs over long periods.

Measurement Innovations

To meet the above challenges, the PMI community should pursue the following strategies:

- Develop compact and resilient sensor technology to assess dust accumulation in multiple regions.
- Develop in situ diagnostics to efficiently survey PFCs throughout an operational campaign and assess PFC degradation in a way that requires minimal operator supervision.

PRO 5: Increase understanding of how neutrons affect the surfaces of components and the underlying bulk material structure.

Scientific Challenges

Defect production in the PMI near-surface region caused by high-flux/high-fluence plasma-ion implantation, induced stresses, and the production of stress-induced vacancies, which can then migrate deeper (~ microns) into the material and act as trap sites for gas atoms, drives many PMI effects (deuterium supersaturated surface layers, fuzz, blisters, etc.). Neutrons will produce defects within PFMs, not only in the surface, but also deeper within the material by energetic particle-induced displacement damage cascades, helium production, and transmutation. Study of the synergy of neutron effects with PMI is an emerging scientific focus as the diffusion, trapping, and de-trapping of dissolved gas atoms within the complex of defects, and the migration, merging, and annihilation of vacancies, voids, and larger defects is unclear. Impact on tritium self-sufficiency and the evolution of the thermomechanical properties of the PMI interface and underlying PFC will require in operando measurement and monitoring.

These scientific challenges raise the following research questions:

- How do the first wall and divertor target material properties change under simultaneous plasma and neutron irradiation?
- Could scientists measure how first wall and divertor materials would possibly withstand neutron damage?
- Could these materials survive the simultaneous effects of plasma irradiation and displacement damage under high temperatures and heat flux and remain compatible with tritium breeding?
- Could researchers predict the evolution, distribution, density, and trapping energies of trapped deuterium and helium atom populations?

Current diagnostic techniques for measuring PMIs include the following:

- Transient Grating Spectroscopy: This nondestructive laser pump-probe technique measures the elastic modulus and thermal diffusivity.
- Positron Annihilation Spectroscopy: This technique probes structural defects in solids.
- Ion Scattering/NRA: These methods measure surface composition.
- Diffuse X-ray Scattering: This technique measures lattice defect distributions and changes.

Current facilities that allow PMIs include the following:

- MPEX: Allows the measurement of divertor-relevant PMI on activated materials with good diagnostic access.
- POSEIDON: Has a PMI platform with good diagnostic access and the ability to simultaneously damage material targets with high-energy-ions.
- TPE: This device allows measuring the effects of tritium on PMI.
- MegajOule Neutron Imaging Radiography Experiment (MJOLNIR): This device generates plasma and radiation that could be relevant to fusion diagnostics and material testing.
- DiMES: This facility allows material evaluation in a tokamak environment.

Opportunities for breakthroughs in PMI understanding include the following:

- In operando measurement of material thermomechanical properties under actual or simulated neutron loads during plasma facility operation.

- Real-time quantification of hydrogen isotope retention in materials undergoing hydrogen isotope transport caused by PMI or permeation in regimes, including actual or simulated neutron loads.
- Development of models that predict changes in material mechanical properties, hydrogen isotope retention, and transport in integrated scenarios that include the effects of neutron damage.

Measurement Innovations

To meet the above challenges, the PMI community should pursue the following strategies:

- Develop neutron-resilient sensors to measure PFC thermomechanical properties, hydrogen isotope concentration, and material degradation under high temperatures and magnetic fields.
- Develop in situ/operando diagnostics to study the properties of PMI surfaces and component structures in environments that simulate fusion material aging in a burning plasma.

PRO 6: Determine the maximum tolerable transient heat and particle loads on PFCs.

Scientific Challenges

Melting and thermal fatigue due to repetitive transient heat flux events leads to microcracking of solid plasma-facing armor materials. Cracking reduces thermal conductivity, provides shortcuts to the surface for outgassing, influences recycling properties, forms leading edges, and can eventually lead to macroscopic material ejection. For liquid surfaces, melt-layer movement and droplet formation are key challenges during transients.

Data on material responses to transients of up to 10^8 ELMs is needed. Their plasma experiments must simulate a broad range of timescales, from seconds — the typical thermal response times — to milliseconds — the timescale for disruptions and ELMs. This research also requires extremely high-heat flux; pulsed, high-duty cycles; high availability test beds; and fast-response diagnostics like fast-response infrared and laser diagnostics and spectrometers that use fast-focal-plane array detectors with high-speed data acquisition and control. In addition, upgrades to existing toroidal facilities could allow testing of a broader range of materials and provide more reactor-relevant plasma environments. Preferably, scientists would simultaneously use both steady-state, high-heat-flux plasmas and frequent transient heat or ELM-like pulses to investigate a true fusion environment.

These scientific challenges raise the following research questions:

- Can we develop an ability to predict how the plasma core drives transient loads, durations, and pulse frequency onto the PFMs?

- What are the dominant PMI mechanisms driving the changes to PFM surfaces through repetitive transient heat and particle loads?
- How do these different mechanisms interact to determine PFM lifetime limits?

The impact of transients on PFMs is primarily diagnosed in operando via ultraviolet, visible, and infrared spectroscopy capable of inferring the material temperature evolution, neutral recycling rate, and gross erosion rate. Recycling and erosion rate measurements are limited by uncertainties in atomic data. Electrostatic techniques can be used to directly measure the incoming ion and heat flux during transients, although they are prone to failure due to rapid changes in current and voltage. Laser-based techniques can also measure plasma parameters at very rapid pulse rates (kHz). Robust X-ray techniques are required to diagnose inertially confined plasmas. Tokamak facilities such as DIII-D and NSTX-U provide realistic steady-state and transient heat loads. Angled samples protruding above the divertor surface, inserted using removable sample exposure probes like DiMES or the material analysis particle probe, can be used as a proxy to increase the heat and particle flux of ELMs while maintaining frequency and pulse duration. Linear plasma devices such as MPEX and the POSEIDON plasma focus facility can provide steady-state heat loading in combination with simulated transients (e.g., via pulsed laser heating). MJOLNIR provides another testing platform, but the relevance to fusion PMI is questionable.

Opportunities for breakthroughs in understanding include the following:

- Imaging the evolution of crack formations on PFCs during transients.
- In operando quantification of material redeposition (net erosion) in real time during transients.
- Building a test stand facility that can allow measurement of realistic transient pulses of plasma heat flux and particle flux/energies.

Measurement Innovations

To meet the above challenges, the PMI community should pursue the following strategies:

- Determine the number of survivable transient events for a given armor material, given the peak duration and footprint of the transient event.
- Validate physics-based, transient PMI modeling and simulation (e.g., computational fluid dynamics, dynamic thermomechanical, kinetic Monte Carlo).
- Perform experiments simulating a broad range of timescales ranging from seconds to milliseconds. Invent new techniques to detect cracks in PFCs.
- Invent new techniques to detect the redeposition of material during transient events.
- Build a facility that can allow measurements of realistic particle movement and pulses of plasma heat.

PRO 7: Develop material diagnostics that help accelerate the technological maturity of LM PFCs so that they can be deployed within a 10-year timeframe in a large confinement device.

Scientific Challenges

LMs are a unique option to traditional solid PFCs because the constant renewal of their surfaces allows them to self-heal. They can also remove deuterium and tritium atoms that have not burned up in the plasma so the fuel can be recycled. They can also retain and remove other impurities and inert gasses such as helium.

There are currently three LMs under serious consideration: lithium, tin, and a tin-lithium combination, along with some salts. All offer advantages and disadvantages. Some of the challenges that LMs face include operational temperatures, maintaining stable flows in magnetic fields despite MHD effects, distributing and collecting the LM over PFC surfaces, sufficiently covering the substrate of surfaces, and in operando monitoring surface and PFC subsystems during machine operations. If these challenges can be overcome, LM could become a serious contender for future fusion reactors.

These scientific challenges raise the following research questions:

- What is the most suitable LM for reactor operations?
- How much tritium and deuterium are retained in the LM PFCs under relevant reactor conditions?
- What are the effects of impurities on the performance of LMs under reactor conditions?
- How can the effects of LM MHD during relevant reactor operations be stabilized and minimized, and how can we measure and monitor these effects?
- How can in operando measurements be made to monitor the performance of LM surfaces during machine operations?

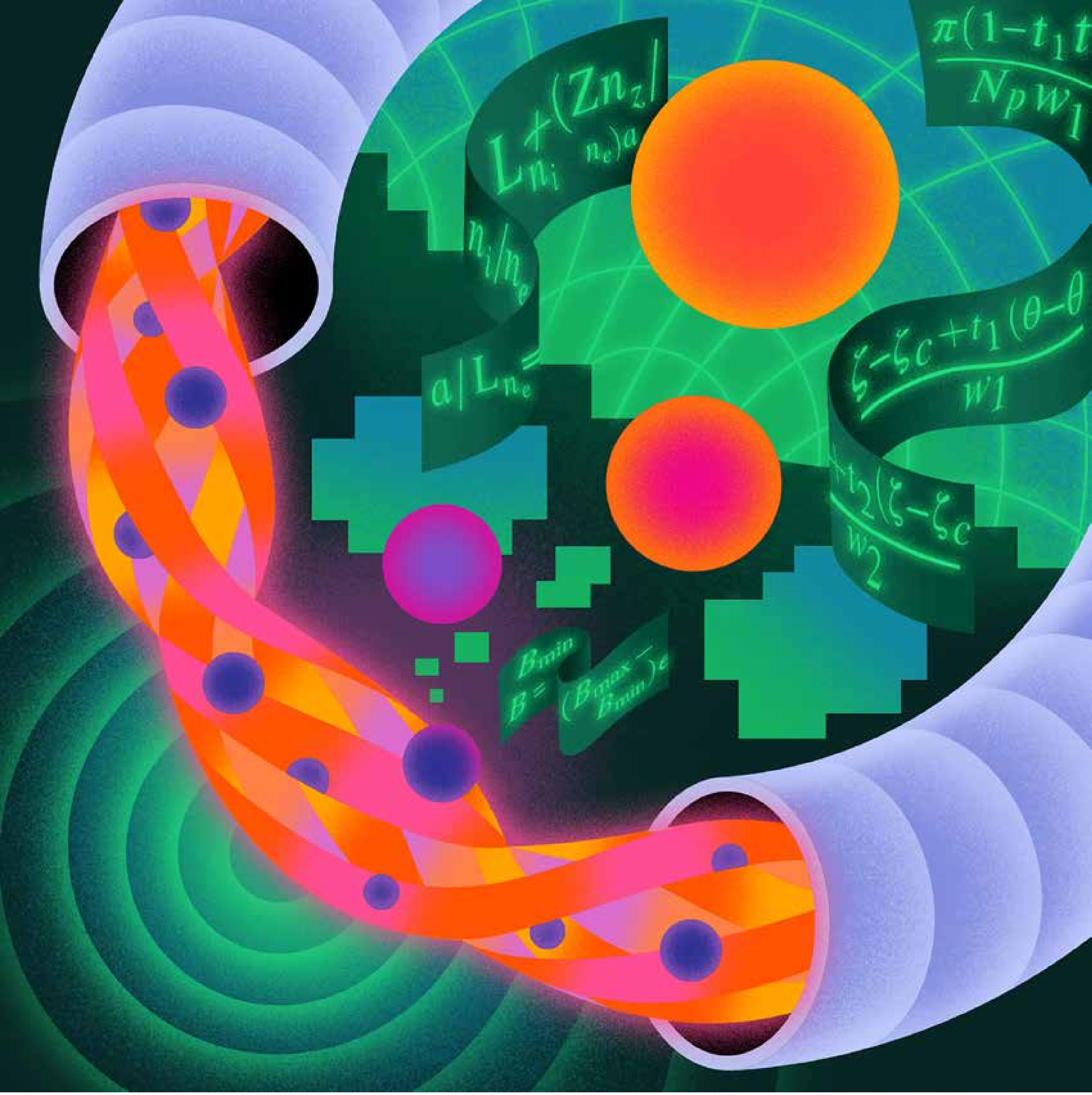
Currently, few facilities have both full flowing LM systems and PFC development. Flowing LM systems currently exist in ORNL for lead lithium as a blanket concept but could be adapted for other materials. The University of Illinois Urbana-Champaign (UIUC) has a full suite of LM testing systems, ranging from basic material compatibility, static and dynamic corrosion testing, and full-flowing Liquid Lithium loops with plasma and PFC exposure to monitoring using flow sensors and resistivity-impurity monitoring sensors. Two loops exist at UIUC, the Actively Pumped Open-surface Lithium Loop (with field) and the Mock Entry Module for East. PPPL has a full-flowing Galinstan LM loop in operation with magnetic fields. Surface monitoring is currently performed using camera systems. A laser height monitoring system exists at PPPL and is being developed in the U.K. Full LM technologies have been developed by PPPL (Flowing Liquid Lithium) and UIUC (liquid metal infused trench) and have been tested on smaller devices and deployed on EAST. Other LM PFC technologies, such as the capillary porous system, exist overseas.

Opportunities for breakthroughs in understanding include developing new diagnostics to monitor LM surfaces. Such a system would include cameras and perhaps X-ray diagnostics to measure flows and diagnostics to quantify the retention of hydrogen and other impurities in LMs.

Measurement Innovations

To meet the above challenges, the PMI community should pursue the following strategies:

- Develop in operando techniques to monitor flowing LM plasma-facing surfaces during device operation.
- Develop in operando measurement innovations to monitor the effects of deuterium-tritium fuel and impurities on liquid-metal performance and the extraction and purification of lithium and fuel.



CHAPTER 4

Magnetic Confinement Fusion Burning Plasma

Introduction

The goal of the magnetic confinement fusion — burning plasma (MCF-BP) working group is to identify and prioritize measurement innovations needed for MCF leading to BP based on the white papers that were submitted by the plasma physics community. The scope of the MCF-BP working group includes operation on existing and future MCF devices independent of any specific fractional or integer value of Q (i.e., the ratio of power generated by fusion to applied power to heat the plasma). The specific needs of BPs (Q>5) will be discussed in chapters 6 and 7). For the time being, all MCF concept devices (e.g., tokamak, stellarator, field-reversed configuration, etc.) are considered here. Innovations in diagnostics have produced fusion energy science advancements, but challenges persist in technology integration and deployment. Recent workshops emphasized diagnostic needs, gaps, and proposed developments for MCF, highlighting progress and priorities.

Diagnostics are critical to operating MCF devices safely and efficiently, as well as for determining which experimental conditions could help scientists design, construct, and operate an MCF power plant. While diagnostic coverage and expansiveness may be limited on MCF fusion pilot plants (FPP) due to radiation issues, limited access, and cost considerations, plasma scientists remain committed to developing the required diagnostics for a full range of MCF machines. Optimization of plasma operating scenarios for the core, edge, and divertor regions will continue as new challenges are encountered with greater power and in the transition to deuterium-tritium operation necessary for MCF-BP and MCF-FPP. Despite advancements, there are significant measurement gaps that require continuously developing and adapting diagnostic techniques, especially those that could help create BP conditions. This continued need to maintain and expand the extent and depth of diagnostics motivates the MCF-BP measurement innovations described in this chapter.

The MCF-BP research area has common challenges with the rest of the Basic Research Needs (BRN) Workshop on Measurement Innovation (MI), including the need for radiation-hardened components, improved data analysis techniques, and enhanced public-private partnerships for accelerated diagnostic development. The report underscores the critical role of diagnostics in advancing MCF toward BP, emphasizing the need for continuous innovation, collaboration, and investment in diagnostic technologies. Furthermore, advancing measurement technologies within operational confinement devices is crucial for lowering their risk in implementation and increasing their technological readiness level for future fusion applications. As fusion moves toward commercialization, addressing these priorities will be crucial for achieving sustainable and efficient fusion energy.

Retrospective

Diagnostic development has been a fundamental part of fusion energy research since the field's inception. Innovations in diagnostics have often led directly to key advancements in fusion science and device performance and have historically provided significant opportunities for collaboration nationally and internationally.

The path from a new diagnostic concept to successful implementation can be quite complicated and often involves innovations in technology development, system integration, and deployment on the fusion plasma machine. Different scales of resources and effort exist for implementing diagnostics on small laboratory or university-class machines as compared to implementing diagnostics at large facilities. Limited funding and machine availability for diagnostic deployment, testing, and demonstration limits the pace of progress to performance qualification of a new diagnostic.

Recent U.S. Department of Energy (DOE) workshops and reports have focused extensively on the role of MCF diagnostics in plasma research. These efforts have assessed progress and achievements in diagnostic measurements and control for MCF devices while also identifying priorities, concepts, and approaches for future diagnostic developments aimed at producing BPs.

Current Status

The current workshop convened experts and stakeholders interested in diagnostic development and advancements for fusion plasmas. A total of 58 white papers were submitted to the MCF-BP working group. Some of the papers were submitted to multiple working groups for their consideration. Of these, 29 were accompanied by presentations during the BRN Workshop on MI. The working group subdivided the white papers into the following six categories: 1) measurement and control needs with eight papers, 2) diagnostic validation with five papers, 3) technology development with 30 papers, 4) atomic physics with four papers, 5) data and simulation with four papers, and 6) funding policies with two papers.

The technology development papers spanned many techniques. While several papers focused on advancing specific techniques on specific plasma devices, many more focused on broader-based technology needs. A strong case was made for radiation-hardened microwave, X-ray, and laser-based diagnostics, as well as radiation-tolerant neutron and photon detectors, and associated electronics. Others focused on measurement needs, particularly in the areas of neutron (deuterium-deuterium (DD) and deuterium-tritium (DT) detection, tritium inventory, and the need for alternate methods to measure internal ion temperatures and details of magnetic field distribution without neutron-beam injection (NBI).

Scientists using collisional-radiative models expressed concern about the uncertainties in atomic data (i.e., energy levels, ionization rates, etc.) for low-Z and high-Z charge states and excitations for nonthermals. On the data and simulation side, a case was presented for better integration of diagnostics and simulations, for increased use of synthetic modeling and machine learning, along with the use of Bayesian inference to better combine measurements from multiple diagnostics.

Two white papers raised points about DOE funding policies. The first one requested a committee investigate ways to reduce the amount of time researchers spend on non-research activities, including grant proposals/reports and mandatory conference/meeting attendance. The second one suggested that the strengthening of the Early Career Research Program would support the next generation of America's scientific workforce, which has remained flat for over a decade.

MCF experiments currently have a diverse range of diagnostics. These diagnostics are often highly sophisticated and provide a wide coverage of plasma parameters necessary for diagnostic control and physics understanding. These diagnostics have been optimized for the accessible plasma parameters in current devices. Although measurement gaps remain in existing devices, new measurement techniques and the extension of existing diagnostics are routinely being pursued. Each MCF concept has different measurement requirements based on the experiment's spatial and temporal scales and expected plasma parameters. Nonetheless, there is substantial overlap in diagnostic techniques employed at different facilities based on concepts that include tokamaks, stellarators, field-reversed configuration devices, and Z-pinches.

In many cases, updating these existing techniques so they can operate in MCF power plants will require substantial measurement innovations. Scientists at universities, national laboratories, and within the private sector will have to develop new techniques that can function in the extreme temperatures, densities, and magnetic fields with appropriate signal-to-noise ratio, with the added challenge of DD (and possibly DT) neutron- and gamma-induced noise. The requirements for neutron, gamma and magnetic shielding are challenging for plasma-facing diagnostic components. The volume and weight of the mass needed to adequately shield the diagnostic components is machine dependent, as well as the number of wall penetrations in the vacuum vessel needed for the diagnostics positioned at sufficient distance from the plasma to have tolerable levels of background signals. The anticipated neutron and hard X-ray exposure to diagnostics from these BP experiments requires separation of radiation-sensitive components from the vacuum vessel and the use of radiation-hardened solutions. The use of heating and diagnostic neutral beams is limited due to penetration depth and tritium safety, and control of tritium inventory introduces limitations on window configurations and in-vacuum placement components. Cooling of components is required due to neutron heating. Activation of cooling circuits in a MCF-BP facility presents technical challenges, and access for calibration and maintenance is limited by the radiation environment. Finally, the sputtering of high-Z metal plasma-facing components (PCFs) (e.g., tungsten) result in redeposition of films ultimately complicating the use of visible vacuum windows, hence the focus on using passive spectroscopy techniques such as microwave, neutron, and X-ray technology.

There is a strong desire across the diagnostic community to make diagnostics affordable and highly available, reliable, calibrated, interpretable, and maintainable. Researchers are strongly interested in adding the capability to integrate diagnostic data into both artificial intelligence (AI) and machine learning (ML)-based systems interpretation and control schemes, as well as making outputs directly comparable to synthetic diagnostics available in both interpretive and forward-projecting modeling codes.

Priority Research Opportunities

Measurement and control are the keys to obtaining a successful future BP. Foremost, there needs to be enough diagnostic and control capability to form and sustain the plasma while avoiding instabilities that could negatively affect system performance or, in the worst case, result in a major disruption. Additionally, to make the leap from startup plasmas to BPs, diagnostics must resolve and optimize plasma performance.

In this section, several priority research opportunities (PROs) are identified with low technology-readiness levels (TRLs) that require a significant effort to determine their future BP feasibilities, as well as those with medium TRLs that require either modest progress or calibration/qualification services to achieve a sufficiently high-readiness level to be installed and operate on a BP device.

PRO 1: Develop Innovative Measurement and Control Techniques/Concepts for MCF-BP.

Scientific Challenges

Develop innovative diagnostic techniques to meet measurement and control needs for MCF-BP experiments in areas where new concepts are needed to meet the requirements and environment or where existing concepts are at low TRLs. The following measurements are needed for MCF-BP experiments:

- X-ray detection capabilities for measuring anisotropies of the X-ray emission.
- X-ray measurements for liquid metal PFCs.
- Multi-energy X-ray measurements with filters, fast photodiodes, and 2D-pixelated systems for magnetically confined fusion plasmas.
- Validation of kinetic neutral simulations for FPP design: Hydrogen femtosecond two-photon absorption laser-induced fluorescence.
- Development of microwave diagnostics for high field, harsh environment, and limited access BP devices.
- Neutron diagnostics requirements for fusion reactors.
- Internal magnetic field measurements for beam-driven field-reversed configuration fusion devices.
- Polarimetry and dispersion interferometry for density and q profile measurement on future fusion reactors.
- Cryogenic in situ radiation challenges for fusion reactor magnets, controls, and monitoring systems.
- Real-time monitoring and control of MHz-scale plasma dynamics with real-time AI and ML and fluctuation diagnostics.

- –Advanced agile Compact Thomson Scattering diagnostic for BPs: pulsed spectropolarimetry.
- –Near-infrared spectroscopy for tokamak plasma diagnostics and controls.
- –Development of compact optical systems for microwave imaging in advanced experiments.
- –Development of next-generation neutron spectrometers for diagnosing alpha heating of fuel ions in inertial confinement fusion (ICF) and MCF experiments.
- –Hypervelocity dust beam injection for internal magnetic field mapping.
- –Laser inverse Compton scattering to measure the runaway electron population.

Measurement Innovations

- –New diagnostic concepts must be tested and validated on existing high-temperature plasmas (e.g., tokamaks, spherical tokamaks, stellarators, or other alternates). As an example, one specific challenge is to measure the internal current profile and understand the equilibrium in a hot tokamak, without using NBI; a 2D temperature measurement is one option and a multi-line of sight or imaging polarimetry is another alternative. An actual experiment to observe the local angle of an ablation cloud from deeply penetrating high-speed dust was made 20 years ago but not quite implemented at the last minute due to scheduling issues at the host facility.

- –New diagnostic efforts need to tackle the conditions for the formation of runaway electrons using the anisotropy of the hard X-ray distribution and electron cyclotron emission (ECE) measurements characterizing the downshift of the electron gyrofrequency due to relativistic effects (γm_e).
- –To control fusion plasma in real time, scientists must develop a so-called “nuclear island” that is designed to provide the signal exchange with full transparency and facilitate long-pulse management. This system would control the shape, position, and burn rate of the plasma by integrating information about the plasma centroid, the plasma current, the electron and ion temperature profiles, and the magnetic field profile. The latter will inform on the plasma stability, pressure, and fusion reactivity, which will allow a comparison between the measured versus expected values of Q.
- –Scientists need new ways to measure the plasma at its edge with higher spatial and temporal resolution, SRNs, and dynamic ranges. Making measurements with these improvements could lead to necessary advancements to characterize and monitor the heat flux width (or lambda-q) because of changes depending on edge turbulence mechanisms and how edge fluxes erode and possibly damage the outer main wall. Real-time surface reflectivity measurements of PFCs are essential to adequately account for reflections and in situ material emissivity

property changes and, thus, properly interpret data from imaging and spectroscopic diagnostics. In the divertor, innovative measurement and control needs range from monitoring radiation dissipation, to feedback on extrinsic impurities, to maintaining electron temperatures below the PFC physical erosion thresholds for fuel and impurities — both intrinsic and extrinsic — as well as heat flux and maximum surface temperatures below material tolerances before unmitigated damage can occur. If reduction of a measurement volume/area/region can't be taken without impacting the safe and efficient operation of the device, such measurements may need to be taken over a greater portion of in-vessel surfaces and volumes but at a lower cost and increased ease of use.

PRO 2: Perform research and development to support measurement innovations for MCF-BP devices.

Scientific Challenges

Development and enhancement of enabling technologies to support diagnostic development and innovation on the path to a MCF-BP device. The following measurement innovations for MCF-BP experiments is needed.

- New X-ray and gamma ray (e.g. diamond, silicon carbide, gallium nitride, aluminum nitride and perovskite) sensors,
- Benefits of high throughput, high-repetition rate, and reduced-cost Thomson scattering,

  Fast and thermal neutron sensors,
- T-boundary windows for X-ray diagnostics in fusion-energy systems,
- X-ray measurements for liquid metal PFCs, tritium breeding blankets and non-proliferation applications,
- Next-generation high-repetition-rate laser system for fusion energy science,
- Measurement needs of 100-m/s drift in tokamak plasmas,
- Enabling q-profile measurements for ITER,
- Microwave reflectometry development for FPPs,
- Critical research and development needs toward reactor-grade fuel-cycle measurement and control,
- Advancing fiber optic sensing for fusion applications,
- Integrated silicon carbide active pixel sensors for plasma monitoring,
- High-speed integrated optical detector arrays for multichannel plasma instability Measurements,

- Neutron diagnostics requirements for next-generation fusion reactors,
- Cryogenic in situ radiation challenges for fusion reactor magnets, control, and monitoring systems,
- Photodiode technology development for fusion plasma spectroscopy,
- Quantum sensing technologies for fusion plasma diagnostics,
- Near-infrared spectroscopy for tokamak plasma diagnostics and control,
- Development of compact optical systems for microwave imaging in advanced experiments,
- Development of next-generation neutron spectrometers for diagnosing alpha heating of fuel ions in ICF and MCF experiments,
- Advancing technologies for high-resolution spatial and temporal measurements of macroscopic stellarator flows,
- Robust sensor development for imaging bolometers, and
- Advancing X-ray diagnosis of BPs with microcalorimetry.

Measurement Innovations

- Plasma diagnostic technology is mature on current experimental MCF machines, but many of them would not meet the requirements for MCF-BP, since MCF-BP devices will have very high-radiation levels from X-rays, gamma rays, and neutrons, high-magnetic fields, high temperatures, long-pulse operations, coatings from impurities (e.g., lithium), and exposure to a tritium environment. Therefore, new techniques will be needed to enable future measurement capabilities.
- Develop robust sensors to record photons from the infrared to the X-ray wavelengths. While some sensors may be borrowed from other fields (e.g., spacecraft, high-energy physics, or synchrotron light sources), long-term research and development with dedicated teams needs to be supported.
- At longer wavelengths (used by millimeter-wave diagnostics ranging from reflectometry to ECE), radiation-hardened electronics would support diagnostic placement significantly closer to the MCF-BP device, thereby reducing the need for multiple relay mirrors (e.g., as is the case on ITER). Higher frequency (> 500 gigahertz) sources and electronics are required for use at high-magnetic fields and high densities, with significant advances in output-power levels compared to current estimates ranging from 1 to 10 watts to overcome the intense electromagnetic radiation created by MCF-BP operations. While higher frequency and power technologies are being developed by non-fusion groups, their devices and systems will not necessarily be compatible with BPs.
- Environmental testing, including exposure to high temperatures and progressively higher radiation levels, is an absolute requirement for characterizing conditions

that must be met to ensure a safe and long-lifetime operation and should be an integral component of future technology development research. High-reliability operation demands solutions resilient to both single-event effects, single-event latch up, and total integrated dose.

- Because of limited diagnostic access, researchers must consolidate diagnostics to make as many measurements as possible using a single-shared access port. Scientists should develop in situ calibration techniques to monitor drifts in key diagnostic elements (e.g., windows, detectors and sensors, electronics, transmission lines, and fibers) in response to the potentially limited access to diagnostic elements.
- Measurement innovations are needed for the following: a) radiation-hardened detectors for the ultraviolet (UV), soft X-ray, and hard X-ray range, (b) radiation-hardened electronics, (c) higher-power and higher-frequency millimeter-wave sources, and (d) plasma-facing mirrors.

PRO 3: Support diagnostic technical demonstrations for MCF-BP.

Scientific Challenges

Technical demonstrations that extend and improve diagnostics that can operate in MCF-BP environments need to be provided.The following measurements for MCF-BP experiments are needed:

- Development of a high spatial and time resolution 2D beam emission spectroscopy system for measuring density fluctuations.
- X-ray detection capabilities for measuring anisotropies of the X-ray emission.
- High-throughput, high-repetition rate, and reduced-cost Thomson scattering.
- Multi-energy X-ray measurements with filters, fast photodiodes, and 2D-pixelated systems for MCF plasmas.
- Validation of kinetic neutral simulations for FPP design: Hydrogen femtosecond two-photon absorption laser-induced fluorescence.
- Diagnosis of 100-m/s drift in tokamak plasmas.
- High-bandwidth charge exchange recombination spectroscopy.
- Development of microwave reflectrometry development for FPPs.
- Measurement of near-UV spectroscopy in edge plasmas to inform power exhaust, particle controls, and plasma material interaction physics.
- Imaging of electron density and electron temperature and fluctuations in the scrape-off-layer plasma for transport studies.

- Development of microwave diagnostics for high field, harsh environment, and limited access BP devices.
- High-speed integrated optical detector arrays for multichannel plasma instability measurements.
- Polarimetry and dispersion interferometry for density and q profile measurement on future fusion reactors.
- X-ray imaging crystal spectrometer diagnostic validation for BPs.
- Near-infrared spectroscopy for tokamak plasma diagnostics and control.
- The advancement of technologies for high-resolution spatial and temporal measurements of macroscopic stellarator flows.
- The advancement of X-ray diagnosis of BPs with microcalorimetry.

Measurement Innovations

- Existing techniques with intermediate TRLs would benefit greatly by validating the technique on existing facilities to raise its TRLs. In many cases, validation would include exposing the diagnostic ex situ to representative environments (e.g., those with high-radiation fluences) and in situ on suitable plasma devices. Ideally, the proof-of-principle demonstrations should be conducted in the required radiation environment.
- Scientists should develop in situ calibration strategies to monitor drifts in key diagnostic elements (e.g., windows, detectors, and sensors, electronics, transmission lines, and fibers) in response to potentially long duty cycles for diagnostic access. As throughput and sensitivity may change in time with transmission losses, damage due to radiation, or the coating and erosion of front-surface mirrors, researchers should make and repeat the calibrations on timescales necessary to ensure that errors remain at an acceptable level of performance.
- Scientists must account for the appropriate diagnostic redundancy for each measurement technique (i.e., the ability to duplicate measurements in multiple locations or remotely switch out damaged diagnostic elements), since it is highly desirable in MCF-BP environments to maintain vital data collection to prevent any risks to reactor stability and safety.
- Proposals submitted in response to this PRO are targeted at diagnostics with intermediate TRLs and designed to improve diagnostic reliability, availability, maintainability, and inspectability in MCF-BP devices. The main objectives of this PRO are: a) diagnostic demonstrations in MCF-BP environments, and b) demonstration of inspection or calibration strategies in situ or ex situ.

PRO 4: Support atomic physics theory, simulation, and validation for MCF-BP experiments.

Scientific Challenges

The development of high-fidelity atomic physics theory and calculations in support of measurement innovations is needed for MCF-BP devices. The following measurement innovations for MCF-BP experiments are needed:

- Validation of line-emission rates for low and high temperatures, as well as overall radiated power-cooling rates for tungsten.
- Exploration of the connection between atomic line radiation and energetic electron tails (e.g., non-Maxwellian distributions during startup, radio frequency and current drive and disruptions).
- Validation of kinetic neutral simulations for FPP design: Hydrogen femtosecond two-photon absorption laser-induced fluorescence.
- Set requirements for atomic data needs for MCF-BP experiments involving high-Z intrinsic and extrinsic impurities (e.g., tungsten, krypton, and xenon).
- Uncertainty quantification of atomic data for diagnosing MCF-BP.

Measurement Innovations

- Atomic data are essential for the interpretation of spectroscopic observations relevant for many MCF-BP diagnostics. For example, in impurity transport experiments, uncertainties in atomic data lead directly to uncertainties in derived transport coefficients. Another important consideration for future MCF-BP devices is recording the emission of highly-ionized tungsten using X-ray diagnostics. X-ray transitions of tungsten have largely been unexplored since previous experiments have not accessed the high-electron temperatures needed to create these radiating charge states that will radiate in future devices. This is important for both direct observations of tungsten lines for determination of the tungsten concentration in the BP and for contamination of spectra from spectral blending with emissions from other tracer elements used for ion temperature or velocity measurements. In particular, for the latter case, neon-like xenon lines in the 2.7 Å range are planned for both the ITER and SPARC X-ray spectrometers. From atomic data and analysisstructure calculations, there are several tungsten lines that fall in this wavelength range, which, depending upon the exact wavelength, could lead to false line broadening or shifts of the xenon emission lines. Unfortunately, the current state of calculations of tungsten X-ray line emission from non-closed shell charge states is not accurate enough to determine whether this line contamination will pose a problem. In the former case of using tungsten lines for impurity density measurements, accurate wavelengths are necessary for the proper charge state identification and modeling. One approach is to use these tungsten charge states and concomitant X-ray emissions using an electron-beam ion trap (EBIT) and associated X-ray diagnostics, which can access an extensive range of previously unexplored X-ray emissions. Support of EBIT experiments is essential for BP X-ray diagnostic development.

- Access to high-performance computing facilities for synthetic diagnostic simulation will be required. This access will allow scientists to optimize the lines of sight to be used for X-ray systems, polarimeters, radiometers, and interferometers.

PRO 5: Support real-time acquisition, data analysis, ML, and synthetic modeling for MCF-BP.

Scientific Challenges

The development of real-time acquisition strategies and analysis techniques is needed to enhance the use of diagnostic data for real-time measurements and active control of MCF plasmas. ML techniques have already become crucial to advancing MCF control strategies, as long as the techniques have been verified and validated. Scientists must test these techniques to ensure that they make accurate predictions and control operations reliably. The following measurements for MCF-BP experiments are needed for both long-pulse and repetitive plasmas:

- Real-time acquisition.
- Mutually enhancing diagnostic information and digital models.
- The prospect of Bayesian inference and overall integrated data analysis.
- A move toward a minimal and robust set of diagnostics for BPs using AI.
- Comparison with reduced theory models.
- Real-time monitoring and control of kHz-MHz-scale plasma dynamics with real-time AI and ML and fluctuation diagnostics.

Measurement Innovations

- The application of AI and ML to the prediction of plasma disruptions has achieved considerable success in recent years. The integration of ML techniques is pivotal for advancing magnetic fusion control strategies, provided there is proper adherence to realistic verification, validation, and uncertainty quantification principles. Specifically, to ensure reliable prediction and control operations, it is imperative to validate proposed ML algorithms within operating experimental facilities with dependable diagnostics that reliably produce multidimensional and multi-field data to enable accurate associated implementation and functionality. The validation process entails successful comparisons of the ML results with experimentally measured data that can verify the plasma's ability to appropriately respond to feedback control. It is also vitally important to account for uncertainties stemming from measurement errors, model approximations, and inherent plasma variability while optimizing the fault tolerances of ML assessments of prediction and feedback control mechanisms. The associated challenge for fusion reactor diagnostics is accelerating progress for the seamless integration of AI with the urgent development of a realistic diagnostic and actuator system.

– Machine control and protection requires rapid analysis of diagnostic data. Diagnostics that generate massive data quantities require immediate processing to minimize the data load sent to the control system. Machine control requires data inputs on a timescale sufficiently fast enough to match the response times of the controls (i.e., gas injectors, plasma shaping and positioning, and plasma currents, etc.). Machine protection data can be provided on a slower timescale but still fast enough to avoid a major disruption and allow the plasma to be safely terminated or scaled back to avoid damage to the BP device. Set requirements to optimize machine control and protection for a MCF-BP device are needed.

– While it is true that device actuators cannot engage or change plasma dynamics on microsecond timescales, it remains that many important macroscopic events are still driven by high-bandwidth dynamics. The kHz- to MHz-scale signals can, in principle, be monitored and evaluated in real time and used for new plasma control schemes. Traditional central processing units and graphics processing units are unlikely to achieve sub-millisecond latency with multi-channel MHz-scale data streams, but computer platforms such as field-programmable gate arrays and new, high-throughput processors for AI and ML applications can handle it. Real-time analysis of fluctuation diagnostics will likely create new enabling technologies to predict and control transient events, such as confinement mode transitions, edge-localized modes, Alfvén eigenmode events, and disruptions.

– Diagnostic synthetic modeling, integrated with either AI or ML, will aid greatly in interpreting the results on a timescale fast enough for machine control. The use of standardized synthetic diagnostic tools (e.g., those in the integrated modeling and analysis suite) and research into accurate noise models for experimental diagnostics should be encouraged. Development of measurement innovations for diagnostic synthetic modeling is also needed.

PRO 6: Support diagnostic testing and characterization to evaluate measurement innovations for MCF-BP operation.

Scientific Challenges

Providing sufficient access to facilities in the U.S. and abroad to calibrate, qualify, and support diagnostic innovation and protoyping is needed to lead to a MCF-BP device. Diagnostic collaborations in long-pulse tokamaks and stellarators in Europe and Asia must be considered. The scientific community must also determine if additional ex situ facilities are needed over the next decade or if the current facilities are sufficient to meet the anticipated needs of the diagnostic community.

Measurement Innovations

- Since a MCF-BP device will operate at significantly higher energies and energy densities than current machines, scientists must ensure the margins for engineering and material requirements meet the requirements for safe operation of the machine. Diagnostic sensors and electronics must fall into one of the following categories: a) they must be located at a distance far from the device where radiation levels are sufficiently low, or b) they must be replaced with much more radiation-tolerant sensors and electronics, or c) a combination of a) and b). These requirements emphasize the need to minimize uncertainties in measurements with accurate calibrations throughout the operational period of the device.

- Calibrations include absolute intensity, wavelength, and spatial and temporal resolution, among others, and involve both in situ and ex situ approaches. As throughput and sensitivity may change in time with transmission losses, damage due to radiation, or coating and erosion of front-surface mirrors, calibrations should be carried out and repeated on timescales necessary to ensure errors remain within the required performance levels.
- Having suitable X-ray, neutron, and charged-particle ex situ source facilities that can be used to characterize and qualify diagnostics would eliminate the need by individual research groups to duplicate these capabilities at a considerable cost savings. A few such fusion-targeted facilities currently exist (e.g., the Facility for Laboratory Reconnection Experiments and the MegajOule Neutron Imaging Radiography Experiment) but are not widely known or accessible to outside groups, or they exist but at insufficient radiation levels to meet the MCF-BP diagnostic needs. Such facilities should have the capability to sufficiently replicate the desired conditions (i.e., flux and/or fluence) in a MCF-BP device.
- While a fusion nuclear science facility would be incredibly valuable for “accelerated aging” experiments and evaluations of performance degradation over time, much of the important work that must be done in the area of microelectronics radiation assurance testing can and should be performed using existing resources

and techniques. Existing facilities, such as fas-burst reactors and accelerators, are used across radiation test communities to develop and test radiation effects models. These models describe the errors, noise, and artifacts that can have a deleterious impact on diagnostic and control electronics performance in real time. Sophisticated techniques have been developed to produce desired radiation effects and representative physics, particularly in application areas where the ultimate radiation environment simply cannot be simulated in the laboratory. Gaining access to and experience with using these facilities will be important to developing a physics-based understanding of the performance of critical systems when deployed in the MCF-BP device's environment.

CHAPTER 5

Inertial Confinement Fusion Burning Plasma

Introduction

Inertial fusion energy (IFE) has greatly benefited by the proof-of-principle laboratory demonstration of achieving ignition and energy gain with inertial confinement fusion (ICF) at the National Ignition Facility (NIF). This historic achievement relied on well-calibrated and shielded diagnostics and precise experimental techniques to make innovative measurements of the plasma conditions. These measurements captured small scales (smaller than one-millionth of a meter) of phenomena occurring on the picosecond to nanosecond timescales, all while sustaining extreme levels of background radiation from X-rays, gamma rays, charged particles, electromagnetic interference, and neutron flux. To forge ahead to higher fusion yields in ICF, several advancements are required in measurement innovation for diagnostics and radiation hardening, targets, data management and analysis, and infrastructure as described in this section.

Researchers must upgrade X-ray, gamma ray, neutron, and charged-particle diagnostics, improving their spatial, temporal, and energy resolutions to guide research and the development of higher fusion-yield implosion designs. With the achievement of ignition, new techniques are required to diagnose alpha heating and burn-wave propagation to realize high energy gains of 10 to 100 in the laboratory. Specific areas of innovation include time-resolved neutron spectra, spectra of the alpha knock-on neutron tail, development of gamma ray imaging and spectrometry, advancement of-monochromatized X-ray imaging, construction of coherent X-ray sources at implosion facilities, solid-state streak cameras, and hybrid complementary metal-oxide semiconductor (hCMOS) detectors. As yields increase by a few orders of magnitude above today's output on the NIF on the path to high yield, new radiation-hardened detector technologies are needed. The community must develop and deploy radiation-hardened detectors for X-ray, gamma ray, neutron, and charged-particle diagnostics.

Measurement innovation must include precise characterization and, subsequently, manufacturing of ICF/IFE capsules. This includes tomographic reconstructions of the shell and visualization of the ice layer in opaque targets. Fabrication and 3D target metrology capabilities must be developed to construct the required target and characterize the initial conditions of the ablator and thermonuclear fuel as well as target defects and engineering features that seed hydrodynamic instabilities throughout the target.

The community must develop unified data architecture and multi-objective data-analysis techniques to gather and interpret data from future facilities. Developing searchable databases that power artificial intelligence (AI) and machine learning (ML) tools is essential. The community must improve the existing research infrastructure, including providing easier access to diagnostic calibration facilities and disseminating information about them to scientists; providing long-term, sustained funding opportunities for required diagnostic developments; and strengthening workforce development to boost the talent pool and increase participation in measurement innovation efforts.

Retrospective

Given that fusion yields have increased by 12 orders of magnitude since the initiation of the ICF program in the early 1970s, the quality of diagnostic measurements has improved significantly, facilitating an exponentially increased level of understanding about the physics governing ICF implosions With the recent historic success of achieving fusion ignition and a gain of >2 at the NIF, burning and ignited plasmas in an ICF implosion can now be studied for the first time in the history of laboratory thermonuclear fusion research. The ICF and IFE communities have a common goal of realizing substantially higher energy gains. It is commonly understood that gains of order 100 are required for a viable IFE facility. Bridging this gap will require dedicated experimental and computational efforts to evaluate the mechanisms that limit the gain achievable in the laboratory. Even assuming ignition and propagating burn, the path to high energy gains requires a large compressed areal density to generate the required fuel burn-up fraction of 30%. This requires a compressed areal density of ~3 g/cm^2, which is typically considered a fundamental requirement for IFE-relevant implosion designs. In current ignition experiments at the NIF, a compressed areal density of ~0.7 g/cm^2 has been achieved with 2 megajoules of ultraviolet laser energy incident on the target.

There are basically two ways to increase the compressed areal density: (a) higher laser-driver energies or (b) lower adiabat implosions. The adiabat of an implosion is a measure of the entropy of the imploding shell, and a lower entropy (or adiabat) enables greater compression of the deuterium-tritium (DT) fuel. It is broadly accepted that IFE requires implosions with significantly lower adiabat and higher compressed areal density than achieved in the NIF experiments. ICF targets typically have spherically concentric layers consisting of an outermost ablator, a cryogenic thermonuclear fuel layer, and an inner vapor region. Lowering the adiabat of an implosion comes at the expense of more hydrodynamic instabilities (i.e., Richtmyer-Meshkov and Rayleigh-Taylor (RT) instabilities) for the imploding target, especially for short-wavelength perturbations, which cause the layers of the target to mix with each other and the void region.

To progress toward high areal density, scientists must develop capabilities to accurately measure average areal density, as well as low- and high-mode areal density asymmetries in an implosion. These asymmetries are common in ICF implosions and are mainly caused by spatial non-uniformities in the drive, issues with the capsule geometry, and initial target positioning. Eliminating low-mode asymmetries is therefore important to the ICF program, and this is mainly an engineering task related to laser technology and target fabrication.

Scientists must also develop newer and more capable multidirectional measurement techniques to understand low-mode areal density asymmetries. Since short-wavelength modes cause a uniform isotropic degradation of areal density, scientists must study the impact of the short-wavelength RT instability must be addressed. This can be mitigated using clever implosion designs.

To guide the ICF program toward higher areal density values relevant to IFE, several priority research opportunities (PROs) have been identified and are described in the following section. Several of these are well aligned with the “Report of the 2022 Fusion Energy Sciences Basic Research Needs Workshop,” which featured diagnostic development as a PRO. This report builds upon those findings to identify more specific diagnostic- and measurement-related research opportunities.

Current Status

The current status of spectroscopy, imaging, and temporal measurements for neutrons, gamma rays, and X-rays are described in this section.

Neutron spectrometers are indispensable tools integral to guiding the ICF research toward achievement of ignition and energy gain. It is recognized that measurements of the ICF neutron spectrum, recorded along different diagnostic lines-of-sight (LOS), with improved energy resolution and faster data analysis times will play a central role in diagnosing primary neutron yield, ion temperature, areal density, as well as asymmetry in areal density and plasma-bulk flows. An assessment of the hot-spot formation, fuel assembly, and implosion performance can be made from neutron spectrometers. It is also recognized that the capability of neutron spectrometers to assess directly alpha heating through measurements of the alpha knock-on neutron (AKN) tail in the ICF neutron spectrum is a groundbreaking development that will guide the program on its path to achieving high energy gain. In addition, given that the first direct measurement of the AKN signature in the neutron spectrum was conducted at the Joint European Torus experiment, the development of next-generation neutron spectrometers for ICF implosions is a crosscutting effort that can be directly transferred to the field of magnetic confinement fusion (MCF).

The recent and historic success of achieving fusion ignition and energy gain over 2 at the NIF has brought experiments into a regime where diagnosing the evolution of the power balance is more important than ever. As energy gain is set by the competition between alpha heating, expansion losses due to pressure-volume work, conduction losses, and/or ablator mix-induced radiation losses, it is recognized that implementing the capability of diagnosing time-evolving dynamics of an implosion is critical for optimization of IFE-relevant, high-gain designs. For example, late-time hydrodynamic mixing could prevent burn-wave propagation in current hot-spot ICF experiments at the NIF. Preventing this late-time mixing could lead to achieving energy gains in the range of 3 to 10. Another concern is that the impact of 3D asymmetries on implosion dynamics needs to be identified and mitigated. Both these implosion degradation mechanisms can be diagnosed by measuring the time-resolved neutron spectrum along multiple LOSs.

When low-mode areal density asymmetries are present in an ICF implosion, the shell kinetic energy is not efficiently converted to thermal energy in the hot-spot plasma, since areas of low areal density reduce the energy confinement and neutron yield. Neutron spectrometry along multiple LOSs will be used to diagnose these low-mode areal density asymmetries, but a higher spatial resolution that is currently available with the NIF Nuclear-Imaging Systems (NIS) is required to understand and mitigate the source of these asymmetries. With the implementation of further improvements to energy discrimination and spatial resolution on the NIF's NIS, diagnosing higher-mode asymmetries in the hot-spot plasma and in the surrounding compressed fuel shell would be possible.

With the ICF community repeatedly achieving burning plasmas and ignition, measurement of the nuclear burn history (i.e., a time-resolved measurement of the neutron production) on the NIF has become a crucial need for assessing alpha heating onset, propagating burn, and disassembly. Having this information will guide the ICF implosion program toward higher energy gain. Because current neutron temporal diagnostic techniques are not fast enough to probe the underlying physics, new techniques have to be considered. Detectors based on optical material, or a rad sensor, which responds to neutron radiation directly or indirectly, have been proposed. Importantly, the response time for these techniques is of the order of picosecond. A related concept that utilizes a Pockels crystal has also been proposed.

In contrast to many types of neutron diagnostics used at an ICF facility, the number of gamma ray techniques used to diagnose an implosion is currently very limited. The main reason for this is that the fusion gamma ray yield per produced neutron is very low, limiting the types of diagnostics that can be used for ICF applications. However, as the ICF program now regularly achieves ignition and energy gain, the use of gamma ray diagnostics will play an important role going forward. Areal density measurements are critical for ICF, since the total areal density and areal density asymmetries in the compressed fuel and ablator layers dictate the energy confinement. Given that gamma rays originate from many sources in an ICF experiment and are predicted to display a broad continuum plus several lines, it was proposed that compact gamma ray spectrometers (i.e., Compton-electron and pair-production designs) should be implemented to differentiate fusion gamma rays from the gamma ray background signals.

Gamma ray imaging systems have been implemented recently on the NIF for detection of gamma rays created by DT-neutrons reacting with the carbon in the remaining ablator. While these systems are still in development, ultimately, the 3D morphology of the ablator carbon and mass remaining can be inferred. To differentiate gamma rays originating from different sources (i.e., 16.7-MeV gamma rays from the DT fuel, 4.4-MeV gamma rays from the carbon ablator, and continuum gamma rays from the hohlraum), energy- and spatially-resolved gamma ray imaging has been proposed, and this type of diagnostic would provide information on fuel assembly and infer which portion of fuel contains high-Z impurities mixed in from the surrounding ablator.

Since gamma rays do not experience temporal broadening (i.e., Doppler broadening), they retain temporal information about the DT nuclear-burn history. This enables systems based on gamma rays to be positioned at relatively large distances from an implosion in well-shielded locations for measurements of the nuclear-burn history in high-yield applications with environments of large X-ray and neutron backgrounds. Having this information is critical for assessing the energy-confinement time, which dictates fusion yield and the overall performance of an implosion. The temporal resolution of gamma ray diagnostics is being improved by incorporating a pulse-dilation technique into the diagnostic. A solid-state streak camera is also proposed for high-speed recording.

X-ray spectroscopy can be used to diagnose the mixing of doped ablator elements into the hot-spot plasma and the remaining amount of ablator material. Additionally, by measuring the slope of the continuum X-ray emission, the electron temperature of the implosion at stagnation can be inferred. It is commonly expected that the hot-spot plasma equilibrates on a timescale that is much shorter than the confinement time of the hot-spot plasma. Therefore, X-ray spectroscopy can be used to supplement the ion temperature measurements inferred from the neutron spectroscopy. Small amounts of krypton gas could also be used to dope a surrogate capsule. The absolutely calibrated time-resolved krypton line emission has been used to measure the evolution of electron temperature and density, the hot-spot radius, and the hot-spot areal density to fully characterize the hot-spot plasma conditions.

X-ray imaging is a versatile ICF diagnostic for self-emission and backlit geometries. It can be used to record implosion trajectories and to diagnose the hot-spot plasma and the compressed shell around stagnation. Selection of the X-ray photon energy of the observation has been achieved with filtered pinhole arrays, reflective Bragg optics, fresnel zone plates (FZP), Kirkpatrick-Baez microscope, and Talbot interferometers. Multiple monochromatic images can be achieved using a pinhole array and a Bragg reflector. Time resolution can be achieved with X-ray framing cameras, hCMOS sensors, and single LOS imagers using drift tubes. Time-integrated images can be recorded on image plates or film. Three-dimensional structures can be resolved using an array of X-ray imagers positioned along multiple LOSs.

External X-ray sources can be used to probe the target and produce radiographs that can be analyzed to infer integrated density profiles and in-flight areal-density measurements. One challenge for backlit radiography is the source quality. Today, backlighters are typically mid- to high-Z foils that are driven with a laser pulse to produce quasi-monoenergetic line emission. However, this limits the photon energies available and can be too broadband to enable quantitative analyses or devices such as FZPs to be used reliably. They also require precise calibration. To fill this gap, the community has proposed a novel X-ray source to provide bright, tunable radiation via inverse Compton scattering. Its primary motivation for use in ICF is to provide a bright, higher-photon energy X-ray source for use in radiography of otherwise opaque targets, though it is also capable of providing coherent radiation required for these high-resolution techniques. In it, an electron beam is created via a linear accelerator and collides head-on with a laser pulse. A dipole magnet strips the electrons from the path of the X-rays, producing a clean 20-50 keV radiation source. If the electrons are bunched, this source can be made coherent. Such a capability at an implosion facility would provide a sea change in the amount of information obtainable in experiments. The spatial resolution of FZP imagers would be drastically improved; Talbot interferometry would be enabled; and error measurements on attenuation and density measurements would be significantly reduced, allowing precise characterization of the in-flight and stagnating shell conditions.

Recording X-ray emission as a smooth function of time over the course of several nanoseconds is often required for implosions. X-ray streak cameras, which provide 2D data with one spatial or spectral axis and one temporal axis, are used to observe the time-evolution of X-ray emission and absorption for one-dimensional imaging and spectral applications. However, streak cameras are large devices with poor conversion efficiency due to the photon-electron-photon conversion process and their footprint limits their geometry and deployment on large facilities. To enable high-conversion efficiency streaked imaging in a more flexible-form factor, solid-state streak cameras are now being developed alongside the 2D time-gated hCMOS detectors. Both technologies should be advanced to facilitate high-resolution streaked and gated imaging with improved signal-to-noise statistics.

Priority Research Opportunities

PRO 1: Accelerate X-ray, gamma ray, neutron, and charged-particle measurement innovations critical to reaching high gain.

Scientific Challenges

Minimizing low-mode areal density asymmetries to achieve high-areal density and high gain has been a challenge in ICF experiments using either laser direct drive or laser indirect drive at the Omega Laser Facility and the NIF, respectively. Indeed, progress in improving the performance with both approaches has come by deliberately sacrificing compression (and areal density) in the interest of increasing implosion stability or increasing implosion velocity, or a combination of both. As low-mode areal density asymmetries and localized low-areal density areas of the shell surrounding the hot-spot plasma reduce the final compression in an implosion, developing capabilities for identifying the presence and dynamics of these low-areal density areas is crucial for the assessment of the confinement properties of the compressed core. While additional diagnostic LOSs diagnosing directional ρR are beneficial in terms of diagnosing ρR asymmetries, a conclusive assessment of these asymmetries and their impact on the core conditions will require the diagnosis of the evolution and 3D morphology of the hot-spot plasma and the surrounding high-density shell.

Measurement Innovations

- In the near term, upgrading the current spectroscopy, imaging, and temporal techniques for X-ray, gamma ray, neutron, and charged-particle diagnostics to meet the requirements of ignition and modest gain should be pursued. This would provide critical experimental insights to guide the ICF implosion campaigns toward achieving higher areal density and energy gain. Although current diagnostic techniques have been essential for guiding the implosion programs at the Omega Laser Facility and the NIF for the last 15 years, there is substantial room for improvements in terms of handling higher yields, performance, and data processing times.
- In the long term, implementation of new transformational diagnostic techniques that build on the lessons learned from current practices and data-analysis techniques, based in part on ML, to improve support of the ICF implosion campaigns is needed. These transformational systems will have substantially better temporal, spatial, and spectral resolution capabilities for diagnosing the physics that affects degradations in implosion performance. All of these measurement innovations require radiation hardening.

PRO 2: Develop alpha heating and burn-wave propagation diagnostics to understand and control the fusion yield.

Scientific Challenges

The key mechanism to achieve high energy gain in ICF is the process of alpha heating and the resulting burn-wave propagation. ICF techniques hold potential to be economically viable because the nuclear fusion reaction can bootstrap, burning a large amount of fuel by supplying only a relatively small amount of energy to start the burn. A detailed understanding of this process has implications for the required size of the facility, what physics conditions (fuel areal density, temperature and confinement time) need to be achieved, and what kind of energy gains could be achieved in various platforms. Only recently with the NIF achieving ignition conditions can detailed data and experimental measurements be made of alpha heating and burn-wave propagation. Alpha heating and burn-wave propagation must be understood and controlled to achieve high energy gain, which requires the development of alpha heating and burn-wave propagation diagnostics.

Measurement Innovations

- Mastery of alpha heating and burn-wave propagation physics must be demonstrated prior to developing a FPP, as this understanding feeds heavily into FPP design. In particular, the community needs measurement innovations for alpha heating and burn-wave propagation to study:
    - The spatial evolution of the density and temperature of a propagating burn fusion plasma.
    - The temporal evolution of the density and temperature of a propagating burn fusion plasma.
    - The sensitivity of alpha confinement and burn propagation to degradation mechanisms.
- The community proposed the following diagnostic techniques fortified with radiation hardening to understand burn-wave propagation:
    - High-temporal speed and dynamic-range fusion reaction history.
    - High-temporal speed and dynamic-range X-ray measurements.
    - Gamma ray spectrometers.
    - Temporally and energetically resolved imaging.
    - Time-resolved neutron spectroscopy to infer the time-resolved ion temperature and density.
    - Feaction-in-flight neutron diagnostics.
    - Radiochemistry measurements for hydrodynamic mixing measurements.

PRO 3: Enhance capabilities for target metrology, including in-flight target imaging, to deliver the critical target conditions needed for an ignition and energy gain.

Scientific Challenges

Targets are a critical component of any robust ICF-burning plasma platform. During the progression to igniting shots on the NIF, it became clear that the quality of a capsule strongly determines performance. Among the important characteristics of a target are its shape and the number, location, and severity of defects. In the phase of burning plasma studies before the establishment of an FPP, it is fundamental to field targets that meet the specified scientific requirements. Doing so requires measurement innovations to perform the necessary target metrology to select the targets that meet the requirements. Enhanced target diagnostics are needed in three phases of a burning plasma experiment: offline characterization, in-chamber monitoring, and in-flight imaging.

One of the challenges in target metrology is that the spatial resolution needed is a small fraction of the system size, meaning that many measurements must be made. This is a challenge even at a low-shot rate. For NIF capsules, metrology techniques have been applied to automate the identification and repair processes for surface domes over the entire surface. Target development efforts seek to speed up capsule defect imaging and to make interior measurements.

Measurement Innovations

The community proposed the following measurement innovations for enhanced target metrology:

- One innovation demonstrates the application of various imaging techniques using a Coherent anti-Stokes Raman scattering (CARS) microscope that can make 3D measurements sensitive to elemental composition. The technique can discriminate regions of missing material or contamination and show contrast at material interfaces.
- Another proposed measurement innovation details various X-ray imaging techniques, including phase contrast imaging and dark-field imaging, which may be applied for measurements of interior features and foam components with submicron spatial resolution.
- Some of the techniques discussed have been performed in a laser chamber environment, and so it may be possible to apply them on the benchtop and in the chamber or in flight.
    - There are also two white papers that point to diagnostic concepts that intend to inform target conditions in flight, which is important in correlating target features to performance. With enhanced target characterizations and post-shot analysis efforts, it is possible to identify target features that are correlated to poor performance. After correlations have been established, target rejection criteria can be established to prioritize high-performing targets.

- Important target features in an ICF platform might include sphericity or cylindricity, wall thickness uniformity, fill tube and tent scars, and material defects such as pits and voids. Deep ablator defects or defects in the fuel material itself may be particularly important. These target features should be correlated to measurables, including low-mode asymmetry, neutron imaging, and mixed metrics and imaging (e.g., X-ray emission from tracers).
- One priority is supporting the development and implementation of fast-scan target imaging methods, such as CARS on a benchtop setup, and offline X-ray imaging techniques applied to ICF targets at light sources, such as the Linac Coherent Light Source. Further, the community thinks that each ICF facility should enhance the availability and resolution of pre-shot, high-magnification imaging of the target in the chamber.

PRO 4: Develop diagnostics that can withstand high levels of radiation.

Scientific Challenges

The successful operation of an FPP will require reliable and radiation-hardened diagnostics that can operate at multi-Hertz rates. Both magnetic and inertial confinement approaches to fusion energy generation will require electronic recording of data near extreme radiation sources that can cause diagnostic damage, including harming both static and passive components over time or instantaneously damaging electronics used for capturing and processing data. Additionally, high-energy particles and photons can induce undesired signal spikes and cause electronic signal disruption and/or circuit failure. In an FPP, diagnostics both near and far from the fusion reaction chamber must be continually available during plant operation, meaning that they and their underlying communications infrastructure must be reliable for at least many months at a time. These challenges present opportunities to develop more robust, radiation-hardened diagnostics that are ready for deployment and likely remote replacement on an FPP.

Measurement Innovations

The following measurement innovations were identified by the working group:

- Use high-flux sources of energetic radiation to study how electronics fail when placed near the fusion reactions.
- Use finite-element modeling with physics models to model the radiation environments and electronic diagnostic technologies to better understand and mitigate failures through radiation hardening.
- Use various types of radiation sources to study the effects of integrated damage to passive and active diagnostic components and assess the degradation of passive components to determine the expected lifetime of diagnostic constituents. This knowledge could further enhance radiation-mitigation strategies, develop failure-prediction models, and help plan for subsequent maintenance and replacement costs (time/labor) in an FPP.

- Compile a list of best practices and work toward formulating governing engineering principles that can be used to design FPP diagnostics.
- Make radiation sources available to researchers in both ICF and and MCF communities to help advance the understanding of how diagnostics withstand radiation damage.
- Plan experiments to help researchers further radiation hardening of diagnostics and improve the understanding and technologies that can aid this goal.

PRO 5: Employ advanced data-analysis techniques to accelerate physics understanding.

Scientific Challenges

Though the ICF community has developed very accurate diagnostic equipment for its experiments, there are only several high-yield implosions per year. Using complex analysis tools, scientists can collect data from the diagnostics in time periods ranging from a few days to a few weeks after a given shot. This data is typically used to tune pre- and post-shot simulations. Despite past success in using these diagnostics, scientists could better understand the relevant physics by combining all the data and performing a detailed analysis. A clearer understanding of the key complexities in ICF implosions could help reduce the uncertainty of inferred quantities, quantify the specificity and uniqueness of measurements, and improve simulations and models.

Measurement Innovations

- The community has suggested multiple techniques to better utilize the collected data through data synthesis. Some techniques allow scientists to vary parameters in many simulations and compare the outputs from actual experiments. Another technique analyzes data using multi-objective data analysis. A third technique, Bayesian analysis, can generate probability distributions for a given theory compared to a set of observables.
- In all these advanced data-analysis techniques, the extremely large parameter space necessitates ML. Developing an ML-based framework will enable rapid scans of a large experimental parameter space to form data-driven models from which measurable quantities will be extracted. Training such a framework will rely on a repository of modeled synthetic data from the diagnostics discussed herein that can be used as a surrogate before experimental data is used to refine these models. Increasing experimental datasets could subsequently be used to update the analysis models through active learning and transfer-learning methods to continually improve the algorithms. Furthermore, this methodology enables rigorous assessment of the uncertainties in the distilled quantities.

– Another possible avenue of data management is high-repetition-rate data analysis. The complexity of the diagnostic analysis means that there is a delay between an NIF shot and reporting diagnostic data. In the near term, focusing on automation and more fault-tolerant automated data analysis could allow quicker data turnaround that could, in turn, help researchers incorporate the lessons of each shot into future experiments. Longer term IFE applications — mid-scale, mid-repetition rate facilities, FPP with multi-Hertz implosions — will definitely require diagnostic systems to have a completely automated and quick diagnostic turnaround. Therefore, investments into faster automation, standardization of diagnostic data, and diagnostics that specifically could scale to fast repetition rates would be valuable. These measurement innovations will involve developing sophisticated AI/ML data-analysis techniques.

CHAPTER 6

Magnetic Fusion Energy Fusion Pilot Plant

Introduction

First-generation fusion pilot plants generating magnetic fusion energy will require comprehensive measurements focusing on plasma control, performance verification, and plant operation monitoring. These requirements differ from those stipulated for present-day devices, where diagnostics are used primarily for detailed physics studies. However, because contemporary diagnostics may not be able to operate in the unprecedented environmental conditions of a magnetic fusion energy fusion pilot plant (MFE-FPP), the community must research and develop alternate or improved methods. New diagnostics require measurement innovations requiring a range of properties, including the ability to withstand high levels of radiation, neutron and gamma fluences, and induced noise; the ability to feed data into an integrated analysis process; adaptability; and long-pulse compatibility; among others. Eventually, the community must determine a minimal set of required measurements that can satisfactorily maintain safe and efficient plant operation. Supporting infrastructure will need to be developed and built to test and validate new diagnostics for MFE-FPP deployment. These considerations are largely independent of the magnetic configuration of the fusion device, but specific aspects will matter at the design stage and will need to be considered, especially for relative priority and needed resources.

In 2019, one of the two main recommendations within the National Academies of Sciences, Engineering, and Mathematics (NASEM) “Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research” was the following: “The United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant that produces electricity from fusion at the lowest possible capital cost.” To reach this goal, the community needs a broad infrastructure to address the technological gaps that exist among advanced diagnostics; control systems; integrated data analysis; robotics; diagnostics’ reliability, availability, maintainability, and inspectability (RAMI) analysis; and other techniques and technologies. Closing the gaps will require development and testing efforts of increasing rigor before deployment; everything must be demonstrated and validated, in so far as possible, before implementation on an FPP.

The first recommendation within “Bringing Fusion to the U.S. Grid,” a NASEM report in 2021, states: “For the United States to be a leader in fusion and to make an impact on the transition to a low-carbon emission electrical system by 2050, the Department of Energy and the private sector should produce net electricity in a fusion pilot plant in the United States in the 2035–2040 timeframe.” This NASEM timeline is ambitious, providing a horizon of slightly more than 10 years from the date of this report. Meeting the milestone requires the U.S. to 1) utilize existing facilities to their fullest potential, 2) specify and construct custom-built facilities as soon as possible, 3) nurture and leverage international resources and collaborations, and 4) institute consistent and appropriate funding levels.

To meet the FPP timeline, the U.S. must institute consistent and appropriate levels of funding across its entire portfolio. In the context of diagnostics, control, data, technology, and techniques, that includes funding for hardware, facilities, and personnel. Moreover, the funding must be consistent and at levels appropriate to advance technology and understanding to levels of maturity compatible with an FPP. Technical personnel are central to the endeavor. Other fusion programs worldwide assembled teams and initiated such efforts more than 10 years ago, so it is appropriate to say that the U.S. is lagging. The U.S. needs to implement a cohesive strategy for realizing an FPP in the 2035–2040 timeframe, and the readiness of diagnostic and control systems must be a core thrust within the strategy. This report explores the proposed measurement innovations from the MFE-FPP Basic Research Needs (BRN); Workshop on Measurement Innovation.

Retrospective

In existing plasma-confinement devices, diagnostics support basic scientific research. In fact, diagnostics have contributed to much of the significant progress in the scientific understanding of plasmas. However, in an MFE-FPP, the diagnostics will have a different task. Their primary goal will be to aid the plant's operation; in other words, the only plasma parameters that need to be measured are those necessary for the operation of the plant, with a limited number of operational scenarios. To aid this goal, the community must first determine the control and monitoring requirements of an MFE-FPP.

No matter which confinement approach is selected for an MFE-FPP, the control and monitoring needs can be broadly classified into the following categories: 1) basic control, 2) advanced control, 3) machine protection and event handling, and 4) plant monitoring. Basic control refers to the category of algorithms essential for maintaining a burning plasma. Equilibrium control (plasma shape, position control), burn control (energy and density control), and heat and particle exhaust control (detachment, first-wall monitoring) fall under this category. Advanced control typically ensures the stability of the confined plasma and optimal scenario evolution. Machine protection and event-handling algorithms ensure that the plasma states are maintained within the stability limits, take corrective actions whenever the limits are breached, predict the onset of magnetohydrodynamics (MHD) instabilities, and take necessary actions to prevent a disruption.

Beyond these control requirements, an MFE-FPP has specific monitoring needs. Since some components of the vacuum vessel may not be readily accessible for extended periods, the structural health of these components must be monitored remotely. There will have to be diagnostics that monitor the conditions of the first wall by measuring erosion, tritium intake, and the operations of any liquid metal systems. Furthermore, diagnostics will also have to monitor the fusion energy cycle and the plant's power output, including monitoring various elements of the energy cycle conversion and tritium breeding systems. Scientists may also have to account for additional measurement needs and monitors beyond the four categories mentioned above to ensure successful commissioning and troubleshooting of the FPP.

Some of these diagnostics will require retractable systems using either a remote handling or robotic approach. It may be necessary to incorporate additional measurement needs and monitors beyond the above mentioned four categories to ensure successful commissioning and troubleshooting of the MFE-FPP. These tools can help identify potential issues and provide detailed information, allowing for quicker and more effective resolution of problems that may arise during the commissioning phase of the plant. However, diagnostic systems required to make these measurements should be designed as temporary packages so they can be removed or retracted once the plant is commissioned and functioning.

In the plasma control system of the MFE-FPP, algorithms handling the four control and monitoring categories discussed above require reliable estimates of different plasma states. Thus, a crucial step prior to defining the measurement needs of the MFE-FPP is translating these control and monitoring requirements into specific plasma state needs. This task involves determining measurement requirements such as statistical properties, spatial resolution for profiles, accuracy, and response time. The community must also define these plasma state needs so they can be adapted to a range of diagnostics. The proposed solutions should be agnostic to the final configuration of the MFE-FPP. A subsequent step is determining whether each plasma state will be directly measured or estimated through integrated data analysis of available measurements. The output of this step is a compiled list of measurement needs with specific requirements.

Diagnostic techniques must be explored and developed to meet each measurement need identified in the process described above. Through this process, an interplay between diagnostic and control algorithm development unfolds. For instance, the numerical validation of a control algorithm necessitates using flight simulators integrated with diagnostic models capable of generating realistic measurements. This means that diagnostic models and control algorithms must be developed simultaneously. Ultimately, this process will yield candidate control algorithms that must be validated empirically and improved through further iterations. Successful iterations require coordination between measurement innovators, diagnostic model developers, and control systems experts.

Current Status

Diagnostics will be key for controlling and monitoring an MFE-FPP's operation. Specifically, they will play important roles in the following functions: 1) equilibrium and configuration control, 2) burn control, 3) heat and particle exhaust control, 4) stability control, 5) device protection and monitoring, 6) blanket and auxiliary systems operation, and 7) balance of MFE-FPP operation. The seventh one is not discussed in detail in this report so the Fusion Energy Sciences program must also prioritize diagnostics to control the fusion energy cycle for a future BRN-like forum.

Many of these functions will require real-time measurements and processing. Accuracy and reliability of the associated diagnostics will also require frequent and in situ calibration, as well as sufficient redundancy. The community expects that although evaluations would vary depending on the configuration of the MFE-FPP, many basic needs would remain the same. Preliminary estimations of the diagnostics' technological readiness levels (TRLs) demonstrate that for most of the proposed techniques, significant research and development are required to achieve realistic implementation. On a scale of 1 to 9, a readiness level of 6 means that a diagnostic concept can be moved into conceptual design. Therefore, validating the measuring techniques at levels above 6 must happen before the early stages of power plant design occur.

Meeting the measurement needs of an MFE-FPP will face a series of challenges originating from the new harsh environment, the unprecedented range of plasma parameters, and constraints arising from the plant's operating conditions and mission. These challenges include the following:

> **Harsh Neutron and Gamma Environment:** High-neutron flux and fluence (time-integrated flux) are expected to be among one of the greatest challenges for diagnostics on MFE-FPPs. Expected neutron and gamma fluxes, as well as the accumulated fluence, will be much greater than the experience from current devices, and even orders of magnitude beyond what ITER will generate. Vulnerable components and associated damage expected due to close proximity of the diagnostics to the burning plasma fall under three main categories: 1) optical elements, which can suffer transmission and reflectivity losses under radiation fields, and be prone to fluorescence; 2) electrical sensors, which will experience radiation-induced noise, modified conductivity (e.g., insulators), and/or overheating due to irradiation; and 3) supporting hardware, which may weaken and possibly become brittle. The large neutron fluence, expected in MFE-FPPs, has ramifications in terms of displacement per atom, transmutation, and helium bubble formation. Mitigation based on increased replacement frequency is not easily implementable on such devices. Solutions are needed, including advanced materials, additional shielding, and, most importantly, new techniques that are less susceptible to radiation effects. Robotic and remote handling techniques will be needed to support the maintenance and calibration of these systems.

Constrained Access: Compared to present-day devices, access to diagnostics will be severely reduced, primarily because the walls of the MFE-FPP will have to be covered with breeding blankets and shielding to breed tritium and to shield escaping neutrons and radiation. The shielding will also impact soft and hard X-ray measurements, which typically require more direct lines of sight. These challenges will require careful planning of the diagnostics and an early integration into the device.

Assessing Diagnostics' RAMI: The environmental conditions, harsh surroundings, and limited ability to access diagnostic systems inside the MFE-FPP will impact RAMI considerations. Reliability and availability of systems can suffer under the large neutron and radiation fluence, as well as the associated heating. Maintainability and inspectability will be hampered due to restrictions on accessing the device and its subsystems; hence, radiation-tolerant robotics solutions for test-cell monitoring should be considered. Radiation hardening, careful deployment, and integration of diagnostics will be critical to handling these challenges, especially at an early stage of the device design.

Surface Erosion/Deposition: Diagnostics with plasma-facing components, particularly visible windows and mirrors near the plasma's edge, will have to deal with erosion and deposition, which can change the window's transmission and/or mirror's reflectivity and affect signal levels and overall calibration.

Relativistic Effects: Relativistic effects can affect many diagnostics, particularly reflectometers, interferometers, electron-cyclotron emission (ECE) systems, and Thomson scattering devices. Specifically, the high-electron temperatures expected in an MFE-FPP will shift and broaden plasma-resonance surfaces, impacting ECE and reflectometry measurements. Therefore, diagnostic designs and associated measurement interpretations will require extensive modeling. Though the theory is mature, developing advanced software to include the effects of relativistic broadening remains difficult. Since verifying these effects tends to be difficult in existing devices, it would be beneficial to deploy modern ECE and hard X-ray equipment in machines with a strong lower hybrid current drive (LHCD) heating (e.g., the Experimental Advanced Superconducting Tokamak in China and the Tungsten (W) Environment in Steady-state Tokamak in France). In addition, the instruments must be adapted to make measurements over different microwave frequency bands, requiring extensive modeling.

Microwave Bursting and Stray Power: In some instances, in high-pressure plasmas, large, transient bursts of microwave radiation have been observed, such as when the magnetized plasma itself becomes a microwave generator. This high-power emission can damage microwave diagnostics that are normally intended to measure relatively low power. Similarly, if electron-cyclotron heating is employed as auxiliary heating, situations can occur where the injected power is poorly absorbed by the plasma, and stray radiation can damage sensors and components, including windows.

To address the above challenges, scientists will use a technique known as integrated data analysis (IDA). This technique combines information from multiple diagnostics into a single unified measurement of a given parameter of interest (e.g., ion and electron temperature). Here, we explicitly separate the idea of a measurement and a diagnostic. A measurement estimates a particular parameter of interest along with its uncertainty levels or confidence bounds. A diagnostic is the physical hardware implementations like sensors, cameras, and electronics that provide data on one or more parameters of interest. Analysis of the data from one or more diagnostics leads to a measurement.

To perform IDA, researchers often use Bayesian analysis, a method that has the following benefits: 1) improved measurement accuracy, precision, and resolution are better than those produced by over single diagnostic estimates, 2) straightforward estimates of uncertainties from both statistical and systematic sources, even when underlying uncertainties are non-Gaussian, 3) the capability to determine parameters for which an estimate is difficult to obtain using any single diagnostic, 4) the ability to account for background information in a quantitative way, 5) the ability to quantitatively assess the amount of information in a given set of diagnostics, and 6) the ability to validate data and identify data, as well as identify diagnostic anomalies.

In summary, IDA will allow scientists to make accurate and wide-ranging estimates using a limited set of diagnostics, even as the hardware degrades. Further, they will be used primarily to confirm the accuracy of plasma simulations and analyze diagnostic data in real time, among other functions. Several priority research opportunities (PROs) have been identified and are described in the following section.

Priority Research Opportunities

PRO 1: Define control and measurement needs for MFE-FPP operation.

Scientific Challenges

The community must clearly define the required controls and associated measurements for an MFE-FPP.

Measurement Innovations

- Determine which measurements will best aid the operation of an MFE-FPP, including controlling the heating and energy conversion systems and monitoring the first wall and lithium-breeding blankets.
- Validate measurement needs using current physics models and control schemes.
- Rely heavily on synthetic diagnostics capabilities to evaluate signal-to-noise-ratios in the presence of deuterium-deuterium (DD) and/or deuterium-tritium (DT) neutrons and gamma-induced noise.

PRO 2: Utilize existing and develop new measurement techniques, diagnostics, and facilities to address technological gaps and anticipated MFE-FPP environmental conditions.

Scientific Challenges

Prior to developing and designing sets of diagnostics, it is important for the community to clearly define the required real-time acquisition and active controls tools, along with associated measurements.

Measurement Innovations

- Use existing medium-scale plasma devices to develop new measurement techniques required for MFE-FPP. The goal is to advance the TRL in preparation for MFE-FPP devices.
- Use vetted diagnostics and techniques on large-scale devices that have conditions (currently) nearest to those that could exist in an MFE-FPP to identify and resolve outstanding issues.
- Collaborate with international institutions that have specialized capabilities for testing prototypes, techniques, and components.
- Establish a program to address technological issues in an MFE-FPP of the control and monitoring needs of basic control, advanced control, machine protection and event handling, and plant monitoring.

PRO 3: Validate diagnostics and control schemes in an integrated test environment for an MFE-FPP.

Scientific Challenges

Prior to implementing measurement innovations on an MFE-FPP, the measurement strategies must be demonstrated and validated as much as possible using existing devices.

Measurement Innovations

- Combine diagnostics with control algorithms and the IDA technique to allow real-time implementation.
- Prioritize implementation and testing in long-pulse machines, such as tokamaks and stellarators, or high-repetition-rate schemes, such as stabilized z-pinches and field reversal configurations.
- Incorporate diagnostic models into physics simulators and synthetic diagnostics.
- Explore how to process data from multiple diagnostics in real time for control and safety.
- Test possible MFE-FPP control systems using existing plasma devices.

PRO 4: Use advanced MCF-BP diagnostics in current DOE and international facilities to support implementation, utilization, and operation for MFE-FPP measurement innovations.

Scientific Challenges

Advanced diagnostics exist but aren’t being fully utilized because program scope emphasizes continuous innovation and stops short of actual utilization in present-day experiments. Additionally, advanced diagnostics are complex systems requiring effort by knowledgeable experts and continued support to reach maturity.

Measurement Innovations

Use advanced MCF-BP diagnostics to support implementation, utilization, and operation for MFE-FPP measurement innovations and determine if alternative or unconventional funding paths could be created to support diagnostic expert groups and advanced diagnostics that are independent of facility funding.

PRO 5: Develop IDA techniques to address measurement gaps, drifts, and failures for MFE-FPP.

Scientific Challenges

Scientists will use a technique known as IDA for MFE-FPP. This technique combines information from multiple diagnostics into a single unified measurement of a given parameter of interest. With the IDA, the idea of a measurement and a diagnostic is explicitly separate. A measurement estimates a particular parameter of interest along with its uncertainty levels or confidence bounds. A diagnostic is the physical hardware implementations like sensors, cameras, and electronics that provide data on one or more parameters of interest. Analysis of the data from one or more diagnostics leads to a measurement. To perform IDA, researchers often use Bayesian analysis. Scientists use the IDA to make accurate and wide-ranging estimates using a limited set of diagnostics, even as the hardware degrades. Further, they will be used primarily to confirm the accuracy of plasma simulations and analyze diagnostic data in real time, among other functions.

Measurement Innovations

- Validate high-fidelity plasma models, synthetic diagnostics, and surrogate models for real-time analysis for an MFE-FPP.
- Identify a set of diagnostics that can provide robust measurements for control and safety of an MFE-FPP (using information from PRO1).
- Develop and validate IDA measurement tools for an MFE-FPP.
- Integrate into control systems envisioned for an MFE-FPP (feed into and partner with PRO2).
- Utilize machine learning and artificial intelligence techniques previously developed in MCF-BP experiments with a goal of developing control strategies that prioritize safety (e.g., against deleterious MHD events and/or the unintended injection of tungsten with a subsequent radiative collapse and the production of runaway electrons).

PRO 6: Investigate relativistic effects on plasma measurements anticipated for MFE-FPP.

Scientific Challenges

At the high electron temperature expected in an MFE-FPP, relativistic effects will need to be included in the analysis of typical plasma measurements.

Measurement Innovations

- Develop a theoretical understanding of the relativistic effects that should be considered for MFE-FPP measurement innovations and test theoretical interpretation with systems deployed on relevant devices.

- Consider using a mixture of modern ECE radiometers, as well as radiation-hardened soft X-ray (SXR) and hard X-ray (HXR) technology to characterize non-Maxwellian features and still extract relevant physics parameters.
- Perform tests in SPARC-like facilities at high temperatures or others in which non-Maxwellian effects are prevalent because of the use of LHCD.

PRO 7: Develop rugged, reliable calibration techniques that can ensure diagnostic accuracy required for MFE-FPP.

Scientific Challenges

The validated output of diagnostic systems for MFE-FPP devices must be maintained for very long periods without direct access or manned calibration.

Measurement Innovations

Develop and integrate neutron, microwave, and X-ray calibration techniques based on in situ or self-calibrating approaches for MFE-FPP devices.

PRO 8: Develop and validate mitigation techniques to protect in-vessel diagnostic components, such as mirrors, cables, and shutters in a MFE-FPP.

Scientific Challenges

In-vessel components that may be deployed in an MFE-FPP will suffer from large neutron/gamma flux and fluences, and in some cases neutral-particle impacts from the fusion plasma. In addition, the likely presence of significant microwave radiation may impact cabling through arcing and heating.

Measurement Innovations

Develop and integrate new calibration techniques, based on in situ or self-calibrating approaches for an MFE-FPP.

PRO 9: Develop new supporting technologies such as X-ray optics, high-frequency microwave components, and quantum sensors for MFE-FPP devices.

Scientific Challenges

In high-temperature plasmas, a wealth of information can be gathered in the X-ray ranges of emitted radiation. However, direct diagnostic lines of sights will not be available in most applications. At higher magnetic fields, high-frequency microwave components will be needed. Quantum sensors may be used on an MFE-FPP to measure magnetic fields within the fusion plasma.

Measurement Innovations

- Develop innovative ways to steer X-rays to diagnostics (e.g., double crystal option) having sensors located in a shielded location away from the neutrons and gamma rays to protect instruments and reduce signal backgrounds from neutrons and gamma rays in MFE-FPP devices.
- Develop multi-energy X-ray techniques to measure X-ray statistics far away from the plasma core (e.g., as low as is reasonably achievable). Consider also the development of neutron-hardened metal-vacuum photodiodes to measure ultraviolet, SXRs and HXRs.
- Develop high-frequency microwave components to reliably measure line integrals of plasma density and local measurements of electron temperature.
- Consider quantum sensors to measure magnetic fields for MFE-FPP devices.
- Continue to develop (along with high-energy physics efforts) radiation-hardened solid-state technology (e.g., diamond, silicon carbide, aluminum nitride, Gallium nitride) to measure DD and DT neutrons as well as X-rays.
- Set the requirements for radiation hardening on MFE-FPP and demonstrate the shielding technique on an existing MCF-BP device.

Unlike conventional diagnostic development, which focuses on implementing or optimizing known measurement techniques, measurement innovation introduces transformative capabilities.

CHAPTER 7

Inertial Fusion Energy Fusion Pilot Plant

Introduction

The recent accomplishments of ignition and energy gain on the National Ignition Facility (NIF) compel the scientific community to work toward an inertial fusion energy (IFE) fusion pilot plant (FPP). Measurement innovations are required to build and operate an FPP. Significant infrastructure diagnostics have to be developed for monitoring the health of the plant and driver, accountancy in the fuel cycle (likely tritium breeding), and innovative target tracking and metrology schemes. All these innovations need to function at possibly high-repetition rates of up to 10 Hertz (Hz) and survive in harsh radiation environments under continuous operation. These FPP requirements mean that in addition to new developments, existing technologies used in research facilities like NIF, Omega Laser Facility, and Z will need to be further developed and adapted with a focus on simplicity and economy.

A renewed focus toward IFE relies heavily on gains made in other plasma research areas shown in this report. The inertial confinement fusion (ICF) burning plasma community will deliver a robust approach to ignition and high gain that will require further research and development to meet FPP requirements. Plant infrastructure diagnostics and tritium breeding and accounting will be areas of diagnostic research shared with the magnetic fusion energy (MFE) community. Development of high-repetition-rate diagnostics for IFE can build on the progress made in the the high energy density plasma (HEDP) community. The push toward fusion energy will also require advanced data handling, especially for large datasets collected at higher repetition rates, an area of research shared with all other areas in this report. Several crosscutting priority research opportunities (PROs) amongst the working groups have been identified. The working groups recognize the need for improved access to facilities for diagnostic calibration, and propose establishing a coordinated network of existing facilities for this purpose (CalibrationNetUS). Similarly, with many new private fusion ventures and public-private partnerships simultaneously coming online, there is a desire to minimize duplication of efforts, motivating a push for a collaborative “DiagnosticNet,” facilitating pooling of resources to develop commonly needed diagnostics. Another overarching goal with shared resources needs to be the development of a workforce of diagnostic experts for the needs of a future plant.

While the ICF community will focus on high gain and high areal densities in a robust ignition scheme, the path to IFE necessitates high-repetition rates and cost-effective scaling of driver and target approach. The measurement innovations identified in this chapter are intended to be driver agnostic and should encompass a diverse set of schemes, including direct-drive and indirect-drive implosions using lasers, as well as ion beams and pulsed-power magnetic concepts, like magnetized liner inertial fusion.

To get to an IFE-FPP, progress compared to current best-performing experiments must be made with respect to energy gain and shot rate. The LaserNetUS network of smaller laser facilities enables experiments at relevant high-repetition rates but without significant energy gain. As an intermediate step to bridge the gap between current capabilities (e.g., NIF) and requirements for an FPP, an IFE research facility will be essential. Such a facility needs capability to operate at intermediate-repetition rate (e.g., of order minutes), both in order to make rapid progress on the physics of IFE and to learn how to handle the practical implications of rapidly repeating implosions. It also needs to operate at significant energy gain, both to reach the physics readiness for IFE and to bridge the gap in terms of neutron impact on ancillary systems.

Retrospective

Future production power plants will likely need an extremely minimal set of target and plasma diagnostics and focus on controls, while the diagnostic requirements for an FPP will be similar to current research facilities albeit with a simplified set of diagnostics. In addition to target and plasma diagnostics, a new set of plant diagnostics that continuously monitor operation will be needed.

The aim of this chapter is to further expand on the concepts established in the 2022 IFE Basic Research Needs (BRN) report chapter on measurement innovation. One of four PROs introduced in that report concentrated on high gain, which is further expanded on in the ICF burning plasma section of this report. The other three concern repetition rate, radiation-hardened diagnostics, and FPP monitoring (infrastructure diagnostics). These are further expanded on in this chapter and add more crosscutting themes needed on the path to an FPP.

The 2022 IFE BRN report also discussed increasing public-private engagement on the path to IFE in mutually beneficial agreements similar to the the Department of Energy’s Innovation Network for Fusion Energy program. Public-private partnerships present a particular opportunity for the road to an FPP in that the private sector can benefit from decades of scientific progress while the private investment currently greatly surpasses public sector investment. For this purpose, the establishment of a DiagnosticNet consortia where the public and private sectors can openly collaborate in the measurement space would be beneficial to the Fusion Energy Sciences community.

Current Status

This chapter builds on previous research on the design and concepts of FPPs, especially for diagnostics. Moving toward higher repetition rates, vastly more data than produced in current experiments will be generated. Incremental progress on data infrastructure would encompass updating existing facility-specific metadata standards, developing new analysis routines, or cross-training existing workforce in data science areas. Transformative progress requires large-scale implementation of community metadata standards, more openly shared community analysis software, and the incorporation of data science as a crucial aspect of the HEDP/ICF field. This represents an infrastructure challenge to the current status and a science opportunity.

The upcoming high-repetition rates place new requirements on rapid diagnostics and experimental controls. In particular, a need for real-time feedback loops, with diagnostic output utilized to optimize run parameters on a timescale too short to allow human intervention, is identified. Projects that make incremental progress on high-repetition-rate diagnostic detection would replace existing low-repetition rate detectors (e.g., Columbia Resin #39) with higher repetition rate (few minute shot rate) compatible detectors (e.g., scintillators). This requires that these existing detectors have been characterized for the high-dose rate. Projects that are transformative require coordinated effort on diagnostic developments compatible with multi-Hertz repetition rates, including the development of new detector technology, the development of diagnostic support infrastructure (control and analysis pipelines), and training of personnel to move beyond the necessity for frequent manual diagnostic intervention.

With the high energy gains required for fusion power production and with near-continuous electromagnetic pulses and load on the FPP target chamber, diagnostics need to be able to withstand harsh conditions for long periods of time. There is obvious overlap between IFE and MFE in this area. Incremental progress could be made by testing existing detector technologies in high-radiation environments, while novel rad-hardened developments are substantial and as fundamental as chip design.

Specific to IFE, with the need to repeat implosions at a level of ~10 Hz, high-quality targets need to be produced economically at a high rate, motivating a need for target metrology measurement innovations. Incremental projects increase the speed of measurement of important target parameters from hours to minutes. Projects that are transformational would reach measurement speeds consistent with 100% inspection at IFE power plant shot rates (~Hz level). Also transformational would be the ability to measure target fuel configuration and quality on a timescale of an IFE target travel from the edge to the center of the IFE chamber.

Another area that overlaps strongly with MFE, and also partly with plasma material interaction, is the need for plant infrastructure diagnostics (e.g., monitoring driver and first-wall health, breeding-blanket integrity, tritium accounting). One project for breeding-blanket material that is incremental is the measurement of the light-Z nuclei with a reduced uncertainty. A transformational advancement would be using continuous data, recorded and diagnosed at a high-shot rate, to learn when any part of the system will need to be replaced before expected failure.

Moving from the current ICF research facilities toward IFE research facilities and an FPP will by necessity include a shift from many diagnostics to maximize physics understanding to minimal diagnostics to maximize performance monitoring. While even an IFE-FPP will need substantially more diagnostic capability than production plants further into the future, there is a need to find ways of down selecting, identifying the absolute key diagnostics, and also maximizing information output from each individual diagnostic. Incremental studies include optimizing current ICF diagnostics for IFE environments (i.e., solid angle subtended by the diagnostic), while more transformational studies would first deduce a minimum suite of diagnostics, as well as develop a completely novel suite of diagnostics optimized for an FPP.

There is a community-wide recognized need for infrastructure and resources to calibrate diagnostics, which will help in all areas of measurement innovation. Similarly, with several new research facilities potentially coming online on a similar timescale, there is a community-wide need to conserve resources by minimizing duplication of efforts. Finally, recognizing that the community is in the midst of a rapid acceleration of fusion activities, there is going to be a broad need for skilled workers. This presents an opportunity to strive to build a more diverse workforce in the field going forward.

Priority Research Opportunities

PRO 1: Develop a diagnostic data infrastructure and the software ecosystem that meets IFE requirements.

Scientific Challenges

The diagnostic data infrastructure and the software ecosystem to advance IFE needs to be developed by the community. This entails creating standardized community metadata and data formats for archiving and sharing experimental data and simulation outputs, as well as building computer infrastructure for storing, sharing, and analyzing large datasets. Creating the necessary software ecosystem entails automated data reduction and pre-processing, preliminary analysis, real-time post-shot visualization software, and modern data science, including artificial intelligence (AI) and machine learning (ML) to extract more information from data-rich diagnostics and large datasets.

A shot at the NIF currently generates over a hundred gigabytes of data. With a similar diagnostic suite, an IFE research facility would generate around two terabytes per hour, while an IFE power plant might generate more than five petabytes per hour. Analysis of large experiments and simulation datasets have already led to significant advances in ICF, and higher data rates at higher repetition rates will enable exciting opportunities. The community should reposition data science as a central effort in the development of IFE, including hiring new experts in this area and developing these skills in the existing workforce.

Measurement Innovations

- Leverage advances in modern data science (including AI and ML) to extract more information from data-rich diagnostics and large datasets. Many diagnostics developed for ICF gather lots of data and will gather even more data as the shot rate increases. Advances in data science, AI, and ML should be used to extract more information from existing diagnostics and to analyze large datasets collected across many shots. Techniques should be developed to combine information from multiple diagnostics to reconstruct implosion features. AI and ML models will likely require pretraining on synthetic datasets, which will require the development of more synthetic diagnostics. Bayesian inference should be applied to experimental data and to determine minimal sets of diagnostics required to constrain important parameters in IFE implosions.
- Develop automated data reduction, preprocessing, preliminary analysis, and real-time post-shot visualization software for both facility and physics diagnostics. While most current ICF experiments involve human-intensive data processing, analysis, and bespoke visualizations conducted post-shot, experiments at high data rates will necessitate real-time automation of these processes. AI and ML can be used to automate parts of this process, but this process has not been im-

plemented for the majority of ICF diagnostics that are relevant for IFE. Data from both physics and facility monitoring diagnostics must be processed and analyzed between shots to enable feedback loops and ensure facility stability and safety. Wherever possible, these tools should be generalizable to multiple diagnostics of a given type and should be developed as open-source software to streamline efforts. This software should be well documented and tested to ensure accuracy and maintainability.

- Develop computational infrastructure at new and existing facilities for storing, sharing, and analyzing large datasets. Transferring, reducing, archiving, and retrieving petabyte-scale datasets will require a new class of data infrastructure to be employed at new and upgraded facilities. Large datasets will be difficult to transfer, requiring local computing power and the ability for users to easily query the database and run analysis on computers close to the data. National computer infrastructure will be necessary to share datasets between institutions. The IFE community should learn from other fields that already handle high data rates and large datasets (e.g., high-energy physics).
- Develop standardized community metadata and data formats for archiving and sharing experimental data and simulation outputs. Standardized data formats are a prerequisite for the development of shared data analysis tools that can be applied across multiple facilities and codes and would enable publication and sharing of data along with publications, improving scientific reproducibility. The data ecosystems in HEDP and ICF are currently highly fragmented. In order to enable the other goals of this PRO, experimental facilities and simulation codes must be updated to take advantage of common data formats (e.g., HDF5) and include comprehensive metadata required to interpret the data. Communities such as Pangeo (geophysics, https://pangeo.io/) provide a template for improved data and software ecosystems. Data formats should follow the findability, accessibility, interoperability, and reusability principles.

PRO 2: Develop real-time, high-repetition-rate diagnostics to accelerate physics understanding and enable stable, long-term, high-average, fusion power output.

Scientific Challenges

For an IFE pilot plant operating at 10 Hz, real-time diagnosis of the plant conditions — the driver, target, and fuel cycle — will be essential to maximize efficiency and minimize downtime. Development of existing and novel diagnostic capability must be compatible with high-repetition rate operation and be conducted in tandem with a deepened understanding of radiation damage and development of supporting data and control infrastructure. To ensure reliable long-term operation of an FPP, scientists and engineers must monitor the key parameters, like the quality of the fuel and status of the driver, at high-repetition rates. Those rates are orders of magnitude faster than the maximum rates of current diagnostics. To enable the development of faster diagnostics, including those for drivers, targets, and the fuel cycle, among others, scientists must create a list of these key parameters and their required sampling rates.

Measurement Innovations

- For some of these diagnostics, an increase in repetition rate can be achieved by updating existing diagnostics with new detector technology. One example is a neutron spectrometer with a single-use plastic detector that could be upgraded to operate at 10 Hz using a digital sensor. However, in many cases, a clear replacement sensor operating at multi-Hertz repetition rates with comparable dynamic range and resolution is not available today. The community needs to demonstrate that current multi-Hertz sensors satisfy requirements to operate in high-noise FPP environments, to overcome data transfer and processing challenges, and to be shielded from high-radiation environments. Initial measurements by the laser-plasma accelerator community exploring the use of scintillators as multi-Hertz detectors for particle beams has highlighted significant issues with afterglow and degrading detector performance after prolonged radiation exposure is a recognized problem.
- Research and development are required to upgrade existing diagnostics to operate at a repetition rate compatible with mid-scale IFE demonstration facilities. Using these facilities, scientists will be able to identify the crucial control parameters that must be diagnosed at the full multi-Hertz repetition rates of commercially viable IFE-FPPs. In addition, these facilities will test the suitability of different detectors and sensors for operation in a high-radiation environment. Moreover, the move to an increasingly high data collection rate will facilitate measurement innovations by accelerating diagnostic testing and troubleshooting.
- For systems operating at high-repetition rates, damage and drift can occur rapidly. It is necessary to develop online analysis of the diagnostics output, operating in real-time on large bandwidth data streams, with systems for feedback to control parameters to maintain the IFE-FPP within optimal operating conditions. For IFE-FPP, key known parameters that must be stabilized include driver spatial and temporal profile and fuel conditions and delivery. The development of online processing and challenges of high data rates can benefit from synergy with other fields such as high-energy physics.
- Some diagnostics in an IFE-FPP would be required to operate at every shot (e.g., total yield and spatial distribution of the fusion burn, driver energy and spatio-temporal profiles, driver health to detect degradation that could lead to reduced yield and facility downtime, and active tracking of the fuel target location). Others would be required to be operated every number of shots (e.g., pre-shot sample

target quality assurance, fuel-cycle diagnostics for tritium accountancy, and facility activation measurements).

PRO 3: Develop diagnostics that are radiation hardened to prompt dose from ignited plasmas, including single-event disruption mechanisms and cumulative damage and diagnostic lifetime studies.

Scientific Challenges

The successful operation of an FPP will require reliable and radiation-hardened (rad-hard) diagnostics that can operate at high-repetition rates. Both IFE and MFE approaches to fusion energy generation will require electronic recording of data near extreme radiation sources of neutrons, X-rays, and gamma rays that are capable of causing diagnostic damage, including both static/passive components over time (e.g., optical components such as lenses or fiber optics) or instantaneous electronic damage in semiconductors used for capturing and processing data. Additionally, high-energy particles and photons can induce undesired signal spikes that cause electronic signal disruptions and circuit failure. In an FPP, diagnostics both near and far from the fusion events must be continually available during plant operation, meaning that diagnostics and the underlying communication infrastructure must be reliable for at least many months at a time. In addition to understanding the cause and type of disruptions, important considerations include the cost of replacing diagnostic components, diagnostic maintenance, and the mean time to failure.

Measurement Innovations

- Single-event disruption mechanisms: High-flux sources of energetic radiation, such as those found in ICF experiments, short-pulse laser-driven interactions, or pulsed power experiments, can be used to study the failure pathways for electronics placed in close proximity to the fusion plasma. In parallel, finite element modeling in tandem with physics models (i.e., radiation hydrodynamics, magnetohydrodynamics, particle-in-cell or other codes) can be used to model the radiation environments and electronic diagnostic technologies to better understand and mitigate failures through radiation hardening.
- Cumulative damage and diagnostic lifetime studies: High-average fluence sources of radiation can be used to study the effects of integrated damage to passive and active diagnostic components. The response and degradation of passive components should also be assessed in order to determine the expected lifetime of diagnostic constituents to further enhance radiation mitigation strategies, develop failure prediction models, and subsequent plans for maintenance and replacement costs in an FPP.
- Crosscutting needs for rad-hard diagnostics and reliability metrics: The ICF and magnetic confinement fusion communities continually push the development of

radiation-hardened technologies for platform-specific diagnostic disruption mitigation and reliability in high-flux and high-average fluence environments. These communities should compile best practices and ultimately work toward governing engineering principles that can be used to design FPP diagnostics. Researchers could look to communities such as the hardened electronics and radiation technology and space electronics designs for both damage mitigation, testing, and modeling capabilities. Additionally, sources of radiation relevant to those expected within a specific IFE approach should be leveraged across communities to study diagnostic robustness to damage. The community thinks that campaigns should be allocated to researchers seeking to further diagnostic radiation hardening and reliability understanding and technologies.

PRO 4: Develop systems to rapidly measure the dimensions and defects of IFE targets.

Scientific Challenges

Currently, successfully igniting ICF targets requires that they be manufactured with extremely high precision and accuracy. Small imperfections, even at the micron level, can seed hydrodynamic instabilities that spoil the implosion of the target. As target designs for IFE evolve and as researchers develop IFE drivers with higher energy, the robustness of the IFE target is expected to improve. This improved robustness could lead to less demanding IFE target tolerances. Fortunately, measurement systems developed for ICF targets can be adapted for IFE targets with adjustment for target size and speed improvements. These systems can then be used for IFE target validation shot campaigns at higher frequencies and for quality assurance for the IFE target factory — measuring sample targets to maintain stable output from factory production processes.

One particular need is determining how well the cryogenic fuel layers of IFE targets made of deuterium and tritium might survive the high temperatures they will encounter as they move from the edge of the reaction chamber to the center. This measurement may be done using numerical modeling for types of targets in which the fuel layer is buried deep within the target. However, since the fuel layer is sometimes near the surface, as in laser-direct-drive targets, the community ought to develop a way to instantaneously inspect the fuel layer for use during or immediately after heat-flux application.

An additional consideration is that the target metrology diagnostics should not significantly impact the cost of the IFE targets. In other words, the life-cycle cost of the instrument amortized over all targets measured should be small compared to the cost of the mass-produced target.

Early capsule and fuel-layer metrology often used optical imaging and interferometry methods from a few discrete directions. Surface roughness via white light interferometry was supplemented with atomic force microscopy scans over several discrete great circle traces around the capsule. X-ray spectroscopy of the capsule is used to assess impurity content. X-ray tomography has been used for measurements of opaque (e.g., beryllium) capsule dimensions and X-ray phase contrast imaging for the fuel contained in opaque capsules. The ability to rotate the capsule and fuel layer under the view of the interferometer optics has led to nearly full 4π measurements. These 4π measurements at high resolution have increased the amount of measurement time but have coincided with improved yield up to and including ignition on the NIF. As an example of the measurement times, a micro-X-ray tomography diagnostic can measure the full volume of an NIF target capsule in about four hours, and a digital holography microscope can map the height of an entire capsule surface in about one hour.

Measurement Innovations

- The "rapid" in this PRO refers to making target measurements faster than currently done — about one shot per hour — to support the intermediate shot rate of future implosion facilities — about one shot every five minutes — that are planned by IFE power companies to validate target performance. The goal here is 100% inspection so the target's initial conditions and performance can be compared to understand any degradation in yield caused by the initial target conditions during the development of a robust igniting target design. The "rapid" also involves shortening the measurement time to as much as the inverse of power plant shot frequencies, which is typically conceived as being between ~0.1 Hz to ~15 Hz. This would permit 100% inspection of the power plant targets. However, for a robust target design and fabrication processes, the intermediate measurement rate is still highly useful. In this case, the community would perform witness sampling of targets to make sure that the production processes stay within particular tolerances.

- The types of measurements desired for the capsule ablator, liner, and fuel layer include but are not limited to the following: diameter, deviation from spherical or cylindrical symmetry, wall thickness and thickness uniformity, surface defects (roughness, bumps, pits, surface contaminants), volume defects (voids, contaminants inclusions, compositional inhomogeneity), and fill hole dimensions and shape, where present. The coherent anti-Stokes Raman scattering (CARS) microscope described in the workshop white paper describes such a system to scan at high resolution through the volume of a capsule and/or hydrogen isotope fuel layer. The CARS system is sensitive to molecular vibrations and, hence, can detect chemical and even isotopic variations in the target and fuel, as well as voids and inclusions.

- To use the large amounts of data gathered by diagnostics as they rapidly measure the IFE targets, the community will need to use ML and AI techniques to reduce the data. Doing so will aid target validations and make the information more intelligible to researchers. Automated data reduction powered by ML will also greatly aid how factories make the targets, aiding the sorting of parts like capsules and liners and other production line control parameters.

PRO 5: Develop critical infrastructure and diagnostic requirements for initial operation of an IFE-FPP.

Scientific Challenges

Successful demonstration of energy gain from plasma ignited using ICF has received considerable attention from the worldwide scientific community. With this successful achievement, there is a growing view that the ignition demonstration has put to rest all major science questions surrounding central hot-spot ignition and that only engineering challenges remain. However, there are many scientific challenges remaining to demonstrate a high fuel burn-up fraction, energy extraction from fast neutrons, tritium accountancy, operational safety, and reliability of a pilot plant infrastructure required for future IFE reactors, including critical infrastructure diagnostic requirements.

Measurement Innovations

- Status monitor of fusion driver and nuclear production rate: An IFE power plant must combine high-gain implosions with a high-repetition rate. To ensure that it does so, there must be diagnostics that monitor the status of the laser, how well the laser is heating the targets, and the quality of those targets. Moreover, those diagnostics must be able to withstand high levels of radiation. Measurement innovations are required to monitor the status of the fusion driver and the nuclear production rate.
- First-wall interaction with high-flux system: Another key challenge for IFE reactors is dealing with damage to the reactor first wall due to fast neutrons and other energetic particles, as well as hard X-ray and gamma ray photons. This challenge creates several difficulties for IFE commercialization, best understood in contrast to conventional fission reactors:
    - IFE reactors are generally designed to run in a pulsed mode, resulting in peak neutron fluxes much greater than that of continuous fission reactors.
    - Charged ion/electron debris energies may be as great as ~10 MeV.
    - The neutron energy of 14 MeV from deuterium-tritium fusion is much greater than the ~2 MeV of neutrons from regular fission reactors, resulting in up to three times more atom displacements expected in first-wall materials for fusion reactors.
    - The tritium burn-up fraction for IFE of 30% will lead to significant contamination and will need to be addressed at the first wall. As a result, measurement innovations are required to better understand and monitor the debris and

radiation damage to first-wall materials. This measurement would include the regions outside of the first wall, where debris shields would be required to allow entry of the designated driver. For a fusion reactor, large-scale simulations and experimental verification of first-wall health, in preparation for a high-intensity neutron source facility for experimental testing, is a necessary step toward solving these challenging problems.

- Verification of tritium breeding rates and migration in blanket materials: Future commercial fusion reactors will be powered by deuterium-tritium (DT) fuel. But since the tritium does not occur naturally, it must be produced in fusion reactors by the interaction of neutrons and lithium. The breeding of tritium in a controlled fusion facility will be processed from the interaction of fast neutrons from the ^{7}Li(n,n′^{3}H)α inelastic reaction. Furthermore, residual thermal neutrons will utilize the ^{6}Li(n,^{3}H)α inelastic reaction channel. But at the moment, the majority of designs are focused on just ^{6}Li to take advantage of the high cross section with decreasing neutron energy.
- There is a substantial cost to enriching lithium to the required ^{6}Li concentration. Therefore, one needs to understand and measure the breeding cross sections as a function of neutron energy for lithium isotopes to balance the benefit against the cost of enrichment. To achieve the accepted level of neutron absorption and tritium breeding for a tritium-breeding ratio ~ 1.2, when combined with material that will moderate the fast neutrons, a different concentration of these two lithium isotopes in the blanket configuration for future planned reactors is required. Cross section measurements for the ^{6}Li(n,n′^{2}H)α and ^{7}Li(n,n′^{3}H)α reactions along with the (n,^{2}n′) reactions for both ^{6}Li and ^{7}Li at 14 MeV are very sparse with some of these reaction channels and presently inconclusive with theoretical models. A direct measurement of the tritium production with fast neutrons from lithium isotopes is needed to constrain the current theoretical models currently being used to model breeding-blanket materials.
- To support the research of tritium breeding, development of a mini blanket on the exterior wall of the Omega Laser Facility target chamber is essential and regarded as a first step. This proposed experiment would first use lithium isotopes to benchmark the experimental setup. Once operational and verified, additional experiments can begin to look at more sophisticated blanket materials to diagnose thermal control and health for extended use in an FPP. On average, the Omega Laser Facility performs up to 100 DT implosions per year, generating up to $2\text{x}10^{24}$ neutrons/second in 4π. The proposed mini blanket would be online, without interruption, and measure the tritium production over the course of the year with one of the highest, if not the highest, neutron fluxes used to test blanket materials currently available.
- Another consideration is determining how tritium permeates through the lithium and chamber materials. It will be important to quantify how much of the tritium

may be trapped in the chamber material itself, which could potentially be difficult to extract. For example, vanadium is a candidate material for blankets, but vanadium alloys have a high hydrogen solubility. Therefore, structural materials made of vanadium require permeation barriers to prevent significant tritium permeation. Atomistic modeling like density functional theory or molecular dynamics can play a key role in determining how hydrogen traps and diffuses in materials. It will be critical to understand the atomic scale processes by which tritium will diffuse through these materials in order to design the blanket for optimizing tritium extraction and accounting requirements.

- Post-shot monitoring: To maintain a high-repetition rate and safe operation, several key components of the facility must be monitored and checked after each high-yield event. This begins with the next-target availability through ready status of the driver system and requires an innovative viewing system to verify target alignment and the required amount of fusion fuel. To confirm the ready status of the driver, a diagnostic must provide feedback to the system informing the health and availability before the impending implosion. This would be a reliable feedback loop from the following subsystems in the post-shot cycle: 1) status of the driver, 2) verification of the next-up target, and 3) readiness of on-shot monitors, including status of current radiation levels.
- Preventative maintenance: The proposed diagnostics are critical to determining an FPP's overall availability and whether it ought to shut down for maintenance. One goal for the FPP is to use data collected by the diagnostics to predict which infrastructure components and diagnostics need to be checked or replaced. Researchers could also use ML techniques to generate expected failure rates.

PRO 6: Develop implosion diagnostics for an IFE-FPP.

Scientific Challenges

An IFE-FPP will require diagnostics to monitor the targets and implosions. These target-monitoring diagnostics would gather information about each shot and give feedback to the target factory and the FPP's driver system, as well as possibly providing feedback that could improve the pre-shot target tracking and alignment system. Power plant diagnostics will be subject to additional constraints not present in any current inertial fusion research facility, including compatibility with the plant systems and minimization of solid angle; these are especially important to maximize solid angle for the tritium-breeding blanket. In addition, an FPP may include a more extensive diagnostic suite than the ultimate fusion reactor or use a more extensive suite of diagnostics during the commissioning phase to ensure adequate performance and robustness of the target. Similarly, a predecessor scientific demonstration facility will certainly be significantly more diagnosed and require transition of the diagnostic methodologies to an FPP.

Measurement Innovations

- Private and public efforts should determine the required measurement techniques for each FPP concept. Determining the minimum number of diagnostics required to target specific physics quantities is absolutely necessary for operation of an FPP.
- Minimize solid angle requirements of existing technologies: Existing diagnostics on leading ICF experiments were predominantly designed with no or minimal constraints on their solid-angle usage. Performing design studies to either minimize solid angle usage of a single diagnostic or combining multiple measurements on one line of sight is needed.
- Transition scientific facility diagnostics to FPP: All state-of-the-art diagnostics on the National Nuclear Security Administration's flagship scientific facilities (NIF, Omega Laser Facility, Z) were designed with a different set of requirements than those necessary to operate an FPP (e.g., requirements on the operating repetition rate, accessibility to replace components between shots, reliability of key components, radiation hardening, activation, alignment tolerances, and cost). Transitioning existing technologies to meet the anticipated requirements of an IFE-FPP by design improvements, component testing, and adaptation of new technologies is needed.

Appendices

Charge to the Community

Basic Research Needs for Measurement Innovation in Fusion Energy Sciences
Chair: Luis F. Delgado-Aparicio (Princeton Plasma Physics Laboratory)
Co-Chair: Sean P. Regan (Laboratory for Laser Energetics, University of Rochester)

The Fusion Energy Sciences (FES) program mission is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundation needed to develop a fusion energy source. This requires the development of advanced diagnostics to make detailed measurements of its properties and dynamics. In addition to fusion energy research and development, the FES program supports the development of the science for other applications of plasmas with high societal impact, such as low temperature plasmas for microelectronics, general plasma science, and high energy density laboratory plasmas.

In response to the Fusion Energy Sciences Advisory Committee's Long-Range Planning drivers report, and the pursuit of the administration's "Bold Decadal Vision" for commercial fusion energy, there is a need to assess the diagnostic needs for public and private sector fusion efforts. To this end, FES is charging the community to conduct a basic research needs (BRN) workshop for measurement innovation for the full FES program, with the following.

Charge

The purpose of this Department of Energy-sponsored workshop is to collect information on:

- Opportunities for advances in diagnostics to enable progress toward fusion energy.
- Where diagnostics are needed to support the desired advances in burning plasma physics and fusion science.
- What plasma measurements are needed to fully explore plasma science and technology activities (e.g., low temperature plasmas, high energy density laboratory plasmas, warm dense matter, and plasma material interactions).

The findings of this workshop will be summarized in a report that should be submitted to FES within three months after the meeting. The structure will follow the usual BRN format of plenary and breakout sessions, with FES as the sponsoring organization.

In addition to the final report, the workshop is expected to provide FES with:

- A diagnostic perspectives factual document that describes the current status of diagnostic development and will be prepared prior to the workshop.
- Panel surveys describing the current and 10-year projected state of science for each panel.
- Prioritized diagnostic opportunities from each panel.
- Science and diagnostic relationships charts completed by the participants.
- A retrospective on the role of advanced diagnostics on the development of tokamak, stellarator, and inertial confinement fusion plasma science and performance.

Membership of Working Groups

Low Temperature Plasma

Chair: Earl Scime, West Virginia University
Co-chair: Sedina Tsikata, Georgia Institute of Technology
Arthur Dogariu, Texas A&M University
Vincent Donnelly, University of Houston
Uwe Czarnetzki, Ruhr-Universität Bochum
Mark Kushner, University of Michigan (UMICH)
Shurik Yatom, Princeton Plasma Physics Laboratory (PPPL)
Ahmed Diallo, PPPL & Advanced Research Projects Agency-Energy (ARPA-E)
Mark Cappelli, Stanford University
Brian Bentz, Sandia National Laboratories (SNL)

High Energy Density Plasma

Chair: Lan Gao, PPPL
Co-chair: Laura Robin Benedetti, Lawrence Livermore National Laboratory (LLNL)
Steven Ivancic, University of Rochester-Laser Energetics Laboratory (UR-LLE)
Gilbert “Rip” Collins, UR-LLE
Yuan Ping, LLNL
Kirk Flippo, Los Alamos National Laboratory (LANL)
George Swadling, LLNL
Carolyn Kuranz, UMICH
Frances Kraus, PPPL
Derek Schaeffer, University of California, Los Angeles

Plasma Material Interaction

Chair: Juergen Rapp, Oak Ridge National Laboratory (ORNL)
Co-chair: Martin de Jesus Nieto, Penn State University
David Donovan, University of Tennessee, Knoxville
Tyler Abrams, General Atomics (GA)
Robert Kolasinski, SNL
Chase Taylor, Idaho National Laboratory
Bruce Koel, Princeton University
Matthew Baldwin, University of California, San Diego
Kevin Woller, Massachusetts Institute of Technology (MIT)
Daniel Andruczyk, University of Illinois, Urbana-Champaign

Magnetic Confinement Fusion — Burning Plasma

Chair: Vlad Soukhanovskii, LLNL
Co-chair: Novimir Antoniuk Pablant, PPPL
Glen Wurden, LANL
Marcel Nations, TAE Technologies
David Smith, University of Wisconsin-Madison (UW-Madison)
Adam McLean, LLNL
Calvin Domier, University of California, Davis
George Vayakis, ITER
Michael Walsh, ITER
John Rice, MIT
Graham Naylor, Tokamak Energy–UK

Inertial Confinement Fusion — Burning Plasma

Chair: David Schlossberg, LLNL
Co-chair: Luke Ceurvorst, UR-LLE
Christian Stoeckl, UR-LLE
Eric Loomis, LANL
Kevin Meaney, LANL
Owen Mannion, SNL
Johan Frenje, MIT
Chris McGuffey, GA
Wolfgang Theobald, Focused Energy
Justin Jeet, LLNL

Magnetic Fusion Energy — Fusion Pilot Plant

Chair: Réjean Boivin, GA
Co-chair: Ted Biewer, ORNL
Diane Demers, Xantho Technologies
Sara Ferry, MIT
Thomas Roche, TAE Technologies
Lisa Reusch, SHINE Technologies
Max Austin, University of Texas at Austin
Jeph Wang, LANL
Sai Tej Paruchuri, Lehigh University
Benedikt Geiger, UW–Madison

Inertial Fusion Energy — Fusion Pilot Plant

Chair: Verena Geppert-Kleinrath, LANL
Co-chair: Maria Gatu Johnson, MIT
Peter Heuer, UR-LLE
Chad Forrest, UR-LLE
Alex Zylstra, LLNL
David Ampleford, SNL
Neil Alexander, GA
Prav Patel, Focused Energy
Dave Montgomery, Xcimer Energy Corporation
Charlotte Palmer, Queen’s University Belfast
Derek Mariscal, LLNL

List of White Papers Submitted by the Community

White Papers Submitted for Low Temperature Plasma

Author	Organization	Title
Paul Bellan	Caltech	How to Make Research Funding More Effective
Paul Bellan	Caltech	Atomic Level Understanding of Plasma-Catalyzed Nucleation
Paul Bellan	Caltech	Exploring the Connection Between Atomic Line Radiation and Energetic Electron Tails
Peter Bruggeman	University of Minnesota	In-situ Plasma-Surface Diagnostics for Advancing Low Temperature Plasma Science and Engineering
Mark Cappelli	Stanford University	Development and Databases of Low-Cost Commonly-Employed Diagnostics
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	Adjust Budget of Early Career Research Program to Maintain Leadership and Cutting-Edge Measurement Innovation Across U.S. Academic Institutions and DOE Complex
Vincent Donnelly	University of Houston	The Challenges for New Diagnostics in Plasma Processing of Microelectronics Materials for Research and Manufacturing
Jonathan Frank	Sandia National Laboratories	Plasma-Assisted Chemical Transformations and Interactions With Interfaces
Ken Hara	Stanford University	Modeling of Plasma Diagnostics for Low Temperature Plasmas
Robert Kolasinski	Sandia National Laboratories	In-vacuo Scanning Probe Microscopy for Deciphering the Effects of Plasma Exposure at an Atomic Scale
Mark Kushner	University of Michigan	Precision in Measurements for Low Temperature Plasmas
Pingshan Luan	Tokyo Electron Limited	Plasma Diagnostic Needs in the Semiconductor Industry
Saskia Mordijck	William & Mary	Optical Quantum Sensing Diagnostic Development for Noninvasive Measurements of Electric and Magnetic Fields in Plasmas
Stefano Munaretto	Princeton Plasma Physics Laboratory	Innovative Magnetic Diagnostics Needs
Yevgeny Raitses	Princeton Plasma Physics Laboratory	Collaborative Plasma Research Facilities — Enabling Facilities for the Low Temperature Plasma Community

Yevgeny Raitses	Princeton Plasma Physics Laboratory	Electrostatic Probes — Beyond Intuitive Perception of Simple Models
R. Mohan Sankaran	University of Illinois Urbana-Champaign	White Paper on Diagnostics for Plasma-Liquid Fixation of Nitrogen
Earl Scime	West Virginia University	Application of Entangled Photon Spectroscopy to Plasmas
Peiyun Shi	Princeton Plasma Physics Laboratory	Measure Nonthermal Electrons via Incoherent Thomson Scattering in Low-Density Low-Temperature Plasmas
Marien Simeni	University of Minnesota	Diagnostics of Laser-Produced Plasma-Based Extreme Ultraviolet Light Sources for Nanolithography in the Semiconductor Industry
Sangeeta Vinoth	Princeton Plasma Physics Laboratory	X-ray Energy Distribution Measurements of a Field-Reversed Configuration Plasma
Yin Wang	Princeton Plasma Physics Laboratory	Integrated Heat Flux Measurement in Convective Liquid Metal Flows
Shurik Yatom	Princeton Plasma Physics Laboratory	Advancing Applications of Machine Learning Approaches in Low-Temperature Plasma Measurements
Shurik Yatom	Princeton Plasma Physics Laboratory	In situ Measurement of Nanomaterials Synthesized in Plasma
Jongsoo Yoo	Princeton Plasma Physics Laboratory	Development of a Portable, Noninvasive, Multi-Diagnostic System for Fundamental Plasma Physics Studies at Basic Plasma Facilities

White Papers Submitted for High Energy Density Plasma

Author	**Organization**	**Title**
Félicie Albert	Lawrence Livermore National Laboratory	Diagnostic Development and Calibration at the Jupiter Laser Facility for High Energy Density and Inertial Fusion Energy Science
Cameron Allen	Los Alamos National Laboratory	Determining Transport Properties of High Energy Density Systems Using Fresnel Diffractive Radiography
Steven Batha	Los Alamos National Laboratory	Diagnostics for Short-Pulse Radiography
Daniel Barnak	Laboratory for Laser Energetics, University of Rochester	Using Filtered X-ray Diode Arrays for Measurements of Areal Densities From Hot Spot Self-Emission of Laser Direct Drive Implosions
Paul Bellan	Caltech	How to Make Research Funding More Effective
Paul Bellan	Caltech	Exploring the Connection Between Atomic Line Radiation and Energetic Electron Tails
Gerrit Bruhaug	Laboratory for Laser Energetics, University of Rochester	Coherence-Boosted Inverse Compton X-ray Source for ICF and HEDP Applications Diagnostics for IFE applications

Fabio Conti	General Atomics	Development of Data Handling Frameworks for High-Repetition-Rate High-Energy-Density Science
Skylar Dannhoff	Massachusetts Institute of Technology	GRASP: A New Compact Gamma Ray Spectrometer Design for ICF, IFE, and Advanced Photon Source Platforms
Matthew Dayton	Advanced hCMOS Systems	Ultrafast 2D Compressive X-ray Imaging for High Energy Density Physics
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	Adjust Budget of Early Career Research Program to Maintain Leadership and Cutting-Edge Measurement Innovation Across U.S. Academic Institutions and DOE Complex
Robert Dorst	University of California, Los Angeles	Applications of Laser Induced Fluorescence to High Energy Density Science
Alexandre Do	Lawrence Livermore National Laboratory	Developing X-ray Optics to Measure Plasma Hydrodynamic Conditions in IFE Experimental Campaigns
Philip Efthimion	Princeton Plasma Physics Laboratory	High Resolution X-ray Spectroscopy
Luke Fletcher	SLAC National Accelerator Laboratory	Advancing Inertial Fusion Energy Science and Technology With the Matter in Extreme Conditions Upgrade
Kirk Flippo	Los Alamos National Laboratory	Advanced High-Resolution, Diffraction-Sensitive, Hyperspectral X-ray Imaging Enabled by X-ray Optics and Machine Learning
Will Fox	Princeton Plasma Physics Laboratory	Advancing Charged Particle Radiography for High Energy Density Plasmas
Lan Gao	Princeton Plasma Physics Laboratory	Absolute Calibration of X-ray Crystal Spectrometers for High Energy Density Science and Inertial Confinement Fusion
Siegfried Glenzer	SLAC National Accelerator Laboratory	High Resolution Multi-Pulse X-ray Imaging Diagnostic
Clément Goyon	Lawrence Livermore National Laboratory	The MJOLNIR Dense Plasma Focus Platform in Support of Advanced Diagnostic Development
Peter Heuer	Laboratory for Laser Energetics, University of Rochester	Measurement Innovation in Inertial Fusion Energy and High Energy Density Science Experiments at High(er) Repetition Rates
Matthew Hill	Lawrence Livermore National Laboratory	Optimization and Stabilization of Outputs From High-Energy-Density Plasmas Through Rapid Feedback and Machine Learning
Frances Kraus	Princeton Plasma Physics Laboratory	Ensemble-Based Data Analysis for High-Repetition-Rate Experiments
Frances Kraus	Princeton Plasma Physics Laboratory	Real-Time Data Visualization at User Facilities: Integrating Facility and User Diagnostics
Sophia Malko	Princeton Plasma Physics Laboratory	Charged Particle Diagnostics Operating at High Repetition Rate to Advance Proton Fast Ignition

Sophia Malko	Princeton Plasma Physics Laboratory	LaserNetUS Facility and User-Driven Diagnostic Initiatives
Roberto Mancini	University of Nevada, Reno	Multi-Objective Data Analysis
Michelle Marshall	Laboratory for Laser Energetics, University of Rochester	Nanosecond Raman Spectroscopy for Dynamically Compressed Matter
Soumyajit Mandal	Brookhaven National Laboratory	Integrated SiC Active Pixel Sensors for Plasma Monitoring
Christopher McGuffey	General Atomics	High-Repetition Rate Diagnostics and Data Acquisition for High Energy-Density Physics Experiments
Stefano Munaretto	Princeton Plasma Physics Laboratory	Innovative Magnetic Diagnostics Needs
Robert Nowak	Laboratory for Laser Energetics, University of Rochester	THz Time Domain Spectroscopy for Electrical Conductivity Measurements
Lieselotte Obst-Huebl	Lawrence Berkeley National Laboratory	High-Resolution IFE Diagnostics With Ultrafast Laser-Based Particle and Radiation Sources
Novimir Pablant	Princeton Plasma Physics Laboratory	X-ray Calibration Sources: Concepts, Extended Area Sources, Anode Materials, Atomic Physics
Danae Polsin	Laboratory for Laser Energetics, University of Rochester	The Next Generation of X-ray Diffraction Measurements at Omega and NIF
John Porter	Sandia National Laboratories	Solid-State Streak Camera for High-Speed Recording of X-ray and Particle Diagnostics
Anthony Raymond	University of Rochester	Addressing the Need for High Throughput, Picosecond-Resolution X-ray Streak Tubes
Jorge Rocca	Colorado State University	Diagnostics for Ultrahigh Power Ultrafast Laser-Matter Interactions at High Repetition Rates Suitable for the Harsh Conditions at the Frontier of High-Energy Density Physics
Maria Pia Valdivia	University of California, San Diego	High-Resolution X-ray Imaging Platform for Laser-Driven Foam Targets and On-Site Metrology to Support HEDLP and IFE Target Development
Christopher Wink	Massachusetts Institute of Technology	Development of Next-Generation Neutron Spectrometers for Diagnosing Alpha Heating of Fuel Ions in ICF and MCF Experiments

White Papers Submitted for Plasma Material Interaction

Author	**Organization**	**Title**
Matt Baldwin	University of California, San Diego	PMI Diagnostic Needs for the Study of Burning Plasma Materials Interactions
Paul Bellan	Caltech	How to Make Research Funding More Effective
Theodore Biewer	Oak Ridge National Laboratory	In situ, Real-Time Measurement of Plasma Facing Component Erosion Using Digital Holography
Jonathan Coburn	Sandia National Laboratories	Integrated, Rad-Resistant MEMS Sensors for Fusion Reactor Wall Tile Diagnostics
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	Adjust Budget of Early Career Research Program to Maintain Leadership and Cutting-Edge Measurement Innovation Across U.S. Academic Institutions and DOE Complex
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	X-ray Measurements for Liquid Metal Plasma-Facing Components (PFCs), Tritium Breeding Blankets and Nonproliferation Applications
Alexandre Do	Lawrence Livermore National Laboratory	X-ray Optics to Measure Plasma Hydrodynamic Conditions in IFE Experimental Campaigns
Clément Goyon	Lawrence Livermore National Laboratory	The MJOLNIR Dense Plasma Focus Platform in Support of Advanced Diagnostic Development
Keisuke Fujii	Oak Ridge National Laboratory	Measurement Needs for Chemical-Physical Synergy in Plasma-Material Interactions
Camilo Jaramillo-Correa	Princeton University	Laser Induced Breakdown Spectroscopy (LIBS) for In-Vessel Plasma Facing Component (PFC) Characterization in Fusion Devices
C. Christopher Klepper	Oak Ridge National Laboratory	Critical R&D Needs Toward Reactor-Grade Fuel-Cycle Measurement and Control
Robert Kolasinski	Sandia National Laboratories	Neutral H Sensor for C-X H Flux on Wall and Divertor
Robert Lunsford	Princeton Plasma Physics Laboratory	In-situ Examination of Plasma Facing Components Through Fiber-Coupled Multiwavelength Raman Spectroscopy
Martin Nieto-Perez	The Pennsylvania State University	Use of Mössbauer Spectroscopy to Detect and Quantify Retention of Hydrogen Isotopes in Tungsten and Its Alloys
Yevgeny Raitses	Princeton Plasma Physics Laboratory	Electrostatic Probes — Beyond Intuitive Perception of Simple Models
Ewa Rönnebro	Pacific Northwest National Laboratory	Hydrogen Isotope Ultrahigh Vacuum Gettering and Permeation Test Capability With Multiple Detectors for Accuracy and Diagnostics

Greg Sinclair	General Atomics	In-Vessel Quantification of Hydrogenic Accumulation in Plasma-Facing Surfaces Using Laser-Based Techniques
Vlad Soukhanovskii	Lawrence Livermore National Laboratory	Near-Infrared Spectroscopy for Plasma Diagnostic and Control Applications

White Papers Submitted for Magnetic Confinement Fusion — Burning Plasma

Author	**Organization**	**Title**
Santanu Banerjee	Princeton Plasma Physics Laboratory	Development of a High Spatial and Time Resolution 2D Beam Emission Spectroscopy (BES) System for Measuring Density Fluctuations on LTX-β
Tullio Barbui	Princeton Plasma Physics Laboratory	X-ray Detection Capabilities for Measuring Anisotropies of the X-ray Emission Produced by RF-Driven Fast Electrons and Runaway Electrons
Paul Bellan	Caltech	How to Make Research Funding More Effective
Paul Bellan	Caltech	Exploring the Connection Between Atomic Line Radiation and Energetic Electron Tails
Dennis Boyle	Princeton Plasma Physics Laboratory	Benefits of High Throughput, High Repetition Rate, and Reduced Cost Thomson Scattering
Aleksey Bolotnikov	Brookhaven National Laboratory	X-ray and Gamma Ray Perovskite Sensors
Filiberto Braglia	General Fusion	Diagnostics for the General Fusion LM26 Machine
Michael Churchill	Princeton Plasma Physics Laboratory	Mutually Enhancing Diagnostic Information and Digital Models
Luca Cultrera	Brookhaven National Laboratory	Fast and Thermal Neutron Sensors
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	Adjust Budget of Early Career Research Program to Maintain Leadership and Cutting-Edge Measurement Innovation Across U.S. Academic Institutions and DOE Complex
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	Multi-Energy X-ray Measurements With Filters, Fast Photodiodes, and 2D-Pixelated Systems for Magnetically Confined Fusion Plasmas
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	T-Boundary Windows for X-ray Diagnostics in Fusion Energy Systems
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	X-ray Measurements for Liquid Metal Plasma-Facing Components (PFCs), Tritium Breeding Blankets and Nonproliferation Applications

Severin S. Denk	General Atomics	The Prospect of Bayesian Inference for the Diagnostic Design of MFE-FPP
Ahmed Diallo	Princeton Plasma Physics Laboratory	Next-Generation High-Rep Rate Laser System for Fusion Energy Science
Ahmed Diallo	Princeton Plasma Physics Laboratory	Validating Kinetic Neutral Simulations for Fusion Pilot Plant Design: Hydrogen Femtosecond Two-Photon Absorption Laser-Induced Fluorescence
Keisuke Fujii	Oak Ridge National Laboratory	Measurement Needs of 100-m/s Drift in Tokamak Plasmas
Matthew Galante	Nova Photonics	Enabling q-profile Measurements for ITER
Trey Gebhart	Oak Ridge National Laboratory	Measurement Needs for Tritium Accountancy in the Inner Loop of the Fusion Fuel Cycle
Benedikt Geiger	University of Wisconsin-Madison	High Bandwidth Charge Exchange Recombination Spectroscopy
Clément Goyon	Lawrence Livermore National Laboratory	The MJOLNIR Dense Plasma Focus Platform in Support of Advanced Diagnostic Development
Xiang Han	University of Wisconsin-Madison	Microwave Reflectometry Development for Fusion Pilot Plants
Suk-Ho Hong	General Atomics	DIII-D Support for Magnetically Confined Fusion (MCF) Burning Plasma Research and Development
Azarakhsh Jalalvand	Princeton University	Toward Minimal and Robust Set of Diagnostics for Burning Plasmas Using Artificial Intelligence
Curtis Johnson	Oak Ridge National Laboratory	Informing Power Exhaust, Particle Control and Plasma Material Interaction Physics Through Near-UV Spectroscopy Measurements in Edge Plasmas
C. Christopher Klepper	Oak Ridge National Laboratory	Critical R&D Needs Toward Reactor-Grade Fuel-Cycle Measurement and Control
Seungsup Lee	Oak Ridge National Laboratory	Advancing Fiber Optic Sensing for Fusion Applications
Jeffrey Levesque	Columbia University	University-Scale Platforms for Advancing FPP-Relevant Plasma Control
Stuart Loch	Auburn University	White Paper on Atomic Data Needs for Magnetically Confined Fusion
Neville Luhmann	University of California, Davis	Decadal Program: Development of Microwave Diagnostics for High Field, Harsh Environment, and Limited Access Burning Plasma Devices
Soumyajit Mandal	Brookhaven National Laboratory	Integrated SiC Active Pixel Sensors for Plasma Monitoring

George McKee	University of Wisconsin-Madison	High-Speed Integrated Optical Detector Arrays for Multichannel Plasma Instability Measurements
Reza Mirfayzi	Tokamak Energy	Neutron Diagnostics Requirements for Next-Generation Fusion Reactors
Marcel Nations	TAE Technologies	Magnetic Field Measurements for Beam-Driven Field-Reversed Configuration Fusion Devices
Graham Naylor	Tokamak Energy	Polarimetry and Dispersion Interferometry for Density and q Profile Measurement on Future Fusion Reactors
Martin O’Mullane	University of Strathclyde	White Paper on Uncertainty Quantification of Atomic Data for Diagnosing Magnetically Confined Fusion Plasmas
Novimir Pablant	Princeton Plasma Physics Laboratory	X-ray Imaging Crystal Spectrometer Diagnostic Validation for Burning Plasmas
Felix Parra Diaz	Princeton Plasma Physics Laboratory	Theory and Simulation for Diagnostic Development and Exploitation in Burning Plasmas and Fusion Pilot Plants
Soren Prestemon	Lawrence Berkeley National Laboratory	Cryogenic In-situ Radiation Challenges for Fusion Reactor Magnet, Control, and Monitoring Systems
Lisa Reusch	SHINE Technologies, LLC	A 14 MeV Neutron Testing Facility for Functional Materials Testing
Kajal Shah	Princeton Plasma Physics Laboratory	X-ray Sources for In-situ Spatial, Wavelength and Absolute Calibrations of the X-ray Imaging Crystal Spectrometer (XICS) for Fusion Plasmas
David Smith	University of Wisconsin-Madison	Photodiode Technology Development for Fusion Plasma Spectroscopy
David Smith	University of Wisconsin-Madison	Quantum Sensing Technologies for Fusion Plasma Diagnostics
David Smith	University of Wisconsin-Madison	Real-Time Monitoring and Control of MHz-scale Plasma Dynamics With Real-Time ML/AI and Fluctuation Diagnostics
Vlad Soukhanovskii	Lawrence Livermore National Laboratory	Near-Infrared Spectroscopy for Plasma Diagnostic and Control Applications
Sangeeta Vinoth	Princeton Plasma Physics Laboratory	X-ray Energy Distribution Measurements of a Field-Reversed Configuration Plasma
Gavin Weir	Max Planck Institute for Plasma Physics	Development of Compact Optical Systems for Microwave Imaging in Advanced Experiments
Christopher Wink	Massachusetts Institute of Technology	Development of Next-Generation Neutron Spectrometers for Diagnosing Alpha Heating of Fuel Ions in ICF and MCF Experiments

Adelle Wright	University of Wisconsin-Madison	Advancing Technologies for High-Resolution Spatial and Temporal Measurements of Macroscopic Stellarator Flows
Glen Wurden	Los Alamos National Laboratory	Hypervelocity Dust Beam Injection for Internal Magnetic Field Mapping
Glen Wurden	Los Alamos National Laboratory	Robust Sensor Development for Imaging Bolometers
Glen Wurden	Los Alamos National Laboratory	Laser Inverse Compton Scattering to Measure the Runaway Electron Population
Kenneth Young (retired)	Princeton Plasma Physics Laboratory	Plasma Diagnostics Required for a Next-Step MFE Device

White Papers Submitted for Inertial Confinement Fusion — Burning Plasma

Author	Organization	Title
Félicie Albert	Lawrence Livermore National Laboratory	Diagnostic Development and Calibration at the Jupiter Laser Facility for High Energy Density and Inertial Fusion Energy Science
Paul Bellan	Caltech	How to Make Research Funding More Effective
Paul Bellan	Caltech	Exploring the Connection Between Atomic Line Radiation and Energetic Electron Tails
Gerrit Bruhaug	University of Rochester	Coherence-Boosted Inverse Compton X-ray Source for ICF and HEDP Applications
Skylar Dannhoff	Massachusetts Institute of Technology	GRASP: A New Compact Gamma Ray Spectrometer Design for ICF, IFE, and Advanced Photon Source Platforms
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	Adjust Budget of Early Career Research Program to Maintain Leadership and Cutting-Edge Measurement Innovation Across U.S. Academic Institutions and DOE Complex
Alexandre Do	Lawrence Livermore National Laboratory	Developing X-ray Optics to Measure Plasma Hydrodynamic Conditions in IFE Experimental Campaigns
Lan Gao	Princeton Plasma Physics Laboratory	Absolute Calibration of X-ray Crystal Spectrometers for High Energy Density Science and Inertial Confinement Fusion
Clément Goyon	Lawrence Livermore National Laboratory	The MJOLNIR Dense Plasma Focus Platform in Support of Advanced Diagnostic Development
Haibo Huang	General Atomics	Advanced Radchem Gamma Ray Spectroscopy System for High Yield Diagnostics and Volume Burn Platform Development on National Nuclear Security Administration Facilities

Justin Jeet	Lawrence Livermore National Laboratory	Characterizing Fuel Conditions and Constraining Ion Transport Models in Inertial Confinement Fusion Plasmas via Reaction-in-Flight (RIF) Neutrons
Neel Kabadi	University of Rochester	Using Differentially Filtered Neutron History Diagnostics to Probe Time Resolved Ion Temperature
Yongho Kim	Los Alamos National Laboratory	Energy-Resolved Gamma Ray Imaging System
Justin Kunimune	Massachusetts Institute of Technology	The MRSt for Time-Resolved Measurements of Ion Temperature and Areal Density for Unprecedented Power-Balance Studies in ICF Implosions at the NIF
Yongfeng Lu	University of Nebraska-Lincoln	Pre-Implosion Target Diagnosis for Laser Inertial Confinement Fusion
Sophia Malko	Princeton Plasma Physics Laboratory	LaserNetUS Facility and User-Driven Diagnostic Initiatives
Roberto Mancini	University of Nevada, Reno	Multi-Objective Data Analysis
Zaarah Mohamed	Los Alamos National Laboratory	Development of a True Gamma Spectrometer for Use at ICF Facilities
Christopher McGuffey	General Atomics	Ultrafast Neutron Detectors for Yield History in Inertial Confinement Fusion Burning Plasmas
Novimir Pablant	Princeton Plasma Physics Laboratory	X-ray Calibration Sources: Concepts, Extended Area Sources, Anode Materials, Atomic Physics
John Porter	Sandia National Laboratories	Solid-State Streak Camera for High-Speed Recording of X-ray and Particle Diagnostics
Lisa Reusch	SHINE Technologies, LLC	A 14 MeV Neutron Testing Facility for Functional Materials Testing
Maria Pia Valdivia	University of California, San Diego	High-Resolution X-ray Imaging Platform for Laser-Driven Foam Targets and On-Site Metrology to Support HEDLP and IFE Target Development
Sangeeta Vinoth	Princeton Plasma Physics Laboratory	X-ray Energy Distribution Measurements of a Field-Reversed Configuration Plasma
Christopher Wink	Massachusetts Institute of Technology	Development of Next-Generation Neutron Spectrometers for Diagnosing Alpha Heating of Fuel Ions in ICF and MCF Experiments

White Papers Submitted for Magnetic Fusion Energy — Fusion Pilot Plant

Author	Organization	Title
Tsuyoshi Akiyama	General Atomics	Essential R&D Areas and Initiatives to Accelerate the Development of FPP Diagnostics
Paul Bellan	Caltech	How to Make Research Funding More Effective
Paul Bellan	Caltech	Exploring the Connection Between Atomic Line Radiation and Energetic Electron Tails
Filiberto Braglia	General Fusion	Diagnostics for the General Fusion LM26 Machine
Thomas Brown	Princeton Plasma Physics Laboratory	D&C Systems Requirement for a MF Power Plant
Pattrick Calderoni	Idaho National Laboratory	A Placeholder to Discuss the Development of Control Systems for Fusion Pilot Plants
Michael Churchill	Princeton Plasma Physics Laboratory	Mutually Enhancing Diagnostic Information and Digital Models
Severin S. Denk	General Atomics	The Prospect of Bayesian Inference for the Diagnostic Design of MFE FPP
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	Adjust Budget of Early Career Research Program to Maintain Leadership and Cutting-Edge Measurement Innovation Across U.S. Academic Institutions and DOE Complex
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	Multi-Energy X-ray Measurements With Filters, Fast Photodiodes, and 2D-Pixelated Systems for Magnetically Confined Fusion Plasmas
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	T-Boundary Windows for X-ray Diagnostics in Fusion Energy Systems
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	X-ray Measurements for Liquid Metal Plasma-Facing Components (PFCs), Tritium Breeding Blankets and Nonproliferation Applications
Daniel Den Hartog	University of Wisconsin-Madison	Advancing X-ray Diagnosis of Burning Plasmas With Microcalorimetry
Daniel Den Hartog	University of Wisconsin-Madison	Quantum Noise Correlation Analysis to Measure Ion Temperature
Stefano Munaretto	Princeton Plasma Physics Laboratory	Magnetic Diagnostics Needs for an FPP and Beyond
Trey Gebhart	Oak Ridge National Laboratory	Measurement Needs for Tritium Accountancy in the Inner Loop of the Fusion Fuel Cycle
Xiang Han	University of Wisconsin-Madison	Microwave Reflectometry Development for Fusion Pilot Plants

Azarakhsh Jalalvand	Princeton University	Toward Minimal and Robust Set of Diagnostics for the Fusion Pilot Plants Using Artificial Intelligence
C. Christopher Klepper	Oak Ridge National Laboratory	Critical R&D Needs Toward Reactor-Grade Fuel-Cycle Measurement and Control
Máté Lampert	Princeton Plasma Physics Laboratory	Imaging of ne and Te Profiles and Fluctuations in the SOL for Transport Studies
Seungsup Lee	Oak Ridge National Laboratory	Advancing Fiber Optic Sensing for Fusion Applications
Jeffrey Levesque	Columbia University	University-Scale Platforms for Advancing FPP-Relevant Plasma Control
Soumyajit Mandal	Brookhaven National Laboratory	Integrated SiC Active Pixel Sensors for Plasma Monitoring
Felix Parra Diaz	Princeton Plasma Physics Laboratory	Theory and Simulation for Diagnostic Development and Exploitation in Burning Plasmas and Fusion Pilot Plants
Soren Prestemon	Lawrence Berkeley National Laboratory	Cryogenic In-situ Radiation Challenges for Fusion Reactor Magnet, Control, and Monitoring Systems
Lisa Reusch	SHINE Technologies, LLC	A 14 MeV Neutron Testing Facility for Functional Materials Testing
Roger Smith	TAE Technologies	An Advanced Agile CTS Diagnostic for Burning Plasmas: Pulsed Spectropolarimetry
David Smith	University of Wisconsin-Madison	Photodiode Technology Development for Fusion Plasma Spectroscopy
David Smith	University of Wisconsin-Madison	Quantum Sensing Technologies for Fusion Plasma Diagnostics
David Smith	University of Wisconsin-Madison	Real-Time Monitoring and Control of MHz-Scale Plasma Dynamics With Real-Time ML/AI and Fluctuation Diagnostics
Vlad Soukhanovskii	Lawrence Livermore National Laboratory	Near-Infrared Spectroscopy for Plasma Diagnostic and Control Applications
Chase Taylor	Idaho National Laboratory	Measurement Innovations Needed to Operate a Fusion Breeding Blanket
Peter Titus	Princeton Plasma Physics Laboratory	Measurement vs. Prediction of the Structural Response to Disruption Dynamic Loading
Christopher Wink	Massachusetts Institute of Technology	Development of Next-Generation Neutron Spectrometers for Diagnosing Alpha Heating of Fuel Ions in ICF and MCF Experiments
Kenneth Young (retired)	Princeton Plasma Physics Laboratory	Plasma Diagnostics Required for a Next-Step MFE Device

White Papers Submitted for Inertial Fusion Energy — Fusion Pilot Plant

Author	Organization	Title
Félicie Albert	Lawrence Livermore National Laboratory	Diagnostic Development and Calibration at the Jupiter Laser Facility for High Energy Density and Inertial Fusion Energy Science
Saumyabrata Banerjee	Lawrence Livermore National Laboratory	Laser Diagnostics for an IFE Power Plant
Daniel Barnak	Laboratory for Laser Energetics, University of Rochester	Using Filtered X-ray Diode Arrays for Measurements of Areal Densities From Hot Spot Self-Emission of Laser Direct Drive Implosions
Steve Batha	Los Alamos National Laboratory	Diagnosing an IFE Power Plant
Paul Bellan	Caltech	How to Make Research Funding More Effective
Paul Bellan	Caltech	Exploring the Connection Between Atomic Line Radiation and Energetic Electron Tails
Aidan Crilly	Imperial College London	Synthetic Diagnostics
Skylar Dannhoff	Massachusetts Institute of Technology	GRASP: A New Compact Gamma Ray Spectrometer Design for ICF, IFE, and Advanced Photon Source Platforms
Luis Delgado-Aparicio	Princeton Plasma Physics Laboratory	Adjust Budget of Early Career Research Program to Maintain Leadership and Cutting-Edge Measurement Innovation Across U.S. Academic Institutions and DOE Complex
Alexandre Do	Lawrence Livermore National Laboratory	Developing X-ray Optics to Measure Plasma Hydrodynamic Conditions in IFE Experimental Campaigns
Luke Fletcher	SLAC National Accelerator Laboratory	Advancing Inertial Fusion Energy Science and Technology With the Matter in Extreme Conditions Upgrade
Chad Forrest	Laboratory for Laser Energetics, University of Rochester	Verification of Tritium Breeding Rates and Migration in Planned IFE/MFE Blanket Materials
Trey Gebhart	Oak Ridge National Laboratory	Measurement Needs for Tritium Accountancy in the Inner Loop of the Fusion Fuel Cycle
Elizabeth Grace	Lawrence Livermore National Laboratory	Exquisite High-Intensity, Short-Pulse Characterization of the Complete Electric Field E(x,y,z,t) of Ultrashort Laser Pulses for Fast Ignition
Peter Heuer	Laboratory for Laser Energetics, University of Rochester	Measurement Innovation in Inertial Fusion Energy and High Energy Density Science Experiments at High(er) Repetition Rates
Patrick Knapp	Los Alamos National Laboratory	Statistical Inference for Discovering a Minimum Viable Diagnostic Suite for High Rep-Rate IFE Experiments

Yongfeng Lu	University of Nebraska-Lincoln	Pre-Implosion Target Diagnosis for Laser Inertial Confinement Fusion
Sophia Malko	Princeton Plasma Physics Laboratory	Charged Particle Diagnostics Operating at High Repetition Rate to Advance Proton Fast Ignition
Sophia Malko	Princeton Plasma Physics Laboratory	LaserNetUS Facility and User-Driven Diagnostic Initiatives
Michael Mangan	Sandia National Laboratories	Measuring DT-Neutron Yields in a High Repetition Rate Environment
Christoph Niemann	University of California, Los Angeles	Diagnostics Needs for IFE Chamber Plasma Physics
Lisa Reusch	SHINE Technologies, LLC	A 14 MeV Neutron Testing Facility for Functional Materials Testing
Abhik Sarkar	Lawrence Livermore National Laboratory	Infrastructure Needs for a High-Repetition-Rate, Robust, Active Control System — Computational Challenges and Directions for an Inertial Fusion Energy Plant
Matthew Selwood	Lawrence Livermore National Laboratory	Nuclear Imaging to Diagnose and Correct Target-Driver Registration at High-Repetition Rate for Improved Reactor Efficiency
Raspberry Simpson	Lawrence Livermore National Laboratory	Virtual Diagnostics for Rapid Retrieval of IFE-Relevant Plasma Parameters
Christopher Wink	Massachusetts Institute of Technology	Development of Next-Generation Neutron Spectrometers for Diagnosing Alpha Heating of Fuel Ions in ICF and MCF Experiments

Critical Cross Thread in the Fusion Energy Science Community: Diagnostic Calibration

The high energy density plasma (HEDP), inertial fusion energy-burning plasma (ICF-BP), and the inertial fusion energy-fusion pilot plant (IFE-FPP) working groups identified a need for community diagnostic calibration. These working groups highlighted scientific challenges and potential cross threads as described below.

HEDP Working Group: Establish, expand, and communicate calibration facilities to leverage calibration needs across the plasma physics community by forming CalibrationNetUS.

Scientific Challenges

The small- and medium-scale facilities in the HEDP community afford the opportunity to calibrate diagnostics that would be prohibitive in time and cost on larger facilities. Facilities operating at high-repetition rate could provide the required statistics in calibrating the instrument response functions of diagnostics. The development of a CalibrationNetUS could have a large impact both within LaserNetUS and at larger scale National Nuclear Security Administration experiments at the National Ignition Facility, Omega Laser Facility, and Z, and would benefit from a funding program and experimental time at both sets of facilities.

Possible Actions

- –All seven working groups at the workshop have reached the consensus that dedicated and collective efforts should be put into better calibration (absolute calibration in many cases) of our diagnostics. The IFE, magnetic fusion energy (MFE), and synchrotron facilities, experts in public and private communities, and the funding agencies should work together to form CalibrationNetUS.

ICF-BP: Develop a CalibrationNetUS.

Scientific Challenges

Assessing the progress of fusion energy science experiments requires advanced diagnostics that measure properties — fusion yield, temperature, density, size — of the plasma generated in each experiment. For these diagnostics to be accurate and reliable, they must be well understood and calibrated before use. Today, many detector calibrations are performed using on-site specialized experiments or cross-calibrations performed at the fusion facility. And some diagnostics are calibrated offline at dedicated calibration facilities, like at synchrotrons, particle accelerators, or short-pulsed laser facilities. But, in general, because of limited funding and restricted facility access, performing these calibrations is difficult. This difficulty has led to inefficiencies and missed opportunities, adversely affecting scientific progress.

Measurement Innovations

A more systematic approach to diagnostic calibrations would benefit the measurement innovations under consideration. The Department of Energy (DOE) supports a wide range of radiation-source facilities that could be used for diagnostic calibrations. Developing a well-advertised network of radiation sources capable of supporting calibration efforts would empower fusion energy sciences (FES) diagnosticians while simultaneously improving the utilization of such facilities. Therefore, the community supports the development of a centralized diagnostic calibration network (i.e., CalibrationNetUS) inspired by the LaserNetUS working model. The following are key parts of a proposed charter for CalibrationNetUS: 1) connect FES diagnosticians to each other and calibration facilities, 2) provide a mechanism by which diagnosticians can get funding and access calibration facilities more easily, 3) curate and advertise a list of calibration facilities and their capabilities, and 4) develop well-characterized X-ray, neutron, and charged-particle sources for calibration purposes. The community has highlighted the importance of having well-characterized radiation sources. Additionally, several radiation source facilities have expressed interest in supporting diagnostic development and calibration, but the mechanism for connecting with diagnosticians was unclear. Finally, the community highlighted the need for high-repetition-rate facilities to test diagnostics that will be used in an FPP environment.

IFE-FPP: Develop a CalibrationNetUS.

Scientific Challenges

Assessing the progress of fusion energy science experiments requires advanced diagnostics that measure performance of the plasma generated in each experiment (e.g., fusion yield, temperature, density, size). For these diagnostics to be accurate and reliable, they must be well understood and calibrated prior to use. Detector calibrations are challenging in the FES community because of limited funding resources and access to calibration facilities. Today, many detector calibrations are performed using specialized experiments or other procedures performed at the fusion facility. Some diagnostics are calibrated offline at dedicated calibration facilities, like synchrotrons and particle accelerators. The lack of priority and the disparate nature of how calibrations are performed today have led to inefficiencies, which have reduced the pace of progress of many FES experiments.

Measurement Innovations

A more systematic approach to diagnostic calibrations would benefit measurement innovations. The DOE supports a range of radiation source facilities that could be used for diagnostic calibrations. Developing a well-advertised network of radiation sources capable of supporting calibration efforts would empower FES diagnosticians while simultaneously improving the use of such facilities. Therefore, the community suggests the creation of CalibrationNetUS, a centralized diagnostic calibration network similar to LaserNetUS and ZNetUS. The CalibrationNetUS charter should include the following goals: 1) connect FES diagnosticians to each other and to calibration facilities; 2) provide a mechanism by which diagnosticians can more easily get both funding and research time on calibration facilities; 3) curate and advertise a list of calibration facilities and their capabilities; and 4) develop well characterized X-ray, neutron, and charged-particle sources for calibration purposes. This measurement innovation is inspired by community input. Having well-characterized radiation sources has been highlighted as extremely important for the community. Several radiation source facilities have expressed interest in supporting diagnostic development and calibration, but the mechanism by which to connect with diagnosticians was unclear. The community highlighted the need for high-repetition-rate facilities to test diagnostics, which will be used in an FPP.

Critical Cross Thread in the Fusion Energy Science Community: Diagnostic Development

The low temperature plasma (LTP), high energy density plasma (HEDP), magnetic confinement fusion-burning plasma (MCF-BP), inertial fusion energy-burning plasma (ICF-BP), and the inertial fusion energy-fusion pilot plant (IFE-FPP) working groups identified a need for community diagnostic development. These working groups highlighted scientific challenges and potential cross threads as described below.

LTP Working Group: Foster working relationships between LTP user facilities and individual researchers in academia, national laboratories, and industry to facilitate the development of new diagnostic resources in individual laboratories and at user facilities that are then developed/reproduced in the broader LTP community.

Scientific Challenges

The LTP field is extremely diverse, addressing a range of pressures, densities, and chemical compositions. This diversity requires an eclectic approach to plasma diagnostics. Therefore, it is essential that LTP researchers support all investigative methods, from individual investigators to user and collaborative research facilities (UCRFs).

UCRFs provide access to plasma sources and advanced diagnostic capabilities that individual researchers would otherwise be unable to use. This access is important to researchers who study plasma sources and their applications but do not specialize in diagnostics. Staff at UCRFs, on the other hand, have extensive experience in using diagnostics and analyzing data. In addition, UCRFs host visits of graduate students and postdoctoral fellows, providing valuable educational experiences. Also, since many UCRF visitors are engineers or researchers from industries that use LTPs, UCRFs help disseminate plasma diagnostic expertise to the broader LTP community.

Individual researchers are equally essential in developing and applying new diagnostics, using established diagnostics under new conditions, and mentoring and educating graduate students and postdoctoral researchers. The development, fabrication, and debugging of diagnostics by students is an irreplaceable experience in maturing new researchers in the field. Individual researchers can also be more flexible than UCRFs can be. In fact, one could argue that the vast majority of LTP scientific and diagnostic breakthroughs have come from individual researchers.

The challenge is to develop a funding program that will support the development and use of diagnostics by both individual researchers and UCRFs. That is, the

Department of Energy (DOE) must keep both methods of investigation healthy and vibrant, a strategy that would benefit the entire LTP field.

Potential Cross Threads

- The DOE should maintain and improve innovative diagnostic capabilities in both individual laboratories and user facilities, maximizing science advances and leveraging prior investments. For example, the DOE should develop long-term funding models allowing both individuals and UCRFs to purchase new equipment and maintain existing machinery. UCRFs need this type of funding because their experimental configurations may change as often as each week, quickening the accumulation of wear and tear. UCRFs must keep their equipment in like-new condition because they serve the larger LTP community, and new, state-of-the-art diagnostics will help users explore new science challenges. Individual researchers need such a DOE funding program since they often cannot support the purchase or construction of new diagnostics with grants, meaning that the scientists have difficulty developing long-term research plans. Since support for equipment purchases and fabrication is uncertain, the LTP community will benefit from specific solicitations that target diagnostics development in individual labs. Individual labs are a source of many novel ideas, and many are led by diagnostics experts. The successful projects will be adapted into UCRFs to facilitate community access to the newly developed methods. These solicitations could also support the collaborative development of diagnostics between individual laboratories and UCRFs.

- The LTP community also needs a plan to facilitate the development of new diagnostics by allowing individual labs and UCRFs to combine forces. Researchers need a system laying out how user facilities can adopt the use of advanced diagnostics created in individual laboratories, as well as helping the two work collaboratively. The community could also use a system allowing these diagnostics to be used by the wider community, as occurs with LaserNetUS and MagNetUS, as well as granting user facility run time to collaborative research proposals that focus on developing new diagnostic methods or adapting existing methods to operate in new environments. These changes would require a new funding framework.
- Encourage the development and acquisition of standardized plasma sources, including those relevant to plasma applications ranging from plasma-water and plasma-surface interactions. Doing so would accelerate the development of new diagnostics through collaborations between individuals and user facilities.

HEDP Working Group: Establish a DiagnosticNetUS.

Scientific challenges

A need was identified for DiagnosticNetUS as a public-private partnership for developing and testing new diagnostics of interest to the HEDP, the IFE, and possibly the ICF and high energy density research communities, which would leverage the public-private partnership to avoid duplication of effort and spur rapid advancement in such diagnostics through a new funding and collaboration model. DiagnosticNetUS could be created for a specific new or improved diagnostic between private IFE companies and national labs. Then, after research and development and testing of the diagnostic, the design and engineering drawings would be shared freely with the community for anyone to build and implement for their use or for a given facility.

Potential Cross Threads

Form a DiagnosticNetUS as a public-private partnership for developing and testing new diagnostics of interest to the HEDP, the IFE, and possibly the ICF and high energy density research communities leveraging the public-private partnership to avoid duplication of effort and spur rapid advancement in such diagnostics through a new funding and collaboration model.

MCF-BP Working Group: Explore a DiagnosticNetUS to develop new diagnostics.

Scientific Challenges

The following measurements are needed for MCF-BP experiments:

- X-ray detection capabilities for measuring anisotropies of the X-ray emission.
- X-ray measurements for liquid metal plasma-facing components.
- Multi-energy X-ray measurements with filters, fast photodiodes, and 2D-pixelated systems for MCF plasmas.
- Validation of kinetic neutral simulations for FPP design: hydrogen femtosecond two-photon absorption laser-induced fluorescence.
- Development of microwave diagnostics for high field, harsh environment, and limited access BP devices.
- Requirements of neutron diagnostics for fusion reactors.
- Measurements of internal magnetic fields for beam-driven field-reversed configuration fusion devices.
- Polarimetry and dispersion interferometry for density and q profile measurement on future fusion reactors.

- Cryogenic in situ radiation challenges for fusion reactor magnets, controls, and monitoring systems.
- Real-time monitoring and control of MHz-scale plasma dynamics with real-time artificial intelligence and machine learning and fluctuation diagnostics.
- Advanced agile CTS diagnostic for BPs: pulsed spectropolarimetry.
- Near-infrared spectroscopy for tokamak plasma diagnostics and control.
- Development of compact optical systems for microwave imaging in advanced experiments.
- Development of next-generation neutron spectrometers for diagnosing alpha heating of fuel ions in inertial confinement fusion and MCF experiments.
- Hypervelocity dust beam-injection for internal magnetic field mapping.
- Laser inverse Compton scattering to measure the runaway electron population.

A public-private partnership like DiagnosticNetUS could provide industry critical diagnostic expertise and give diagnostic researchers access to new MCF-BP devices to field innovative equipment and techniques.

Potential Cross Threads

- Encourage public-private partnerships to both provide industry critical diagnostic expertise and give diagnostic researchers access to new MCF-BP devices to field innovative equipment and techniques.
- Develop standardized data and metadata formats to aid the sharing of data and data analysis tools.
- Improve communication between different diagnostic communities to promote the cross-application of diagnostics developed for one class of BP device to another.

IFE-FPP Working Group: Develop a DiagnosticNetUS.

Scientific Challenges

The private IFE landscape in both the United States and around the world is rapidly evolving. In recent years, several private companies have formed and begun raising capital to build scientific demonstration systems and FPPs, both of which will require state-of-the-art diagnostics. At the same time, publicly funded entities like labs and universities are also developing diagnostics for use on their more research-based facilities. To avoid duplicating efforts, and to make sure that advances in the overall field occur as rapidly as possible toward IFE-FPPs, the community proposes to develop DiagnosticNetUS.

Potential Cross Threads

DiagnosticNetUS would help scientists design particular diagnostics, including but not limited to the following: a new technology, an adaption of existing technologies to FPP-relevant conditions, or an evolution of a present diagnostic in use on flagship facilities. Areas of interest would include but not be limited to the following: neutron spectrometry and imaging, gamma ray detection, X-ray imaging and spectroscopy, and optical diagnostics. Unlike existing diagnostic-sharing models like LaserNetUS and the Advanced Research Projects Agency-Energy diagnostic program that have sharing agreements for physical hardware, the community anticipates that while DiagnosticNetUS would develop a common set of shared diagnostic engineering drawings, response and/or calibration functions, synthetic diagnostics or simulation tools, and analysis routines, each entity would be responsible for physical implementation at its own facilities. DiagnosticNetUS could consist of one or multiple private sector companies partnered with national laboratories and universities. The model would be based on existing public-private partnership programs (e.g., Innovation Network for Fusion Energy, PPP, IFE-STAR Hubs) but would incorporate aspects unique to diagnostic development, including the provision that the technology developed by the DiagnosticNetUS would not be proprietary. Funding could be structured such that private sector participants provide in-kind contributions while public-sector participants receive funding from the DOE.

Critical Cross Thread in the Fusion Energy Science Community: Workforce Development

The high energy density plasma (HEDP), inertial fusion energy-burning plasma (ICF-BP), and inertial fusion energy-fusion pilot plant (IFE-FPP) working groups identified the critical need for community workforce development in measurement innovations. These working groups highlighted scientific challenges and potential cross threads as described below.

HEDP Working Group: Enhance workforce development and training within the Fusion Energy Sciences (FES) community.

Scientific challenges

HEDP is entering an exciting time characterized by advancements in facilities, innovations in diagnostics, and a recent inertial confinement fusion ignition breakthrough. Just as the achievement of ignition was made possible by a suite of diagnostics and comprehensive data analysis, continuous investment in diagnostics development, facility improvement, and novel techniques could significantly advance the HEDP field in the coming decade. Scientists expect growth in applications using ignition-generated extreme plasma conditions or outputs such as X-rays, gamma rays, high-flux neutrons, and other novel sources. New instruments and techniques will measure complex structures from multiple lines of sight with excellent spatial and temporal resolution to reveal new phenomena in HEDP. Scientists also anticipate advances in IFE enabled by high-repetition rate and robust systems for fusion energy generation. All these possibilities rely on today's investment in the development and innovations of diagnostics, including improving calibration and data processing, as well as workforce development.

Potential Cross Threads

- With recent advancements in high-power lasers, particle beams, and pulsed-power machines, researchers can now generate the extreme high energy density conditions in the laboratory, exploring many fascinating and exotic phenomena related to laboratory astrophysics, planetary science, nuclear physics, material science, particle physics, and atomic physics. HEDP is, therefore, a fascinating area that attracts students and scientists from all other fields, providing a vital pipeline for the next generation of HEDP and IFE scientists. The Department of Energy (DOE) should enhance workforce development efforts in measurement innovations for the FES community.

ICF-BP Working Group: Enhance workforce development and training.

Scientific Challenges

Beyond the focus on technology and facility development, careful attention must be paid to developing the workforce and training around diagnostic research. In general, most researchers in the field believe that writing scientific research papers is more prestigious than developing diagnostics. In fact, research leading to the publication of papers does lead to more recognition and funding. Yet, this type of scientific research advances through diagnostics, so the current perception of diagnostic research could hinder measurement innovations. Therefore, elevating the prestige of diagnostic development must be put in place, starting from funding sources such as the DOE's FES and working down through facilities' upper management to their constituent researchers. Teamwork and collaboration and, subsequently, shared appreciation of and credit toward group members should be promoted. For instance, the distinction between first authorship and co-authorship has impacted hiring and funding practices, producing conflict within teams and disincentivizing collaboration. Continuous recruitment of scientists and engineers to become the next generation of leaders in the fusion energy field is essential.

Potential Cross Threads

- Dedicate funding specifically for diagnostic development.
- Encourage publications resulting from FES funding to list authors in alphabetical order and treat all existing publications similarly.
- Develop a dynamic fusion workforce that recruits talent from a wide range of science and engineering fields, including untapped resources.

Magnetic Fusion Energy-Fusion Pilot plant (MFE-FPP) Working Group: Develop a dynamic fusion workforce that recruits from a wide range of science and engineering fields, including untapped resources.

Scientific Challenges

To successfully develop an MFE-FPP, the United States will need a dynamic workforce that recruits from a wide range of science and engineering fields. The working group identified concerns about today's low numbers of eligible scientists, engineers, and technicians with expertise for basic FPP needs, such as tritium handling and accountancy, as well as emerging FPP needs, such as artificial intelligence (AI) and machine learning (ML) of big data. In order to develop the FPP workforce, the community will have to include untapped resources by broadening the usual pipeline programs and developing new dedicated programs, as well as increasing private industry funding. In the context of measurement innovations, the working group points out an important need to better value and recognize diagnostic research and development work, as evidenced by invited talk nominations, fellowships, and facility access.

Potential Cross Threads

The MFE community should develop a dynamic workforce to support measurement innovations needed for an FPP. It should train more scientists, engineers, and technicians to handle and account for tritium, to handle AI/ML big data needs, and to drive measurement innovations needed for an MFE-FPP. The strategy should include creating new programs to introduce science, technology, engineering, and mathematics (STEM) and technical students to the fusion field. It is crucial to explore these untapped resources. The workforce that drives measurement innovations should be provided the necessary resources to complete their experimental objectives and be recognized for their successes through invited talk nominations, fellowships, and awards.

IFE-FPP Working Group: Develop a dynamic fusion workforce that recruits from a wide range of science and engineering fields, including untapped resources.

Scientific Challenges

To successfully develop an IFE-FPP, the United States will need a dynamic workforce that recruits from a wide range of science and engineering fields. The working group identified concerns about today's low numbers of eligible scientists, engineers, and technicians with expertise for basic FPP needs, such as tritium handling and accountancy, as well as emerging FPP needs, such as AI/ML big data. In order to develop the FPP workforce, the community will have to include untapped resources by broadening the usual pipeline programs and developing new dedicated programs, as well as increasing private industry funding. In the context of measurement innovations, the working group points out an important need to better value and recognize diagnostic research and development work, as evidenced by invited talk nominations, fellowships, and facility access.

Potential Cross Threads

The IFE community should develop a dynamic workforce to support measurement innovations needed for an FPP. It should train more scientists, engineers, and technicians to handle and account for tritium, to handle AI/ML big data needs, and to drive measurement innovations needed for an IFE-FPP. The strategy should include creating new programs to introduce STEM and technical students to the fusion field. It is crucial to explore these untapped resources. The workforce that drives measurement innovations should be provided the necessary resources to complete their experimental objectives and be recognized for their successes through invited talk nominations, fellowships, and awards.

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