FESAC International Benchmarking Subcommittee Report on International Collaboration Opportunities, Modes, and Workforce Impacts for Advancement of US Fusion Energy

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Executive Summary

Background and Motivation

A subcommittee of FESAC was formed in July 2022 to evaluate the status of international collaborations in fusion energy development, fundamental plasma science, and related technology areas and identify opportunities for such collaborations in the coming decade. The present report answers charges to the subcommittee (see Appendix A4), focusing on the needs and context of the Bold Decadal Vision (BDV), and including assessment of international collaboration opportunities, identification of optimal modes of international collaboration, identification of ways to leverage the growing private sector in fusion, assessment of US leadership status in key areas of fusion research, and identification of strategies to address US workforce needs including recruitment from traditionally underrepresented groups. International collaboration remains important to the advancement of US plasma and fusion science and realization of the BDV. Key collaborative opportunities complementary to US efforts include experimental programs, collaborations focusing on theory, simulation, computer science, and mathematics areas, and technology testing and development activities. Both the BDV energy mission and foundational plasma science goals can benefit significantly from international collaboration.

Five charges were identified for a FESAC subcommittee to address, *abbreviated* versions of which are shown in the text following, along with high-level summaries of responses. Note that the subcommittee has effectively divided Charge 2 into separate Charges 2a and 2b, as described and illustrated below.

Abbreviated Charges and High-Level Summaries of Responses

Charge 1: In what areas of research and on which international facilities are there compelling opportunities for US researchers over the next 10 years?

There are compelling international opportunities for tokamak and spherical tokamak research to optimize design and operation of divertors, scenarios, and disruption avoidance/mitigation in conditions not available in the US: long pulses with high beta, higher B-field, metal walls, and different divertor geometries at high heat flux. Key facilities include KSTAR, EAST, JT60-SA, DTT, MAST-U, and ST80-HTS. International stellarator facilities substantially exceed domestic capabilities and continued US leadership in stellarator physics will require enhanced collaboration with international programs, particularly W7-X. International facilities also present opportunities for advancing alternative magnetic confinement concepts that are not publicly funded in the US. The US currently leads in Inertial Confinement Fusion (ICF) science and technology, and this competitive advantage should be maintained and expanded by augmenting strong domestic efforts through strategic partnering with the international community to advance areas not already strongly pursued, such as Inertial Fusion Energy (IFE)-specific materials, full fusion energy system modeling and analysis, and waste streams. International collaboration in the area of plasma-facing and bulk structural materials present significant opportunities, and should be pursued with particular importance in the interim before the MPEX facility becomes available. Collaboration opportunities include international tokamaks with solid and liquid metal Plasma Facing Components (PFCs); only the EAST device in China is currently able to assess these physics areas at scale, though additional devices in Europe are in various stages of conceptualization and construction. Fast spectrum reactors or spallation sources can provide neutrons with sufficiently high energies to probe several important threshold transmutation reactions, and triple-ion beam irradiation facilities can capture multi-species effects on materials evolution. There are compelling and important opportunities for international collaboration in the areas of tritium breeding blankets and related balance of plant (BoP) technologies, which are at a low level of technology readiness but are critical to close the D-T fuel cycle in a future fusion pilot plant. Opportunities to accelerate US development in BoP exist in the areas of breeding blankets (including liquid metal MHD), tritium handling, fusion safety, and waste management. The H3AT facility for tritium processing and CHIMERA facility for blanket component testing in the UK appear particularly promising for these purposes. Key areas in supporting and enabling technologies for which compelling opportunities are found abroad include proofing of ion cyclotron resonance heating (ICRH) in an all-metal environment (e.g., WEST Tokamak); high energy CW neutral beams (IPP-Garching and the National Institute for Quantum Science and Technology in Japan); increasing the manufacturing capability of HTS magnets (e.g., Tohoku University and the Robinson Institute); development and production of high-frequency gyrotrons (e.g., University of Fukui, KIT, Kyoto Fusioneering, Thales). Key areas of US fundamental plasma research which can benefit from international collaboration in the next 10 years include ignition science, quantum electrodynamics, and laser-plasma interaction science. These scientific areas are in critical need of US scientists gaining access to key international collaborations to bring their expertise for developing/exercising high repetition rate as well as Machine Learning / Artificial Intelligence (ML/AI) enhancements to achieve 10-year national goals. Key facilities include: ELI Beamlines, ELI NP, ExFEL, Apollon, LMJ, LULI, CORELS, and EPAC. (See Sec. IV for detailed Findings and Recommendations on Charge 1, organized by research topical area)

Charge 2a: What is the potential of these facilities to help US scientists address priorities and recommendations in the LRP and the NASEM report "Bringing Fusion to the US Grid", contribute to the Administration's bold decadal vision for commercial fusion, and increase the US readiness for ITER operation?

Operating facilities KSTAR, EAST, and MAST-U have high potential to help the US close key gaps in the tokamak/ST physics basis for making ITER successful and designing a Fusion Pilot Plant (FPP) on the BDV timescale. Three new devices expected to come online before 2030, namely JT60-SA, DTT, and ST80-HTS, offer opportunities for larger steps towards ITER and FPP conditions. The facilities described in the areas of plasma-facing and bulk structural materials (Charge 1) can help address some of the priorities and recommendations of the Long Range Plan (LRP) and BDV goals, but with remaining gaps. These gaps motivate the US MPEX and FPNS development programs, which target gap closures that cannot be addressed internationally. These two US facilities featured prominently in the LRP report. Recommendations to collaborate in the H3AT and CHIMERA facilities are made with the ambitious timeline of the NASEM report and Bold Decadal Vision specifically in mind. Given the long lead time associated with the design and construction of large-scale facilities of this nature, these facilities offer greater confidence that the necessary integral tests of blanket and tritium processing technologies can be achieved in time to inform FPP design and construction. The technology facilities identified in the response to Charge 1 have been recognized as having capabilities that are first of their kind and world leading; thus, they have great potential to help US scientists address R&D issues for an FPP. Since comparable technology facilities do not exist in the US, these (operating) facilities have high potential to accelerate the US program by parallelizing R&D efforts. The discovery science facilities identified as key in response to Charge 1 have high potential to address priorities for LRP and BDV goals. Collaboration with these facilities will contribute strongly to advancing US foundational plasma science and have the potential to increase understanding in ways that can support FPP and commercial fusion energy system development. It is likely that these efforts will contribute only moderately to US readiness for ITER operation. International collaborations based on theory, simulation, computational physics, modeling design, and control mathematics offer strong potential for enhancement and acceleration of US efforts toward the LRP/BDV. Key opportunities in these areas include CEA/IRFM, the Max-Planck Institute for Plasma Physics, CCFE, CREATE, DIFFER, EPFL/SPC, as well as continuing strong engagement in ITPA. (See Sec. IV for detailed Findings and Recommendations on Charge 2a, organized by research topical area)

Charge 2b: Assess whether the existing modes of collaboration are adequate for maximizing the impact of international collaborations on the US fusion program and objectives.

Existing modes of international collaboration incorporate a wide range of practices with varying effectiveness and impact on the US fusion program. This charge has therefore been addressed by identifying the features that characterize effective collaborations in general, rather than assessing the adequacy of specific existing collaboration modes. Practices that maximize the effectiveness and impact of collaborations in general include establishing strong collaborative frameworks that define the roles and goals of participants, establishing clear understanding of use and expectations for experimental and technology development facilities with timely and effective communication to manage schedules and responsibilities, ensuring low administrative barriers for cyber and data access while maintaining strong security, and using modern best practices for software development and management in data-intensive collaborations. Remote operation and participation are particularly valuable for, and can significantly enhance, off-site collaborations with experimental facilities. Safety procedures training is uniquely important for on-site collaborations. (See Sec. V for detailed Findings and Recommendations on Charge 2b)

Charge 3: How can the US take advantage of its fusion private sector in international engagements, and how can we cooperate with overseas public-private partnership programs that focus on accelerating the development of commercial fusion?

While there are numerous mechanisms to facilitate public-private partnerships within the United States (e.g., ARPA-E, INFUSE, others), there are extensive and sometimes unique resources outside of the United States that could accelerate the technological development of fusion if opened to the private sector. A public-private partnerships program should be created to facilitate the collaboration of domestic private companies and international resources. Collaborations supported through this program should be limited in scope but bear well-defined deliverables, strike a clear balance between openness and IP protection, and model successful agreements (e.g., the INFUSE CRADA). Such a program would benefit the federal program by accelerating the development of fusion technology and eventual commercialization. (See Sec. VI for detailed Findings and Recommendations on Charge 3)

Charge 4: What are the areas where the US is leading, where US leadership is threatened in the near- and long-term, and in which [the] US is not leading at present but where investing resources could offer significant opportunities for leadership?

The US leads in many aspects of tokamak physics, including high-performance scenarios with demonstration in short pulse, disruption avoidance and mitigation physics/control, and core-edge integration. However, the US only has access to superconducting tokamaks through international collaborations to study long pulse performance, and burning plasma experiments have been led by JET. This range of leadership levels in tokamak physics areas implies key opportunities for investment of resources to enhance US leadership through collaboration. As demonstrated by the recent ignition achievement, the US is the international leader in ICF now. However, in order for the US to grow and maintain its leadership in ICF/IFE, it is important to keep science open as much as possible for international collaboration while still retaining and protecting US intellectual property. The US lacks a sufficient number of large facilities to maintain overall leadership in the operation of large fusion facilities. The US should leverage international collaborations on large-scale fusion facilities to develop and maintain the necessary skill-set in building, operating, and executing fusion research at scale. Two key technology areas in which the US is not leading and could benefit from international collaborations are gyrotron source development and high-repetition rate laser testing and diagnostics development. (See Sec. VII for detailed Findings and Recommendations on Charge 4)

Charge 5: How can the US ensure availability of a highly trained and internationally competitive workforce in fusion science and technology and related areas, including the recruitment of talent from traditionally underrepresented groups within the US?

Workforce expansion to meet the needs of the BDV is a central challenge of the present US path to commercial fusion energy. Dedicated, well-funded efforts will be necessary to reach both domestic and international communities outside traditional fusion fields, and access and support underrepresented communities. Specific training and educational funding mechanisms should be established to attract and prepare secondary, undergraduate, and graduate students to create pathways toward a sustainable workforce pipeline. Foundational, discovery science and technology programs with strong educational components (both academic and research) should be supported as powerful vehicles to attract and train the next generation of students for the fusion workforce. International collaboration provides access to workforce resources otherwise not readily available to the US, which can significantly complement domestic workforce development efforts. Explicitly incorporating student development and integration of international experts into collaborative research programs will maximize their effectiveness in enhancing workforce development. Personnel gains through such collaborations can access the statistically greater diversity of many international communities and fields, thereby naturally enhancing the diversity of the US workforce. (see Sec. VIII for detailed Findings and Recommendations on Charge 5)

I. Introduction

I.1. Background

There is a long DOE/FES history of international collaboration that has richly complemented domestic plasma and fusion science, strengthened engagement with worldwide community efforts, and nurtured international sources for US workforce expansion. Roughly every decade, a process has been launched to evaluate the status of international collaborations and identify opportunities for the coming decade (e.g. [FESAC 2012]). The present report answers charges to FESAC made in mid-2022 (see Appendix A4), focusing on the needs and context of the Bold Decadal Vision, and expanding the scope beyond previous evaluations to include assessment of international collaboration opportunities, identification of optimal modes of international collaboration, identification of ways to leverage the growing private sector in fusion, assessment of US leadership status in key areas of fusion research, and identification of strategies to address US workforce needs including recruitment from traditionally underrepresented groups. International collaboration remains important to the advancement of US plasma and fusion science and realization of the BDV. Key opportunities complementary to US efforts include experimental programs, collaborations focusing on theory, simulation, computer science, and mathematics areas, and technology testing and development activities. Both the BDV energy mission and foundational plasma science goals can benefit significantly from international collaboration.

I.2. Charges to Subcommittee

Five charges were identified for the FESAC subcommittee to address, full text of which are shown here (see also Appendix A4 for full charge letter). Note that the subcommittee has effectively divided Charge 2 into separate Charges 2a and 2b, as they refer to somewhat distinct assessments. The original Charge 2 text is simply the union of the texts shown below for Charges 2a and 2b. Detailed findings and recommendations to the charges are provided in later sections following.

Charge 1: Since the last time FESAC assessed the opportunities afforded to US scientists by international fusion facilities with unique capabilities, a number of new facilities have come online, and existing facilities have undergone significant upgrades. In what areas of research and on which facilities are there compelling opportunities for US researchers over the next 10 years?

Charge 2a: What is the potential of these facilities to help US scientists address priorities and recommendations in the LRP and the National Academies report on “Bringing Fusion to the US Grid”, contribute to the Administration’s bold decadal vision for commercial fusion, and increase the US readiness for ITER operation?

Charge 2b: In addition, please assess whether the existing modes of collaboration are adequate for maximizing the impact of international collaborations on the US fusion program and objectives.

Charge 3: How can the US take advantage of its considerable and growing fusion private sector in international engagements, and how can we cooperate with overseas public-private partnership programs that focus on accelerating the development of commercial fusion?

Charge 4: Within the Fusion Energy Science-supported research areas and facility capabilities for fusion energy science and discovery plasma science, what are the areas where the US is leading, the areas where US leadership is threatened in the near- and long-term, and the areas in which US is not leading at present but where investing resources could offer significant opportunities for leadership that would be beneficial to the US fusion program goals and objectives?

Charge 5: How can the US ensure the availability of a highly trained and internationally competitive workforce in fusion science and technology and related areas, including the recruitment of talent from traditionally underrepresented groups within the US?

I.3. Subcommittee Process

The process determined by the subcommittee included the assessment of BDV goals and international collaborations, analysis of characteristics of effective collaborations, identification of leadership status in specific research areas, identification of public-private collaboration opportunities and approaches, and determination of effective means of expanding the fusion workforce through both domestic and international efforts. The subcommittee created subpanels to study and assess these charge elements in specific topical areas, including fusion core, materials / Plasma Material Interactions (PMI), balance of plant, technology, and discovery science (see Sec. III for further details of mappings between panel areas and LRP/BDV topics, and Sec. IV for results of panel deliberations for Charges 1 and 2a). The subpanels solicited extensive expert inputs, including US and international sources, to inform their identification of opportunities and facilities in each topical area (see Appendix A3 for experts consulted).

I.4. Guide to the Report

Sec. II describes the context of the Bold Decadal Vision for fusion energy, which provides the key framework for assessing international collaboration and answering the charges. Section III provides an overview of the research needs identified and assessed, along with a mapping to the topical areas used for the assessment process. Section IV contains detailed breakdowns and assessments of international collaboration opportunities by topical area (responses to Charges 1 and 2a). Section V describes characteristics of collaborations that maximize their impact, along with findings and recommendations for Charge 2b. Section VI discusses public-private activities and impacts on international collaboration, along with findings and recommendations for Charge 3. Section VII discusses US leadership in the context of international collaboration, and provides findings and recommendations for Charge 4. Section VIII discusses mechanisms for workforce development to meet the challenges of the BDV, including recruitment from underrepresented groups, along with findings and recommendations for Charge 5. Section IX provides summarizing and concluding remarks, as well as a listing of all recommendations. Appendices following provide additional information.

II. Context of Bold Decadal Vision for Fusion Roadmap

In March 2022, the Biden-Harris administration announced a Bold Decadal Vision (BDV) for Commercial Fusion Energy in the US, with the aim of enabling fusion to contribute meaningfully to the goal of net-zero greenhouse emissions by 2050. This vision emphasizes the central role of commercialization for realizing the delivery of fusion power in the US, and recognizes the importance of developing fusion energy in a way that serves the broader population and contributes to energy justice. Meeting this timeline requires demonstration of electricity generation from fusion energy in the timeframe of roughly a decade, as outlined in the recent reports from the Fusion Energy Sciences Advisory Committee (FESAC) on "Powering the Future: Fusion and Plasmas" [FESAC 2020], and the National Academies of Science, Engineering, and Medicine (NASEM) on "Bringing Fusion to the US Grid" [NASEM 2021]. Consequently, the BDV seeks to align and coordinate the US fusion program toward the timely demonstration of a Fusion Pilot Plant (FPP).

The BDV represents a departure from the prior approach toward fusion energy development in at least three important ways: first, it seeks to empower private industry to lead in the development of fusion technology; second, the aggressive timeline requires that some significant scientific and technological risks will need to be retired in parallel with, rather than before, the design and construction of an FPP; and third, the FPP mission necessitates expanding the scope of fusion research to include systems beyond the fusion core, including materials, blankets, magnets, fuel cycle, and power conversion. This change in approach not only affects the domestic research and development program, but also potentially affects the way in which the US can most usefully interact with its international partners. Therefore, a reevaluation of these interactions in the context of the BDV is merited.

The importance of international collaborations in achieving fusion energy is recognized both by the BDV and in previous reports ([FESAC 2012], [NASEM 2021], [FESAC 2020]), and the US fusion research Community Planning Process (CPP) [CPP 2020]. Each of these reports endorses US participation in ITER, the only facility in the world presently under construction that will be capable of producing a long-pulse burning plasma at the scale of a power plant. In addition to ITER, rapid progress toward commercial fusion power will likely rely in part on research at existing or near-term international facilities that provide capabilities presently unavailable in the US, such as long-pulse magnetic confinement, materials testing in a fusion nuclear environment, and tritium processing. A detailed survey of research and development needs and priorities was given in the recent FESAC and CPP reports, and these needs continue to form a basis for evaluating the research capabilities of international facilities here, though the timeline and strategy for US fusion research have evolved since those reports were released.

The charge for this report highlights those areas in which international collaborations are most valuable in the context of the BDV: by helping to advance the readiness of fusion science and technology, by providing opportunities for partnering with private industry, and by allowing the US to contribute or develop its leadership in targeted areas; and to assist with the development of a workforce that can help the US accommodate an expanding fusion industry.

III. Research Needs and Opportunities for International Collaboration

Charges 1 and 2a (See Sec. I) address research opportunities to inform the BDV/LRP priorities, which are expressed in those studies with various approaches to categorizing topical research areas. The subcommittee has approached the assessments corresponding to these charges by creating mappings between a topical breakdown derived from the analysis done in the LRP/NASEM reports [FESAC 2020], NASEM 2021], and a set of five topical panels, in order to identify the critical collaboration opportunities. Fig. III-1 illustrates these mappings.

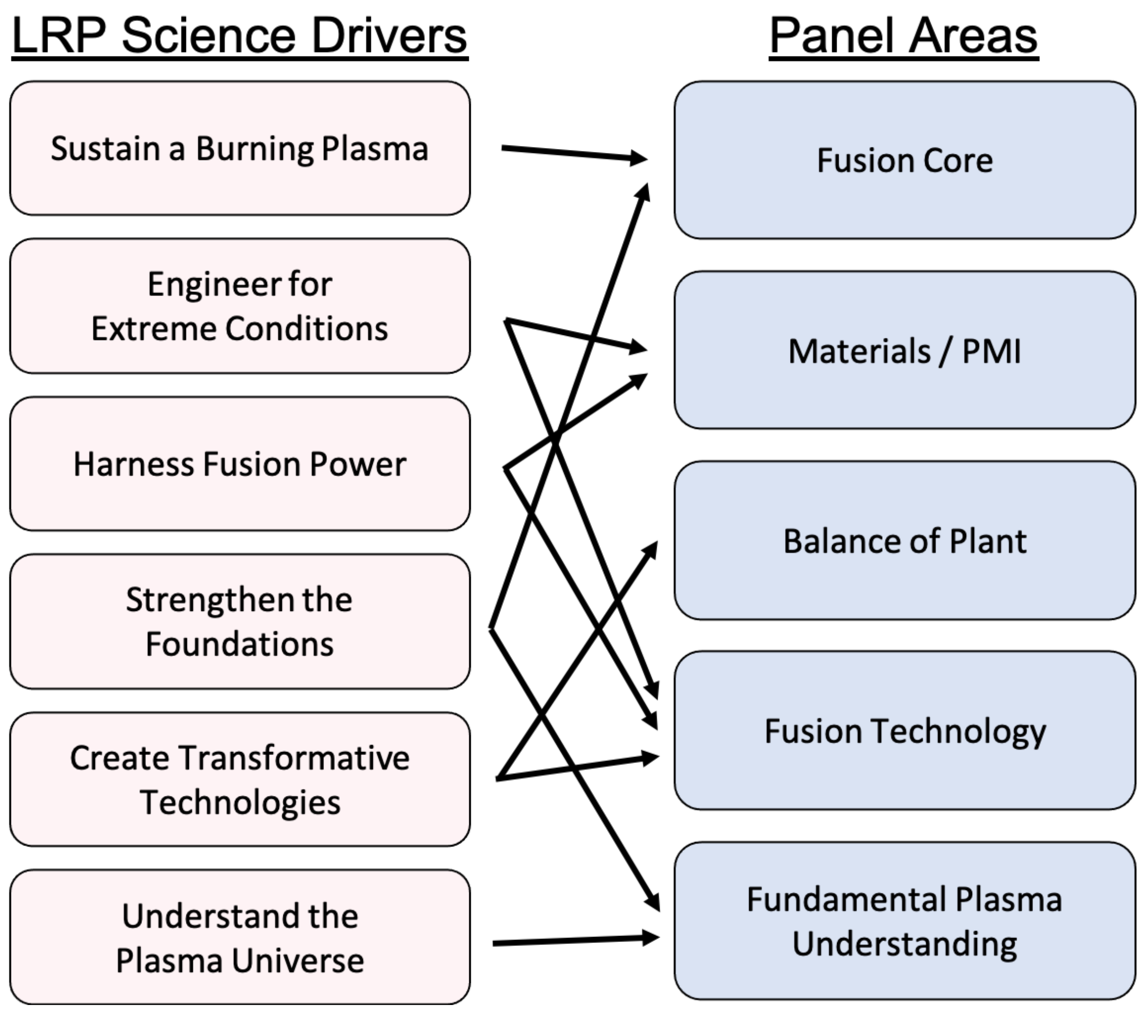

Figure III-1. Mapping between LRP/NASEM/CPP topics and topical panel areas in subcommittee opportunity assessments.

The subcommittee panels shown in Fig. III-1 assessed international collaboration opportunities and other charge elements under each of their topical areas. This enabled a focused process organized by topic to identify relevant experts and consider facilities and institutions that largely map to those areas, rather than the largely cross-disciplinary areas identified as LRP Science Drivers.

The fields of theory, modeling, simulation, computational physics, control mathematics, design, advanced algorithms, machine learning (ML), and artificial intelligence (AI) are related through their high reliance on computational algorithms and platforms, and are cross-cutting through the topical research areas shown in Fig. III-1. Discussions of the roles these fields play can be found in the reports of each panel. In addition, a separate Section IV.6 has been included which highlights compelling international collaboration opportunities in these fields.

III.1 - Metrics Utilized for Opportunity Assessment

To ensure uniform appraisal of opportunities, the subcommittee used consistent metrics across the different technical panels. These metrics were designed to identify facilities and research needs that responded to the charge of this report. In particular, the following assessment metrics were used:

Probability of Realization on Projected Timeline - Several facilities assessed are still in the conceptual design or early construction phase. These projects have more schedule risk than facilities near completion and overall uncertainty regarding when or if they will be completed in a timescale that will enable a positive impact on fusion development in the US on the NASEM and LRP timelines.

Comparison to Domestic Facilities - The international facility assessed was critically compared to existing capabilities in the US. If a facility was duplicative of a facility or capability already existing in the US, this would be seen negatively by the subcommittee. Some international facilities could be seen as complementary to US capability, or even surpassing US capability.

TRL Advancement Potential and Likelihood - The capability or resource available at the international facility was assessed in terms of its potential to advance the Technical Readiness Level (TRL) of a given technology or technique. This included an assessment of the likelihood that the potential TRL advancement could take place in a timely manner.

Potential Impact on the Bold Decadal Vision (BDV) and US Fusion Pilot Plant (FPP) - Some international facilities can directly contribute to the US FPP effort by for example qualifying a material, component, or technique. Facilities that could contribute and impact choices taken in the BDV and US FPP were rated highly against this metric.

Relevance to US Technology Drivers - Not all techniques and technologies are emphasized in the US Fusion Program. This metric assessed alignment of an international capability to efforts already ongoing in the US program.

Potential to Contribute to US Leadership - This important metric, related to the comparison with domestic facilities, assessed whether embarking on a collaboration with an international facility would enhance US leadership or not. The level of leadership and involvement given to US participants varies widely across facilities, from full equal partners to negligible status. Areas where US leadership both in the facility and overall in the world program could be enhanced were rated highly.

Ability to Advance US Private Sector - US leadership goes beyond the work of the public program. Facilities that could accelerate the US private fusion industry, due to the alignment of techniques or capabilities, were rated highly.

Ability to Grow US Fusion Workforce - The growing US fusion program (public and private) is suffering from an acute workforce shortage. Some international collaborations and capabilities can accelerate workforce growth, even domestically in the US. Programs and collaborations that can accelerate US workforce growth were rated highly.

Ratings against these metrics were made for the various facilities and capabilities, both domestically and abroad. If a facility did not score highly, it was not included in the relevant topical area of this report.

III.2 - Experts Consulted for Input on Opportunities

Experts in various topical areas were requested to provide input to the subcommittee, either through written correspondence or by speaking to either the full subcommittee or the specific technical panels. A list of experts who were consulted can be found in Appendix A3. These experts provided important context for the work of the subcommittee and also shared their views of what high-priority research opportunities existed internationally. The experts were often drawn from the international community, and thus could speak definitively on the status of work ongoing in their home countries or systems.

IV. International Collaborations for Advancement of US Fusion Energy

Charge 1: Since the last time FESAC assessed the opportunities afforded to US scientists by international fusion facilities with unique capabilities, a number of new facilities have come online, and existing facilities have undergone significant upgrades. In what areas of research and on which facilities are there compelling opportunities for US researchers over the next 10 years?

Charge 2a: What is the potential of these facilities to help US scientists address priorities and recommendations in the LRP and the National Academies report on "Bringing Fusion to the US Grid", contribute to the Administration's bold decadal vision for commercial fusion, and increase the US readiness for ITER operation?

International collaboration opportunities, including programs, laboratories, facilities, and institutions, were assessed by each subcommittee topical area panel (see Sec. III and Fig. III-1) to quantify impact and priority of each, along with aspects of various charge elements (see Sec. I). This section summarizes the results of the panel deliberations, including findings and recommendations, related to each topical area for Charges 1 and 2a. Tables are shown in each topical area section, highlighting key facilities and collaboration opportunities considered and assessed, with potential for recommendation. Formal recommendation statements throughout the report specify those opportunities identified for collaboration roles in response to the charges.

Sections IV.1 - IV.5 respectively address opportunities involving the fusion core (IV.1), materials/PMI (IV.2), balance of plant (IV.3), technology (IV.4), and fundamental understanding of plasmas (IV.5). Cross-cutting topics including theory, modeling, simulation, computational physics, control mathematics, design, advanced algorithms, machine learning (ML), and artificial intelligence (AI), are separately called out and key collaborations identified in Sec. IV.6. This cross-cutting section emphasizes that these topics represent important research areas and collaboration opportunities in and of themselves. However, many activities in these areas are also identified in each panel/topical subsection where relevant to addressing those specific areas. Panel recommendations related to other charges can be found integrated with responses to Charges 2b-5 in the corresponding Secs. V-VIII.

IV.1. Fusion Core

IV.1.1 Introduction

The performance of the fusion core plasma, and in particular the energy gain it is able to produce, is a major driver for the viability and cost-effectiveness of any fusion energy concept. To achieve sufficient energy gain, the plasma must be able to be heated to 10s of keV and must confine this heat long enough for the fusion reactions to exceed the energy lost from heating and confining the plasma. These conditions must also be achievable with high reproducibility and high availability to translate to a viable power plant design. The APS Community Planning Process Report [CPP 2020] details a number of research needs pertaining to the fusion cores of different confinement concepts: tokamaks (CPP Strategic Objective D), stellarators (CPP Strategic Objective E), alternative magnetic confinement concepts (CPP Strategic Objective H), and inertial confinement concepts (CPP strategic Objective H). These research needs include understanding how to ensure plasma stability, how to optimize magnetic geometry to minimize thermal transport, how to maintain a high-performance core while operating in a way consistent with power handling requirements in the plasma edge, and how to design IFE targets that maximize fusion gain, among other topics.

In this section, we identify opportunities to address the research needs identified in the CPP report pertaining to the fusion core through international collaborations over the next ten years, and assess the potential of these collaborations to contribute to US priorities as expressed in the FESAC Long Range Plan and the Bold Decadal Vision for fusion energy.

It is not within the scope of this report to make findings and recommendations about US participation in ITER. This report assumes that, in accordance with recommendations of other recent reports, the US will "remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant" [NASEM 2021]. For a detailed overview of opportunities arising from US participation in ITER, we refer the reader to the recent US ITER Research Program Research Needs Workshop report [USIRP 2022].

IV.1.2. Narrative

The scope of international collaborations needed to advance the Fusion Core topical area is divided into the subtopics of tokamak physics basis, tokamak burning plasma physics, tokamak diverter solutions, tokamak scenarios, tokamak disruptions, stellarator physics basis, stellarator optimization, stellarator core physics, stellarator diverter solutions, alternative magnetic confinement concepts core physics, and inertial fusion energy core physics. Findings and recommendations for each of these topical areas are provided within the corresponding subsections.

Tokamak Physics Basis

The 2020 Community Planning Process (CPP) final report [CPP 2020] section on strategic objective D: "Advance the tokamak physics basis sufficiently to design a low-cost fusion pilot plant" identifies broad categories of gaps in the tokamak physics basis. Our findings and recommendation of the most valuable international collaborations are based on how well they can help the US fill these gaps for a tokamak- or ST-based fusion pilot plant (FPP). Gaps in physics understanding identified in these reports for the tokamak and ST include: core plasma confinement and stability physics, burning plasma physics, diverter and edge plasma physics, plasma scenarios, disruption avoidance and mitigation (see **Table IV.1.2-1,** last column).

Table IV.1.2-1. Key tokamak facilities for US international collaboration.

Facilities	Type	Characteristics/ Capabilities	Research Focus	US Goals/Gains from Collaboration
ASDEX-UG	Tokamak	W-coated walls, NBI, ECH, ICH, RMP coils, mature diagnostics. R=1.6 m, B=3.2T, P_{heat}=27MW, t_{pulse}~10s.	Broad program to solve ITER & EU-DEMO issues	Now, compare domestic diverter (SO-D.2) & scenario (SO-D.3) approaches with similar capabilities.
DTT	Tokamak	Superconducting, configurable divertor geometries, modules, materials at high PB/R. RMP coils. ITER-like heating & current drive systems. R=2.2m, B=6T, P_{heat}=45MW, t_{pulse}~95s.	Power exhaust for EU-DEMO	After 2030, key opportunity to optimize long pulse diverter solutions for FPPs (SO-D.2)
EAST	Tokamak	Superconducting, Mo wall, DN W-diverters, Li coatings, ECRF, ICRF, LHRF, and NBI. RMP coils. R=1.9m, B=3.5T, P_{heat} up to 29MW possible (3-5 years), t_{pulse}~1000s	Steady-state core-edge integration for BEST/CFETR	Now, develop FPP scenarios (SO-D.3) with heat & particle exhaust control (SO-D.2) in long pulses
JT60-SA	Tokamak	Superconducting, single null divertor, ITER-like heating & current drive systems. R=3.0m, B=2.3T, P_{heat}=41MW, t_{pulse}>100s	Complement ITER; develop high β_N non-inductive operation	After 2029, key opportunity to optimize steady-state core scenarios for FPP (SO-D.3)
KSTAR	Tokamak	Superconducting, C-wall, DN W-diverters, ECRF & NBI, possibly other RF soon. RMP coils, SPI disruption mitigation. R=1.8m, B=3.5T, P_{heat} up to ~21 MW possible in next few years. t_{pulse}~300s.	Steady-state core-edge integration for KDEMO	Now, develop FPP scenarios (SO-D.3) with heat & particle exhaust control (SO-D.2) in long pulses. Develop disruption mitigation (SO-D.4)
MAST-U	ST	High divertor leg length, Super-X geometry. R=0.9m, B=0.5T. Up to P_{heat}=10MW & t_{pulse}~5s planned.	Test alternative divertor concepts, explore case for ST fusion energy system	Now, assess novel divertor designs not available in US (SO-D.2); compliment domestic ST core scenario research (SO-D.3)
ST80-HTS	ST	Highest B ST with HTS magnets. t_{pulse}~15 minutes.	Record high sustained $nT\tau$. Builds on ST-40, prepares for ST-E1 pilot plant.	After 2026, extend ST long pulse core scenario (SO-D.3) physics basis and heat flux management (SO-D.2)
TCV	Tokamak	Versatile plasma shaping and divertor geometry. NBI, ECH. R=0.9m, B=1.5T, P_{heat}=6.5MW,	Support ITER, DEMO, fundamental	Now, assess novel divertor designs (SO-D.2)

		t_{pulse}~4s	research	

Tokamak Burning Plasma Physics

There is a need to validate models for prediction of self-consistent alpha heating, energetic-particle-driven instabilities, and ash removal in potential tokamak FPP designs. JET has recently conducted a successful DT campaign, but will cease operating as a research tokamak in ~2025. ITER burning plasma operation before 2033 is unlikely. In the next decade, the US has very little opportunity to conduct new studies using actual burning plasmas in international tokamaks or STs. Nevertheless, some non-DT international tokamaks or STs can access energetic particle regimes that can help discover new physics and validate models.

Finding F1-1: JET has an extensive, valuable database of operation with different isotopes, including fusion-generating DT operation, and continued access to this database is of significant value to the US.

Finding F1-2: Well-diagnosed, non-burning MAST-U largely complements NSTX-U's abilities to access more burning plasma-relevant v_{α}/v_{Alfven} and β_{fast} than in conventional aspect ratio tokamaks, although likely at less-relevant ϱ^*_{fast}.

Finding F1-3: Non-burning MAST-U, ASDEX-UG, and EAST largely complement NSTX-U's and DIII-D's ability to diagnose fast ion physics perhaps better than will be possible in future burning plasmas, so the US can leverage collaborations with these programs to validate energetic particle physics models.

Tokamak Divertor Solutions

A major knowledge gap for tokamaks is how to best exhaust the heat and particle flux at the boundary in a way that avoids damage to plasma-facing surfaces while maintaining adequate core performance. To close this gap, there is a need to test candidate divertor solutions at conditions relevant to and informative of FPP's and ensure these can be integrated successfully with FPP core operating scenarios.

International collaborations offer various opportunities for the US to accomplish these goals. MAST-U and TCV offer opportunities for testing divertor geometries not accessible in US facilities, including long-legged divertors, but at lower power density and PB/R than available on existing and planned domestic devices. ASDEX-UG enables studies in a mid-size tokamak like DIII-D but in a full tungsten wall environment, which is unavailable domestically. Additionally, ASDEX-UG is going through a major upgrade for the installation of a new upper divertor that offers studies of alternative configurations like X-divertor and snowflake divertor, at relatively high power density. Fully superconducting KSTAR and EAST have tungsten divertors, good control systems for studying detachment, and long pulse capability important for encountering significant changes in the plasma-wall interactions (*e.g.,* particle inventory, recycling, erosion, redeposition, wall thermalization). These devices surpass any existing or planned domestic tokamak pulse lengths, but do not exceed planned heating power density and diagnostic capabilities. EAST's wall is often dominated by lithium coating, a choice that presently makes it less suited in some ways for answering questions about impacts of tungsten than KSTAR. Collaboration with WEST offers a similar but somewhat more limited opportunity compared to EAST and KSTAR for closing gaps for high power density divertors. WEST is a hybrid system with superconducting toroidal field coils and conventional coils for poloidal field and inductive current drive, and as such does not have all the constraints of fully superconducting devices. It is designed to test a particular W-diverter design to inform ITER, at long pulse lengths sustained by auxiliary current drive. Longer term, DTT is projected to come online with limited capabilities in 2030, and begin testing a series of new diverter designs at PB/R closest to ITER of any device, sustained for at least four current diffusion times. Note that SPARC is projected to have higher PB/R than ITER and DTT, but will have much shorter pulses. With a focus on supporting ITER and EU-DEMO, DTT presently does not plan to aim for integration of edge and advanced core scenarios envisioned by some US FPP concepts. This timescale also is too late to significantly impact US FPP decisions on the BDV timescale, but US collaboration with DTT could be very valuable longer term to inform FPP upgrades, or generation-2 fusion energy system designs. Tokamak Energy's ST80-HTS is projected to begin operations in 2026, with a goal of obtaining record-high $nT\tau$ in an ST for 15-minute sustained pulses and the highest B-field of any ST. Expected PB/R is presently unavailable, but the program goal suggests optimizing plasma-surface interactions and heat flux handling will be important.

Finding F2a-1: Exploration of a range of divertor geometries and conditions not available in the US using MAST-U, TCV, and ASDEX-UG, including comparative divertor closure studies, can help the US make an initial evaluation and down-selection of FPP designs on the BDV timescale that would need further testing at higher power density and for high-performance core-edge integration on other devices.

Finding F2a-2: Collaborations with KSTAR and EAST offer the primary opportunities over the next decade to work out control solutions for W-divertor detachment in stationary long pulses with modest core performance at low-to-medium power density or PB/R. Operational experience in long pulse on these devices can contribute somewhat to US preparation for ITER operations.

Finding F1-4: Increased collaboration with DTT over the next decade could position the US to influence the design of some DTT diverter stages for testing after 2036, and the choice of core scenarios DTT will explore core-edge integration physics.

Finding F1-5: Longer term, the US could work with DTT and ITER, and possibly ST80-HTS, to validate diverter operation with higher power density and PB/R, and to test integrated core-edge scenarios.

Tokamak Scenarios

Another tokamak knowledge gap is how to design optimal core plasma operational scenarios that project to high average fusion and electrical output power in candidate FPPs. Eliminating this gap requires testing a range of scenario options in more FPP-relevant conditions.

International collaborations provide various opportunities for the US to develop the physics basis for scenarios. Several superconducting facilities focus on long-pulse and/or steady-state operation. JT60-SA's integrated operations phase 1, planned to begin in 2029, represents an opportunity for the US to engage in long pulse/steady-state FPP scenario development. Planned capability increases in 2033 (actively cooled W diverter and higher power) will extend this opportunity. Three rows of six 3D coils make JT60-SA an important facility to collaborate on ELM control in relevant scenarios. The combination of size, B-field, plasma current, and heating/current-drive power make JT60-SA the device with the greatest potential for testing simultaneous high β_T and high bootstrap current fraction operation (*i.e.* high β_N). The timescale can impact the US FPP on the BDV timescale, but the present JA-EU arrangement is a potential barrier to greater US leadership and influence at JT60-SA. Collaboration on EAST and KSTAR offers the US an opportunity now to develop long pulse/steady-state scenarios with W divertors. Both devices have 3D coil sets that can be used to test ELM control. Compared to existing domestic devices and JT60-SA, EAST and KSTAR have lower existing and planned heating and current drive, and less mature diagnostics, making access to very high performance scenarios for FPP less likely. International ST experiments also offer opportunities for scenario development. ST-40 is the highest B-field ST, making it capable of testing scenarios at burning plasma-relevant high temperature and low collisionality (After 2026, ST80-HTS is expected to extend this to long pulse). QUEST allows investigation of non-inductive startup and sustainment methods for ~60 minute pulses. SMART enables assessment of negative triangularity shaped ST operation. MAST-U provides capabilities for exploring steady-state core ST scenarios similar and complementary to NSTX-U.

Finding F1-6: The US needs to leverage international superconducting facilities to test and project any FPP scenarios beyond 1-2 current profile relaxation times.

Finding F2a-3: Ongoing US collaboration with EAST and KSTAR is important for developing long pulse scenario solutions with moderately-high performance ($\beta_N \sim$ 2- 3.5) to full current profile relaxation with W divertors on timescales long enough to see and solve plasma-material-interaction challenges.

Finding F2a-4: US collaboration with JT60-SA is likely the best option for testing the highest β_N (~3.5 - ~5) steady-state scenario options to long pulse, but the present EU-JA agreement and lack of an official path for US participation is a barrier that needs to be overcome.

Finding F1-7: Collaboration with presently operating spherical tokamaks MAST-U, ST-40, SMART, and QUEST, and possibly soon operating ST80-HTS, can help develop ST operation in regimes for which the US lacks capability to enter, such as higher field and longer pulse length.

Tokamak Disruptions

In an FPP, disruptions need to be reliably avoided and, failing that, to be reliably mitigated. Development of stable operating scenarios is a first step, augmented and possibly enabled by development of real-time forecasting and control. Common causes of disruptions must be foreseen and managed in pilot/power-plant relevant conditions; these include vertical displacement events, neoclassical tearing modes, and radiative collapse caused by impurity influx in long pulses. ECCD preemptive or asynchronous suppression of NTMs is a technique that can be further developed in joint experiments between domestic DIII-D and international facilities with ECH power, notably ASDEX-UG. TCV is a leader in real-time forecasting and control for disruption prevention. Considering superconducting tokamaks, real-time disruption forecasting and avoidance by physics-based and machine-learning models is a high priority for KSTAR, and to a somewhat lesser extent, for EAST. Deployment of US-developed plasma control systems and predictive tools on these devices enables scenario regulation and development of asynchronous responses to potentially disruptive events across a wide range of plasma conditions relevant to FPP. A frequent challenge in these efforts is successfully developing disruption prevention techniques that work on multiple devices. If disruption avoidance fails, a reliable disruption mitigation system is needed, and here again, multi-machine comparison is extremely important to provide confidence in broad application of the method. A few mitigation techniques, notably shattered pellet injection, have been compared on DIII-D, KSTAR, and JET. JET will cease operating as a research tokamak in ~2025, but has collected useful data on disruptions and disruption mitigation. KSTAR's existing symmetric, multi-barrel, dual-SPI offers an excellent collaboration opportunity to test this mitigation technique. New large international tokamaks coming online soon like JT60-SA and DTT will also need reliable mitigation systems, and they may look to the US for collaboration to develop these.

Finding F1-8: Disruption avoidance requires developing robustly stable operating scenarios, and key international collaboration opportunities identified will help close the disruption gap.

Finding F1-9: Developing a real-time disruption forecasting and avoidance control system for maintaining stable operation in an FPP is best accomplished by comparing efforts on multiple devices with a range of conditions, including those not available in the US; key devices for this are ASDEX-UG, TCV, KSTAR, EAST, and eventually JT60-SA and DTT.

Finding F1-10: Testing of disruption mitigation systems and scaling these to FPP benefits from multi-machine comparisons, but so far these have been limited to only a few tokamaks (JET and KSTAR); expanding comparative disruption mitigation system research to new devices, like DTT, would help.

Finding F1-11: JET has a valuable database on disruptions and disruption mitigation, to which continued access would be significantly valuable to the US.

> **Recommendation R1-1:** Prioritize support for collaborations primarily on KSTAR, EAST, ASDEX-UG, MAST-U, JT60-SA, DTT, and ST80-HTS to close key gaps in design and operation of divertors, operational scenarios, and disruption avoidance and mitigation in conditions not available in the US: long pulses with high beta, higher B-field, metal walls, and different divertor geometries at high heat flux.
>
> **Recommendation R2a-1:** Pursue collaborations involving KSTAR, EAST, ASDEX-UG, MAST-U, JT60-SA, DTT, JET (latter focused on database analysis), and ST80-HTS, with high potential to close many key burning plasma and MFE-based fusion energy system design gaps to achieve the BDV [FESAC 2020, NASEM 2021], and to help prepare for ITER operation.

Stellarator Physics Basis

The 2020 Community Planning Process (CPP) final report [CPP 2020] section on strategic objective E: "Advance the stellarator physics basis sufficiently to design a low-cost fusion pilot plant" identifies broad categories of gaps in the stellarator physics basis. Gaps in understanding identified for the stellarator include: stellarator optimization, core physics, long pulse power handling (see **Figure IV.1-1,** and **Table IV.1.2-2,** last column).

Table IV.1.2-2. Key stellarator facilities for US international collaboration.

Facility	Type	Characteristics / Capabilities	Research Focus	US Goals/Gains from Collaboration
W7-X	Stellarator	Superconducting Quasi-isodynamic Island divertor Steady-state at high power	Testing optimization Steady-state, high-power operation	Validating stellarator optimization (SO-E.2) Long-pulse power handling (SO-E.3)
LHD	Heliotron	Significant database of prior results. Superconducting, high-power heliotron.	Potentially transitioning to basic science research.	Validating stellarator optimization (SO-E.2)

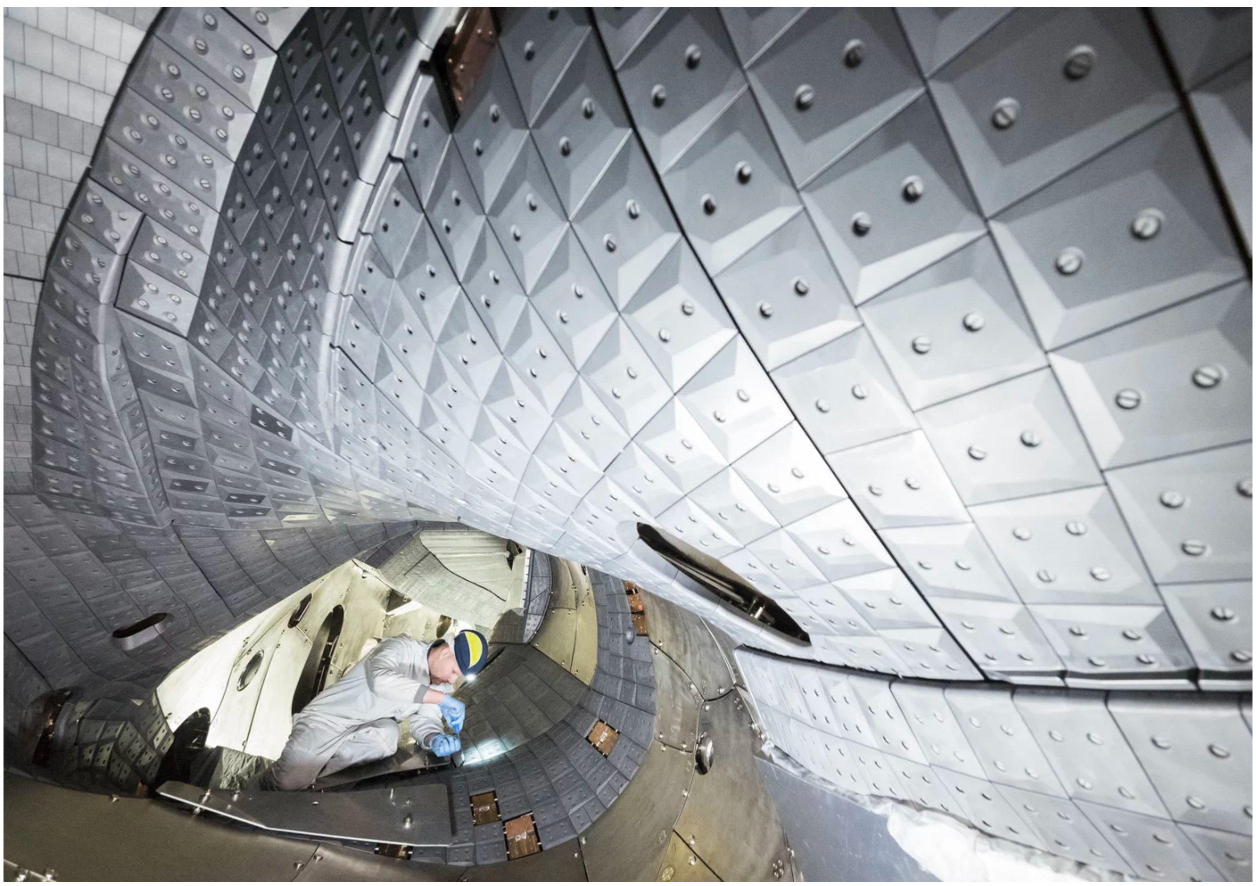

Figure IV.1-1. International facilities such as W7-X (pictured here) provide opportunities for testing novel plasma configurations and conditions not accessible by domestic facilities. Shown here is a view inside the W7-X plasma vessel with graphite tile cladding. Photo: MPI für Plasmaphysik, Jan Michael Hosan [from article "Wendelstein 7-X achieves world record" (June 25, 2018), https://www.ipp.mpg.de/4413312/04_18]

Stellarator Optimization

The US produced many of the key tools and solutions for stellarator optimization, some of which have been successfully applied to design and analysis of operating devices outside the US (e.g. W7-X). However, effort is required to sustain and expand US capabilities in the areas of integration, design, and optimization in order to identify candidate stellarator configurations that scale to an FPP. In addition to sustainment of fundamental stellarator optimization codes, there is a significant need for US development of systems codes and advanced design and integration tools relevant to stellarator-based fusion energy systems. There are active stellarator/heliotron demonstration fusion energy system design efforts led by IPP Greifswald (HELIAS 5-B) and NIFS (FFHR-d1) that are complementary to efforts in the US. HELIAS uses the PROCESS systems code (Culham) [Lion 2021], and FFHR uses the HELIOSCOPE systems code. There is an opportunity to engage with HELIAS and FFHR design teams to improve exchange of knowledge regarding design workflows and capabilities. There is also significant interest among US private companies in stellarator design, including leveraging of international resources.

Stellarator Core Physics

The primary needs for the Stellarator core physics basis center on the importance of demonstrating ways of achieving high confinement of both thermal and fast ion populations while also allowing for the adequate removal of impurities. In particular, previous community planning activities identified the need "to demonstrate…turbulent transport reduction by design of the 3D magnetic field, in addition to good energetic particle confinement" ([CPP 2020] SO-E.2). The ability to optimize stellarator core plasma configurations to minimize fast ion, neoclassical, and turbulent transport has greatly advanced over the past decade, but few experimental facilities exist to validate these new techniques.

W7-X is the world's only large stellarator to have been designed using principles of transport optimization. Results from this facility have provided a partial validation that realizable quasi-isodynamic configurations can reduce neoclassical transport below turbulent transport. US researchers are well-integrated into the W7-X program, providing crucial diagnostic capabilities and contributing to program planning. Investments from the US could expand the unique capabilities of W7-X, including for continuous fueling, accelerated metal wall operation, and additional diagnostic support.

LHD in Japan is of comparable size to W7-X, and has historically featured the ability for high-power operation. LHD operation has been approved for two additional campaigns, through December 2025. Presently there exists uncertainty about whether these campaigns will be able to utilize high input power or whether the focus will be on fusion science or basic plasma science. In either case, continued collaboration with LHD will be valuable, both for utilizing the facility for new experiments, and accessing its considerable record of experimental data, which can continue to be used to validate new modeling capabilities and theoretical understanding.

There is no planned or operating facility comparable to W7-X to test the principles of quasisymmetric configurations, which have been pioneered by US scientists. A relatively small, copper-magnet quasi-axisymmetric stellarator, CFQS, is presently being constructed at Southwest Jiaotong University in China. The design of this facility did not employ recent advances in stellarator optimization techniques, and therefore will not serve as a test of these methods. The capabilities, schedule, and accessibility of this facility are uncertain at the present time, but could conceivably present an opportunity for collaboration within the decade.

Finding F1-12: Depending on the focus and capabilities of LHD going forward, which are presently uncertain, there may or may not be significant opportunities for continued collaboration on fusion-relevant experiments. In either case, the extant LHD dataset will continue to be a useful resource to the US for validation of new modeling capabilities.

Finding F2a-5: W7-X is likely to remain the only existing optimized stellarator in the near future, other than the much smaller-scale HSX. W7-X allows steady-state high-power operation and provides a critical, unique platform for testing models of turbulence and transport in optimized stellarators. Presently, it relies on US expertise for some diagnostics. Near-term upgrades will further increase available power from ECRH and NBI. The US is a leader in stellarator theory, and experimental participation by US scientists on W7-X would be extremely valuable for validation purposes.

Finding F1-13: CFQS could provide a unique platform for studying some aspects of quasi-axisysmmetric configurations; however, there are presently significant uncertainties surrounding the date of operation and the capabilities and diagnostic coverage of the facility.

> **Recommendation R1-2:** Expand collaboration with W7-X, and the programs of HELIAS and FFHR, to maximize opportunities to study core confinement in optimized stellarator configurations, validate modeling capabilities, and improve exchange of design workflows and capabilities.

Stellarator Divertor solutions

Stellarators offer unique opportunities and challenges for power exhaust and divertor solutions. Stellarator plasmas are routinely observed to operate well in excess of the Greenwald-equivalent density limit, enabling high edge density scenarios that are compatible with stable detachment and a high fraction of radiated power. Inherently complex geometries pose challenges for design but also enable new concepts such as the island divertors employed by W7-X. With actively cooled divertors and long-pulse, high-power operation, W7-X offers unique capabilities for studying plasma-wall interactions.

All major stellarator facilities presently use carbon plasma facing components, with the exception of TJ-II, which has used lithium wall coatings. The W7-X program is planning on eventually converting to tungsten plasma-facing components after suitable baselines with carbon components have been demonstrated; however, all-metal operation is not anticipated before 2030.

Finding F1-14: TJ-II provides a capability to study impurity transport in stellarators, including the effect of liquid metal divertor components. Conditions are not relevant to FPP power handling requirements, but could be useful for basic understanding of plasma-material interactions and impurity transport.

Finding F2a-6: W7-X's combination of superconducting coils, actively-cooled plasma facing components, high input power, and ability to operate stably in a detached state make it a unique platform for studying steady-state divertor operation and plasma-material interactions. PFCs are presently carbon, but longer-term plans exist to test tungsten components.

> **Recommendation R2a-2:** Expand collaboration with W7-X to maximize opportunities to study steady-state divertor solutions, including core-edge solutions. Explore ways to accelerate W7-X experimental capabilities to address operation in a tungsten PFC environment on a timescale consistent with the BDV.

Alternative Magnetic Confinement Concepts Core Physics

The 2020 Community Planning Process (CPP) final report [CPP 2020] section on strategic objective H: "Develop alternative approaches to fusion that could lead to a lower cost fusion pilot plant, utilizing partnership with private industry and inter-agency collaborations" identifies gaps in alternative fusion approaches. These include confinement in alternative concepts, core physics, active and passive control, pulsed power and plasma formation, and power handling (see **Table IV.1.2-3,** last column).

Table IV.1.2-3. Key alternative magnetic confinement facilities for US international collaboration.

Facilities	Type	Characteristics/ Capabilities	Research Focus	US Goals/Gains from Collaboration
RFX-mod2 (Consorzio RFX - Italy)	RFP	Largest current (and field) RFP Advanced active mode control Close-fitting wall for tearing mode stabilization Large diagnostic suite	Tearing mode stabilization Active control	Active and passive control of plasma Workforce development (SO-H.3)
UH-CTI/QUEST (Kyushu University - Japan)	Spheromak	Steady-state spheromak	Developing spheromak for fusion energy Studies of particle transport Heavy Ion Beam Probe (HIBP)	HIBP Active control of plasma Model validation and verification (SO-H.3)

			Advanced control	
FAT-CM (Nihon University - Japan)	FRC	Pulsed FRC device	Pulsed-power Collisional formation	Pulsed-power and plasma formation techniques Advance basic plasma science: magnetic reconnection (SO-H.3)
GAMMA-10/PDX (University of Tsukuba - Japan)	Mirror	Largest tandem mirror with Neutral beam + ECR heating	Stabilization of drift waves Divertor/SOL studies PWI studies	Divertor/SOL/PWI (SO-H.3)

The FESAC LRP Report cites research in non-tokamak confinement approaches as a top priority due to its potential to serve "as both a risk-mitigation strategy for the tokamak approach, and to support innovations that have the potential to accelerate progress towards an FPP and deployment of commercial fusion energy." While the report highlights this need for alternatives research, funding in the domestic program has been reduced dramatically in recent years, even as interest in alternatives has been reinvigorated by investment in the private sector. In order to leverage both the private sector and the intellectual capacity in the domestic program built-up over decades of research, the US should enable and encourage collaborations on alternative confinement concepts abroad.

Finding F1-15: FES funding for alternative MFE approaches (i.e., non-tokamak, non-stellarator) has fallen off dramatically in recent years, even though the number of private companies exploring alternatives has increased. There are considerable resources in alternative concepts abroad that can be leveraged by domestic partners, public and private, to mitigate risk in developing fusion through a diversity of approaches.

Finding F1-16: Research in alternatives can inform tokamak physics. For example, Gamma-10 can provide high heat flux (10 MW/m^2) for PWI studies and high temperature end-loss plasma for detachment studies in various tokamak-relevant divertor geometries.

Finding F1-17: Research in alternatives can lead to the development of enabling technologies. For example, research on the UH-CTI has led to the development of advanced tokamak fueling scenarios.

> **Recommendation R1-3:** Support international collaborations on alternative magnetic confinement concepts between domestic partners (university, national lab, private sector) and institutions outside of the United States where the US has no comparable domestic facility (e.g., those listed in **Table IV.1.2-3**).

Inertial Fusion Energy Core Physics

With the recent demonstration of ignition (defined as more energy out of the target than was delivered to it by the lasers) on the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in the US, the promise of decades of R&D and investment into Inertial Confinement Fusion was realized.

The NIF is presently the only full-scale integrated facility currently capable of achieving burning plasma anywhere in the world. There are several other facilities around the world currently under construction designed to have similar characteristics to the NIF and intended to study implosion physics (such as the Laser Megajoule (LMJ) in France, UFL-2M in Russia, and Shenguang-III in China). However, none of these facilities are currently slated to be collaborative, open science facilities.

The 60-beam OMEGA laser at the Laboratory for Laser Energetics (LLE) at the University of Rochester, US plays an important role in studying plasmas with symmetric drive. However, its total energy is not sufficient to achieve burning plasma and ignition.

The laser facilities mentioned thus far are long-pulse laser facilities for the study of compression and implosion physics. There are only a limited number worldwide, and the US currently maintains leadership in hosting and operating such facilities. However, there are numerous short-pulse laser facilities worldwide that exceed the US in capabilities, which can allow for the study of fundamental high energy density plasma physics, are needed for the study of particle acceleration for some alternate ICF approaches, or can provide testbeds for component or systems development. There are also a handful of subscale joint long-pulse (few beam) plus short-pulse laser facilities where novel physics can be studied. It is on these facilities that international collaborations in IFE may be most fruitful. In addition to laser-based compression approaches, pulsed-power accelerators are a key driver for fusion target concepts that combine features of both magnetic and inertial confinement. There are several university-scale pulsed-power machines at international universities offering additional opportunities for technology innovation and international collaboration that can add to the diversity of IFE approaches.

The US also possesses significant capability in modeling and simulation of ICF physics, ranging in multi-scales and multi-physics, and validated against a large body of experimental work. This advantage is again in large part due to the sustained investment by the DOE NNSA over decades. Thus, the US leads in ICF target physics and ICF science, but substantial investment and support are imperative if it is to maintain its competitive edge in translating this to the fusion energy application space. This is an opportunity for the US to collaborate with other countries to share our knowledge and resources in order to tap into an international workforce, and potentially figure out where our weaknesses are that other countries can help fill.

The IFE area is included in the 2020 Community Planning Process (CPP) final report [CPP 2020] section on strategic objective H: "Develop alternative approaches to fusion that could lead to a lower cost fusion pilot plant, utilizing partnership with private industry and inter-agency collaborations." Relevant subtopical areas in the CPP are listed in **Table IV.1.2-4,** last column.

Table IV.1.2-4. Key inertial confinement facilities for US international collaboration.

Facilities	Type	Characteristics/ Capabilities	Research Focus	US Goals/Gains from Collaboration
Gekko-LFEX (Osaka University, Japan	Laser	1 x Short Pulse + 12 x Long Pulse	Fast ignition Particle acceleration Magnetically-assisted approaches	Coupling, compression & heating studies Alternate IFE concept development (SO-H.1, SO-H.2)
ELI Facilities (BL, NP, Atto)	Lasers	range of lasers and laser combinations: mJ - kJ / single shot to kHz / up to 10 PW	Laser-plasma interactions	Active control of experiments + plasma Model validation and verification Development of high-repetition-rate subsystems (SO-H.1, SO-H.2)
PETAL (CEA, France)	Laser	Short pulse laser coupled to Laser Megajoule facility, 0.5 - 10 ps, few-kJ pulse at 1053 nm.	Particle acceleration	Alternate IFE concept development (SO-H.1, SO-H.2)
CLF (Rutherford Appleton Laboratory, UK)	Laser	Gemini: dual beams of high power, ultra-short pulse, 15 J, 30 fs, shot/20s Vulcan: PW, 2.6 kJ, 500 fs	Particle acceleration Laser-plasma interactions	Active control of experiments + plasma Model validation and verification Development of high-repetition-rate subsystems (SO-H.1, SO-H.2)
FAIR (GSI, Germany)	Heavy Ion	UNILAC: < 11.4 MeV/u SIS18 < ~1-4 GeV/u Species: anti-protons, p to U	Heavy ion target and coupling physics	heavy ion beam control, focusing, and target interactions (SO-H.1, SO-H.2)

		Design proton beam: 2x10^13 x 0.1 Hz, 29 GeV		

There remain numerous challenges and gaps, as recently laid out in the 2022 IFE Basic Research Needs report. There are several that would specifically benefit from international collaboration, including:

In the area of Target Physics, techniques for Laser Plasma Instability (LPI) mitigation and control can be both studied and tested across a number of facilities around the world. This includes mid- to high-intensity LPIs for all laser fusion concepts and laser pre-heat for MagLIF and pulsed power coupling. For alternate IFE concepts (beyond direct or indirect drive hotspot ignition), there is a need to demonstrate localized heating of compressed fuel to thermonuclear temperatures, which can be broken into parts and investigated at short-pulse, high-intensity laser facilities both inside and outside the US. This information can be coupled to studies on compression physics at larger-scale long-pulse facilities such as Omega or NIF in the US.

IFE driver development will require IFE driver system-level architecture conceptual design studies. At the moment, there are nodes of excellence around the world (including UK, Germany, and Japan) that can make significant progress, particularly in collaboration with the US. Reducing the cost of diode pumps in diode-pumped solid-state laser technologies will require standardization and capacity scaling, and will necessarily need partnerships between laser diode manufacturers (many that are international companies) and the public sector. Finally, it is a common need to design and implement final optic survivability at ultra-high intensity as this constrains the energy per beamline and will influence systems designs - there is significant expertise for this that sits outside the US.

The diamond capsules that were used on the NIF leading to the ignition shot were fabricated in Germany. The US would benefit from tapping into manufacturing processes and advanced manufacturing techniques developed across the world can support the demonstration of high-volume techniques for spherical capsule or wetted foam capsule fabrication. Similarly, while there has been work in the past in the US on demonstrating accurate engagement on-the-fly of IFE targets by a driver beam, there is significant room for collaboration in this area.

IFE diagnostics will need to be developed, both for high-repetition-rate experiments for HED/ICF/IFE in the near-term, as well as radiation-hardened diagnostics critical for IFE power plants in the future. While the US has significant expertise in diagnostic development for large-scale facilities such as NIF, there are many opportunities for international collaboration as the many international laser facilities will require a set of unique instrumentation.

Simulation and Modeling needs include improving predictive calculations via a combination of benchmark/validating experiments, improved computational capability, and developing AI & ML techniques to automate and improve data processing and analysis, particularly to make use of the large data rates of high repetition rate facilities. Due to the longstanding NNSA investment into ICF, historically much of the code development in this arena has resided in the US. However, experimental data to validate those codes, and the application of novel ML techniques can be an excellent avenue for opening new opportunities for international collaborations. And as big data grows in importance, it will benefit the community to develop common interoperable metadata standards, which can be done at an international scale. Another area of potential international collaboration is to develop multi-scale, multi-physics simulations (enabled by AI/ML) in order to bridge small/mid-scale experiments that occur internationally to full-scale IFE facilities.

Overall, in IFE, many of the existing facilities are centered around basic/fundamental plasma science in high energy density regimes. We are lacking in dedicated IFE facilities worldwide, and lacking in integrated capabilities.

Finding F1-18: The US is currently the undisputed leader in inertial confinement fusion, as evidenced by the demonstration of ignition on the NIF. No other country currently possesses an ICF facility capable of achieving propagating fusion burn. However, there is considerable interest internationally, and several countries are building near-NIF replicas. To advance toward the common goal of achieving inertial fusion energy as quickly and efficiently as possible, international partnerships will enable a coordinated approach with mutual development and sharing of complementary knowledge and tools. Maintaining the US leadership position will require substantial investment and support, which will also provide opportunities for the US to tap into an international workforce.

Finding F2a-7: Substantial European and Asian investments in laser development and laser science research coordination have overshadowed related efforts in the US, resulting in a relative loss of US technological leadership and scientific capabilities. While the US has huge diagnostic expertise, and continues to maintain considerable laser technology prowess, it is lagging in high energy, high-repetition-rate laser facilities that enable novel studies of high energy density physics and IFE science. Europe and Asia have laser facilities with high repetition rate capabilities that we do not have in the US

Finding F1-19: Key driver technologies for a diversity of approaches, such as capacitors for both laser and pulsed-power concepts and diode pumps for diode-pumped solid state laser components and final optic survivability, still require significant R&D. Global supply chain issues are foreseen for many of these technologies.

> **Recommendation R1-4:** Leverage US leadership in ICF through collaboration on complementary international facilities to help realize IFE.
>
> **Recommendation R2a-3:** Pursue collaborative research on international high repetition rate laser facilities to advance IFE physics and technology. Partner with other countries that possess laser, optical, materials, and processing expertise (e.g. Germany or UK) to co-develop crucial pre-competitive technologies, which have high potential to help realize the BDV.

IV.2. Materials and Plasma-Material Interactions

IV.2.1 Introduction

Although ultimately connected both physically and through the overall fusion plant engineering, materials effects can be broadly subdivided into 'bulk' structural materials and 'plasma-facing' materials. Key environmental conditions for the former include neutron dose rate and dose, neutron spectrum characteristics, corrosive media, and temperature; while for the latter, neutron effects are generally accepted to take a secondary role relative to Helium (He), Hydrogen (H), and possibly Beryllium (Be) ion influx and deposition, as well as intense transient heat load due to off-normal or instability events occurring near the plasma-wall interface. Illustrations of the neutron loads and ion fluxes in various ITER components are shown in **Figure IV.2-1**, together with a sequence of micrographs showing the degradation of W surfaces during exposure to He under divertor operation conditions.

IV.2.2 Narrative

IV.2.2.1 Bulk materials neutron testing

For bulk materials, fusion neutrons at 14 MeV result in unique effects that cannot be captured with lower energy fission neutrons except in very specific situations. This has driven the fusion materials community to push for the development of a 14 MeV neutron source for materials testing and qualification through an international collaboration known as the IFMIF (International Fusion Materials Irradiation Facility). Through various iterations, a compact, more economical, version of IFMIF is now being considered, known in the US as a 'fusion prototypic neutron source' (FPNS).

The requirements for FPNS were initially developed by the fusion materials and technology community in 2018–2019, and in 2020 the American Physical Society Division of Plasma Physics [CPP 2020] further elaborated on the need and priority, rating the FPNS as the most pressing need among potential activities for realization of fusion energy. In light of the significant changes and advancements within the private fusion industry, a two-part workshop was convened and hosted by the Electric Power Research Institute (EPRI) comprising a half-day webinar on August 29, 2022, followed by a two-day hybrid workshop on September 20–21, 2022, to update the public and private fusion community consensus on FPNS requirements and development timeline. Commensurate with the US government's Bold Decadal Vision for Commercial Fusion Energy announced in March 2022, the need for a sense of urgency with respect to the timeline to design, build and operate an FPNS with an upgradeable path to improved performance has been emphasized on multiple occasions. Through a substantially similar process, the EU has approved the building of IFMIF-DONES, a neutron source essentially satisfying the same technical requirements as FPNS, which has commenced construction in Spain (as of January 2023).

While plans to build FPNS are discussed and finalized, US-based researchers studying bulk fusion structural materials have access to a number of irradiation facilities that may fulfill some, but not all, of the necessary aspects of FPNS. **Table IV.2.2-1** lists the most important available neutron irradiation facilities for fusion materials testing outside the United States, addressing CPP objective B "Determine the structural and functional materials that will survive under fusion energy system conditions" [CPP 2020].

Table IV.2.2-1. Key bulk materials neutron testing facilities for US international collaboration.

Facilities	Location	Characteristics/ Capabilities	Research Focus	US Goals/Gains from Collaboration
High Flux Reactor (HFR)	The Netherlands (NRG-Petten)	Thermal spectrum materials test reactor (steady irradiation mode)	Medical isotopes, nuclear fuel testing	EU user facility, possibility of collaboration (SO-B.3)
BR2	Belgium (SCK/CEN-Mol)	Thermal spectrum materials test reactor (steady irradiation mode)	Isotope production, fuels and materials testing	Designated as a user facility (available through US-Belgium collaboration programs) (SO-B.1, SO-B.3)
HANARO Reactor	South Korea (KAERI)	Thermal spectrum materials test reactor (steady irradiation mode)	Neutron beam applications, nuclear fuel and material test, radioisotope production, neutron activation analysis and neutron transmutation doping	By direct collaboration with KAERI (SO-B.1, SO-B.3)
BOR60	Russia (RIAR)	Fast spectrum materials test reactor (steady irradiation mode)	Structural materials under irradiation	As of Jan 2023, outside the possibility of collaborations
JOYO	Japan (JAEA)	Fast spectrum materials test reactor (>1MeV)	Development of fuel and materials for fast reactors	Designated as a user facility (available through US-Japan collaboration programs) (SO-B.2, SO-B.3)
China Experimental Fast Reactor (CEFR)	China (China Institute of Atomic Energy)	Fast spectrum materials test reactor	Structural materials	Unknown at this stage
The Swiss Spallation Neutron Source	Switzerland (Paul Scherrer Institute)	Spallation neutrons (>2 MeV) in continuous	Structural materials (through STIP program)	SINQ is an open access facility, fully open to both the

(SINQ)		irradiation mode		national and the international user community (SO-B.2, SO-B.3)

The table lists some basic characteristics of each facility and the status of collaborative possibilities with US researchers. While the US has clear leadership in the availability and operation of thermal test reactors (through the High Flux Isotope Reactor - HFIR at ORNL, Advanced Test Reactor - ATR at INL, and the MIT research reactor), there are some gaps that cannot be fulfilled with domestic facilities. In particular, mimicking transmutation inventory buildup in fusion environments requires hard neutron spectra that cannot generally be accessed in low-power thermal test reactors. Fast spectrum reactors can provide neutrons with sufficiently high energies to probe several important threshold transmutation reactions, and that makes them an essential accompaniment to thermal test reactors. While at present, there are no facilities with those characteristics operated within the United States, the number of operational fast reactors for fusion materials irradiation testing is very limited, with two of the options operated in Russia (BOR60) and China (CEFR) and currently outside the realm of possibilities for collaboration, and another (JOYO in Japan) undergoing frequent interruptions in operation due to maintenance upgrades and antiquated instrumentation. Spallation sources (which US researchers can access domestically) can partially fill this gap, although significantly missing the transmutation He and H atom production rates, and can have detrimental solid transmutation products that are not present in a fusion spectrum irradiation.

However, being able to complete bulk neutron irradiations is not enough to garner viable data for the design and operation of a FPP or other fusion device. Irradiated materials must be characterized through a range of techniques such as mechanical testing, microscopy-based characterization, and environmental testing such as corrosion exposures and evaluation. Most facilities listed in the table above have complementary post-irradiation examination (PIE) facilities capable of handling activated materials and performing the necessary evaluations and tests. Given this, it is common for both domestic and international programs to move bulk irradiated samples between research facilities - either to access critical evaluation methods not available at the facility in which the materials were irradiated or due to over subscription of the local PIE facilities themselves. Movement of radioactive material requires careful consideration of both the sending and receiving country's regulations and norms and thus commonly involves the use of ground transportation that is both costly, and in the case of container ship movements, highly time intensive leading to doubling or more of the irradiation campaign timeline. Thus, the evaluation of the bulk neutron irradiation facilities should also include an examination of the PIE facilities and the transportation capabilities of each one.

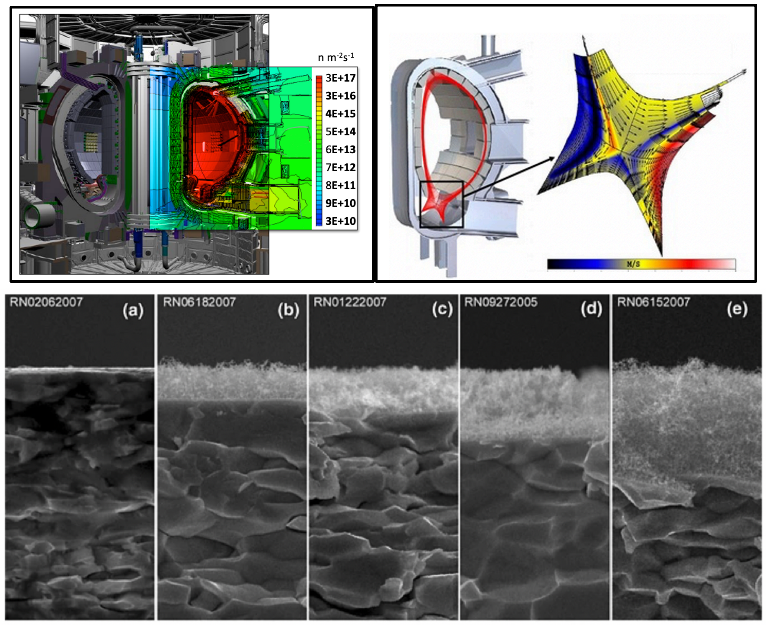

Figure IV.2-1: Resolution of materials/PMI issues will be critical to a successful fusion energy system. (Top left) Expected neutron load in the different ITER chamber and structural components. (Top right) Contour plot of the particle flux in the diverter region. (Bottom) Sequence of SEM images showing the degradation of a W surface through the development of 'fuzz' structures.

In addition to neutron irradiation testing facilities, as summarized in **Table IV.2.2-1**, significant research and materials development has historically been completed using charged particles and ion beams. This includes low energy ions (*e.g.*, keV range) for plasma-facing materials (see Section IV.2.2.2) and higher energy (>1 MeV) ion irradiations for functional and structural materials. Ion irradiations can produce higher damage rates (commonly 10^{-3} to 10^{-4} displacements per atom per second - dpa/s) than neutron irradiation facilities (10^{-6} to 10^{-8} dpa/s), meaning accelerated testing is commonly used. In addition, dual and triple beam irradiations can be used to enable both the displacement damage and transmutation products, commonly He and/or H, at the same time to emulate the 14 MeV and softened neutron spectrum expected in components and structures within a FPP and other fusion device designs. Challenges exist to fully emulate the expected structural and compositional changes in materials using ion-based irradiation programs, but the technique serves a critical role both in screening new material concepts and enabling a critical bridge to advanced modeling and simulation efforts. Furthermore, the method provides complementary data and analysis to bulk neutron irradiation from fission test reactors at a much faster rate. While there is wide availability of ion-beam irradiation facilities domestically and worldwide, the US fusion community suffers from limited accessibility to triple-ion beam facilities for simultaneous implantation of damage (with multi-MeV heavy ions), He, and H ions to emulate operation conditions in structural materials. The following table lists the triple ion beam facilities with MeV-ion capabilities.

Table IV.2.2-2. Key charged particle beam bulk materials testing facilities for US international collaboration.

Facilities	Location	Accelerators/ Capabilities	Research Focus	US Goals/Gains from Collaboration
IAE	Japan (Kyoto)	1.7 MV Tandetron 1 MV Van de Graaff 1 MV Singletron	Evolution of microstructure under multi-irradiation	Through pre-established international exchanges (SO-B.2)
TIARA	Japan (JAEA)	3 MV Tandem 3 MV Van de Graaff 400 kV ion implanter	Synthesis of nanostructured ceramics assisted by irradiation Behavior of alloys and ceramics under irradiation	Within the ITER collaboration agreement (SO-B.2)
JANNuS	France (DMN, Saclay)	3 MV Pelletron 2.5 MV Van de Graaff 2.25 MV Tandetron	Irradiation behavior of nuclear materials and ion beam modification of materials	User facility open to international research proposals (SO-B.2)

IV.2.2.2 Plasma-facing materials

Taming the plasma-material interface is one of the critical challenges of fusion energy research. All fusion concepts must integrate a high-temperature core plasma with a material boundary, though the details of the challenge vary significantly between concepts. Magnetic fusion concepts generally sustain high-temperature conditions for longer, requiring longer exposures to simulate fusion energy system conditions. Inertial fusion concepts feature repetitive impulsive loads on the material interface. Nearly all fusion concepts also produce fusion neutrons, which increases the challenge of taming the plasma material interface. These were recognized in the recent FESAC Long-Range Plan under “Engineering for Extreme Conditions”, and the report explicitly prioritizes the MPEX facility currently under construction at ORNL. Once operational, the MPEX facility will deliver world-leading capability to the US fusion program, for the benefit of both the public and private sector programs. However, the current estimate is that the MPEX facility will only be operational in 2028 and not reach full capability until 2030.

In the interim, international and domestic facilities exist to tackle elements of this challenge. Magnetic confinement facilities (and in particular tokamaks) have been equipped with solid metal plasma-facing components, providing opportunities to understand the interaction of tokamak plasmas with metal PFCs (in particular Tungsten). The US is already taking advantage of this capability within the Long-Pulse Tokamak program, where a collaboration with the WEST device in France is supported by DOE-FES. Additional international tokamak facilities exist to further enable the study of the interaction of high-power plasmas with Tungsten PFCs.

In the area of liquid metal PFCs (called out in the recent DPP-CPP community planning process [CPP 2020] under Fusion Science & Technology Strategic Objective A.2) there is a pronounced lack of high heat flux facilities (test stands or confinement facilities). In China, the EAST device is the only facility (domestically or internationally) currently able to assess the impact of liquid lithium PFCs on high-power plasma discharges. Future capabilities are in various stages of conceptualization and construction, such as COMPASS-U and the Italian DTT, and domestically NSTX-U intends to explore this direction after that program's core physics milestones are met. It is thus difficult to assess the ideal path forward for collaboration until facility capabilities are closer to being realized.

ITER itself will provide valuable input on PMI physics even during its early operational periods. The heat fluxes achievable will be higher than existing devices, owing to the narrow scrape-off layer widths expected at high plasma current. While not listed on the table below, any experimental facilities fielded by US fusion private sector participants will also provide additional experimental results in the area of PMI physics, though it is not expected that these results will be made available to the scientific community for detailed study.

Table IV.2.2-3. Key plasma facing materials facilities for US international collaboration.

Facilities (Location)	Type	Characteristics/ Capabilities	Research Focus	US Goals/Gains from Collaboration
JET (UK)	Magnetic Confinement Facility (Tokamak)	High-flux low fluence short duration exposures to tungsten and beryllium PFCs. Operations conclude in 2023.	Preparation for ITER and EU DEMO	Validate PFC models with extant data.
AUG (Germany)	Magnetic Confinement Facility (Tokamak)	All-tungsten PFCs, high-flux, low-fluence exposures. Strong diagnostic suite.	Preparation for ITER and EU DEMO	Assess W PFC under high heat flux in MCF device. Advance solid metal PFCs (SO-A.1).
WEST (France)	Magnetic Confinement Facility (Tokamak)	All-tungsten PFCs, long-pulse PMI exposures.	Preparation for ITER and EU DEMO	Assess W PFC under high heat flux in MCF device. Advance solid metal PFCs (SO-A.1). Existing US collaboration
DTT (Italy)	Magnetic Confinement Facility (Tokamak)	Proposed (2030). High heat flux, possibility to test alternate magnetic geometries and multiple PFC types including liquid metals. Significant schedule uncertainty.	Preparation for ITER and EU DEMO	Advance solid metal PFCs (SO-A.1). Possibly advance liquid metal PFC (SOA.2)
EAST (China)	Magnetic Confinement Facility (Tokamak)	Long-pulse, moderate flux testing of lithium PFCs. Only operating international device with liquid metal PFCs.	Preparation for ITER and CFETR	Advance solid metal PFCs (SO-A.1) and liquid metal PFCs (SO-A.2). Existing US collaborations.
COMPASS-U (Czech	Magnetic Confinement	Divertor mission includes testing liquid metal PFCs. High fluxes, high	Preparation for	Possibly advance liquid

Republic)	Facility (Tokamak)	Bt, operation with hot first wall. Significant schedule uncertainty.	ITER and EU DEMO	metal PFC (SO-A.2). US leadership degraded if LM PFCs deployed before NSTX-U.
MAGNUM-PSI (Netherlands)	PMI Test Stand	Long-pulse material exposures. Simultaneous stationary and pulsed heat source. World-leading facility until MPEX comes online.	Focus on PMI issues for ITER and EU DEMO	Opportunity for near-term testing of ITER-relevant components.
JULE-PSI (Germany)	PMI Test Stand	Proposed (TBD). High heat flux testing of irradiated materials. Significant schedule uncertainty as device is only at concept stage.	Focus on PMI issues for EU DEMO with irradiated samples.	Premature until device construction timeline is clarified.

The above table lists some basic characteristics of each facility and the status of collaborative possibilities with US researchers. A key conclusion is that for solid metal PFCs, and in particular Tungsten PFCs, ample magnetic confinement facilities exist abroad and with metal wall capabilities ahead of US facilities. In terms of test stands, MPEX will provide a world-leading capability later this decade, but until then Magnum-PSI offers the world-leading capability. Liquid metal work can only proceed at high power on the EAST device in China, owing to the lack of high-power confinement facilities or test stands domestically or internationally.

IV.2.2.3 Computational Modeling

In light of the wide gaps that exist between available materials testing facilities (both bulk and plasma-facing materials), modeling is expected to play a pivotal role in helping bridge those gaps and improve our understanding of the key differences between available facilities and fusion power plants. Among the most important developments needed to build a robust, validated, modeling infrastructure for materials evolution under experimental testing conditions are listed as follows. Sponsorship of coordinated efforts between cognizant testing facility operators/administrators and materials modelers to identify conditions for optimal collaboration is needed, including the design of specific experiments under 'clean' conditions that are well suited for models, as well as well-defined guidelines for validation. Equally valuable is ensuring the availability of large-scale computational platforms to carry out intensive atomistic simulations that can encompass fusion-operation relevant timescales. This availability must consist of both access to 100,000-processor machines as well as long-term machine availability for extended-time simulations. Coordination among materials modeling teams to 'hand-shake' numerical models simulating plasma-materials interfaces and bulk materials evolution is also required. In all cases, SciDAC Institute expertise and leadership-class DOE architectures must be leveraged to position the US in a leading position worldwide. At present, the US maintains global leadership in exascale computing capabilities and data storage facilities for fusion materials research, and no immediate need or benefit for international collaboration can be identified at the time of this report.

IV.2.3 Findings and Recommendations (Charges 1 and 2a in PMI/Materials)

Finding F1-20: In the absence of a FPNS, the US currently lacks operational fast neutron spectrum test reactors that could enable high-energy threshold nuclear reactions to (partially) map the high-energy transmutation yield of a fusion spectrum. The current geopolitical environment does not favor international collaborations with countries with available fast reactors. As well, the US currently lacks high (>40 MeV) energy ion irradiation capabilities, particularly triple-beam facilities for co-implantation of He. H, and damage.

> **Recommendation R1-5:** Strengthen ties with IFMIF-DONES to enable US researchers (including private sector) to access prototypical fusion neutrons when the facility comes online. Consider international triple-ion beam irradiation facilities as a bridge to fusion prototypic neutron irradiation testing. See also **Finding F1-30.**

Finding F2a-8: MPEX will be a world-leading capability when it comes online, but the MPEX timeline (operational 2028) will be too late to impact many private industry FPP design choices. Until then, Magnum-PSI is the only PMI test stand at scale available.

> **Recommendation R2a-4:** Facilitate international collaborations (including the private sector) on Magnum-PSI to test materials at high heat flux until MPEX is ready.

Finding F1-21: No suitable high flux PMI test stand for liquid metal PFCs exists domestically or internationally.

> **Recommendation R1-6:** Leverage international tokamaks using EAST (existing) or COMPASS-U (under construction) and DTT (planned) liquid metal PFCs to advance US expertise and experience with liquid metal PFC's until NSTX-U installs a liquid metal divertor.

Finding F1-22: International tokamak programs strongly emphasize solid metal PFC development for ITER (W, Be).

> **Recommendation R1-7:** Leverage international collaboration with existing solid metal wall tokamaks such as AUG, WEST, EAST to advance US capability in fusion-relevant solid PFC's. Explore collaborations with planned tokamaks as they approach operational readiness.

Finding 1-23: The current methods for international collaboration for irradiated materials typically require public-private interactions/agreements and no method for air-travel-based transit exists which increases both the time towards implementing the irradiation program and the production of significant results.

Recommendation R1-8: Work with international partners with critical irradiation testing facilities to facilitate rapid implementation of bilateral programs and design, and develop protocols for ease of transport of irradiated materials across international research programs.

IV.3. Balance of Plant

IV.3.1 Introduction

In a future D-T fusion pilot plant or power plant, the plasma must be surrounded by a blanket that 1) reproduces tritium, via transmutation of lithium, at the same rate it is consumed by fusion reactions; 2) captures the 80% of the fusion energy emitted in the form of 14 MeV neutrons; and 3) converts this energy to electricity. In addition to the development of lithium-bearing breeder materials and neutron multipliers that are necessary to achieve a tritium breeding ratio (TBR) >1, closure of the D-T fusion fuel cycle requires the development of a wide variety of tritium processing technologies for recovery and reuse of tritium as fuel. In addition to the radioactivity of tritium itself, the neutrons produced from fusion will significantly activate the surrounding structures, resulting in a non-trivial radiological hazard that requires certain safety measures, remote handling of components during maintenance, and which places additional constraints on the reliability of the fusion energy system and its components. Accordingly, this section addresses the status, research needs, and collaboration opportunities in the areas of tritium breeding blankets, tritium processing, safety, remote handling, reliability, availability, maintainability, inspectability (RAMI), and power conversion.

IV.3.2 Narrative

Though once an area of significant US leadership, in recent years a programmatic focus on fundamental science has resulted in US programs in breeding blankets, tritium processing, and ancillary systems that are less robustly funded than comparable international programs. US leadership in these areas has waned. The US presently does not participate in the ITER Test Blanket Module (TBM) program, which has been a key driver of breeding blanket and related technology development for international programs. Experimental activities have been limited in the US in recent years, with R&D largely driven by design studies.

The new focus on a fusion pilot plant introduced by NASEM in 2017 [NASEM 2017] and the explicit energy mission that it implies prompted a high-level re-assessment of research needs in these power plant technologies by the 2019-2020 APS-DPP Community Planning Process (CPP) [CPP 2020], the 2020 FESAC Long Range Plan subcommittee [FESAC 2020], and a subsequent report by NASEM [NASEM 2021]. Tritium breeding blankets and fuel cycle technologies were identified as critical systems for a future US FPP and a need for significantly increased investment in these areas was identified by both the CPP [CPP 2020] and FESAC LRP [FESAC 2020] reports. These gap areas were identified under CPP strategic objective C: "Develop the science and technology necessary to breed, extract, and safely manage large quantities of tritium" (see **Table IV.3.2-1**, last column).

The CPP report outlined a blanket research program driven initially by foundational research activities, experiments at modest scale to understand the fundamental properties and behavior of breeding and coolant materials and the production and transport of tritium in them, compatibility of these with structural materials, and technologies needed to extract and reprocess tritium. These progressed to progressively integral scales through a blanket component test facility (BCTF) and Volumetric Neutron Source (VNS), which would conduct large-scale prototype tests with and without neutron irradiation and tritium, respectively.   A similar "process intensification" was outlined for tritium exhaust and processing technologies, permeation barriers, pellet injection, and tritium measurement capabilities, leading to deployment first on existing continent devices and/or a VNS, followed by the FPP.

The urgency of these research needs is only amplified by the ambitious timelines outlined by the subsequent NASEM report and Bold Decadal Vision, and international collaboration can be leveraged to help accelerate the development of these programs. Because new domestic experimental capabilities are critical to the viability of an enhanced domestic program, collaborations should focus initially on *programmatic* collaborations rather than specific facilities.

The small size of US programs in these areas relative to those of potential international collaborators, in many cases hinders our ability to meaningfully contribute to collaborations. Still, there are strengths that are valued by international partners (see below) and these should be capitalized on. In particular, in early 2020, the US and EU jointly proposed a variety of bilateral collaborations on specific research topics including materials, breeding blankets including liquid metal MHD, tritium handling, fusion safety, and waste management. The recommendations were specific, identified performers and levels of effort, and specific collaborative research topics. Those recommendations are of interest to both parties and should be enacted.

As noted above, though an increase in domestic experimental capabilities remains a high priority, a variety of international facilities may prove complementary, and some of these are summarized in the table below. Many experiments and facilities have a research capability/focus that is specific to a particular blanket concept and its support systems. The value of collaboration on these experiments depends on US technology preferences, and the US would benefit from a more specific blanket technology development plan, i.e., including primary candidate concepts and down-selection criteria, that would inform this.

The limited time afforded by the Bold Decadal Vision places some particularly difficult constraints on integral test facilities, which are critically important to inform the design and construction of an FPP but difficult to advance from pre-conceptual to operational status on this timeline. Here especially, international collaboration should be looked to in coming years as a potential means of addressing US technology development needs within this time constraint. The H3AT facility for tritium processing and CHIMERA facility (**Figure IV.3-1**) for blanket component testing in the UK, appear particularly promising for these purposes.

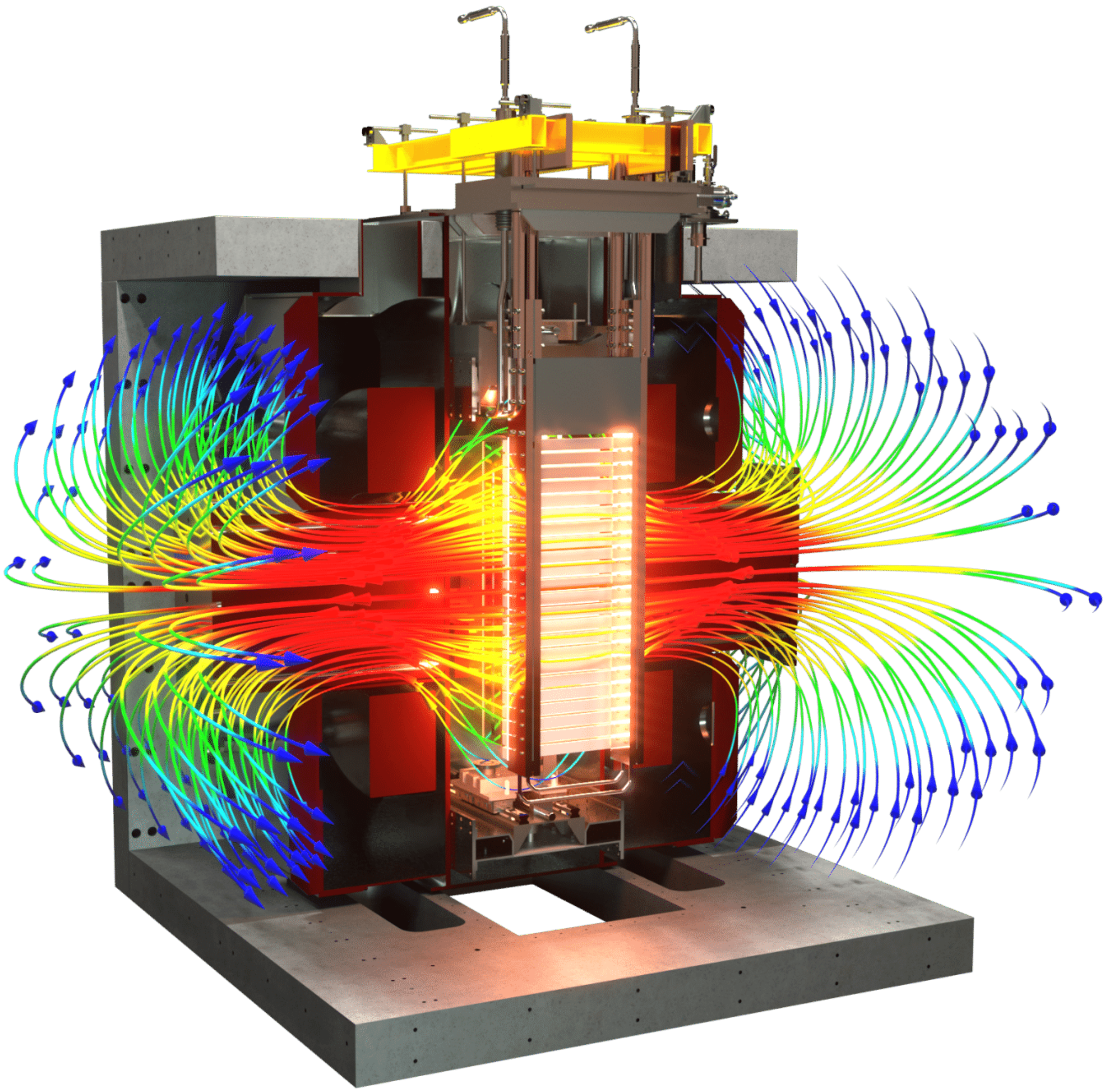

Figure IV.3-1: Illustration of the UKAEA CHIMERA facility, which will test meter-scale blanket prototype components in fusion relevant (non-nuclear) conditions. [reproduced from https://ccfe.ukaea.uk/wp-content/uploads/2021/10/Image-6-e1633430612727.png],

Table IV.3.2-1. Key balance of plant testing and development facilities for US international collaboration.

Facilities	Type	Characteristics/ Capabilities	Research Focus	US Goals/Gains from Collaboration
HELOKA (KIT)	Helium loop	Blanket mockups (< 3 m length) under prototypic helium temperatures	High heat flux testing of blanket mockups	Potential test bed for DCLL or other FW helium coolant configurations (SO-C.1, SO-C.2, SO-C.5)

		(100-500 C) and pressures (4-9.2 MPa		
LIFUS5 (ENEA)	PbLi/H2O reaction vessel	Multiple liquid metal mixing vessels (up to 100 L) into which steam can be injected	PbLi/steam reaction data to support safety analysis of WCLL in-box LOCA	Not a critical data need for presently favored US blanket designs (e.g. DCLL), which are not water-cooled. May support industry designs if these use water cooling.
KALOS (KIT)	Research program/lab	Lab scale facility for melt-based production of advanced ceramic breeder pebbles	Advanced ceramic breeder pebble production	Fundamental knowledge on the fabrication and performance of solid ceramic breeder materials (SO-C.1, SO-C.2, SO-C.5)
IELLO (ENEA)	PbLi loop	High (350-550 C) temperature PbLi loop	Heat transfer, corrosion, instrumentation testing PbLi loop	Potential test stand for heat exchange or instrument prototypes; code validation
CHIMERA (CCFE)	Component test facility	TBM-scale non-nuclear component testing with magnetic field (5 T), surface and volumetric heating	Non-nuclear fusion energy system component testing	Pre-irradiation testing of blanket prototypes or subcomponents. General applicability of water cooling system needs to be assessed. (SO-C.1, SO-C.2, SO-C.5)
H3AT (CCFE)	Tritium facility	1/20th scale ITER fuel processing	Many aspects of tritium fuel processing technology	Potential test bed for a variety of tritium processing technologies and fuel cycle components (SO-C.3, SO-C.9, SO-C.10)
TARM (CCFE)	Remote handling	Telescopic articulated remote mast with 11m range and horizontal boom	Remote handling approaches and procedures research	Testing remote handling scenarios and procedures for US facility designs
Oroshhi-2 (NIFS)	PbLi and FLiNaK loop	Twin PbLi and FLiNaK loops with 3 T magnet	Study of MHD flows, heat transfer, corrosion, and hydrogen transport	Experiments conducted on this loop are prioritized via a user-facility like arrangement; there are many possibilities here given the wide-ranging capabilities of the facility. (SO-C.1, SO-C.2, SO-C.5)
UNITY (Kyoto Fusioneering)	Component test facility and PbLi loop	Simulated power core, 4T magnetic field for blanket/ divertor component testing	Advancement of PbLi BoP technology to TRL 5-6	Potential test bed for DCLL blanket mockup and other PbLi balance of plant technologies (SO-C.1, SO-C.2, SO-C.3, SO-C.5)

		Integrated PbLi loop testing at temperatures up to 1000 C	High temperature (1000 C) heat extraction/electricity generation Tritium extraction systems	
ITER TBM	Blanket / Volumetric Neutron Source	Testing of large-scale breeding blanket prototypes in the fusion nuclear environment provided by ITER.	Breeding blanket operation and study	Integral test data on tritium breeding, heat transfer, mechanical performance, and ex-vessel processing systems for a US-preferred TBM concept. 2nd round of TBMs potentially available to the US in ~2040, subject to ITER schedule uncertainty. (SO-C.1, SO-C.2, SO-C.5, SO-C.3, SO-C.9, SO-C.10)

IV.3. Findings and Recommendations (Charges 1 and 2a in Balance of Plant)

Finding F1-24: In many aspects of tritium breeding blanket, fuel cycle, and balance of plant technology, US programs are no longer world-leading. Investment of additional resources in these program areas could offer significant opportunities for leadership and strengthen the ability of the US to collaborate in these areas.

Finding F2a-9: The 2019/2020 APS-DPP Community Planning Process and subsequent FESAC Long Range Plan Subcommittee emphasized the critical importance of the tritium breeding blanket, fuel cycle, and balance of plant technology to the FPP mission. Successful execution in these program areas will require both a strong domestic program and leveraging international collaboration.

> **Recommendation R1-9:** Target international collaboration on tritium breeding blanket, fuel cycle, and balance of plant technologies to leverage the resources of international partners and offer additional opportunities for US leadership.

Finding F1-25: In early 2020, the US and EU held a technical workshop that proposed a variety of bilateral collaborations which captured priority shared interests of the US and EU. These included collaborations in specific research areas including Safety and Licensing, Tritium handling, and Materials and Breeding Blankets. The recommendations outlined specific tasks as well as performers and levels of effort.

> **Recommendation R1-10:** Pursue the programmatic collaborations outlined by the 2020 technical workshop with the EU, in the areas of safety assessment, nuclear design integration, tritium permeation and handling, MHD flow in blankets, and waste management.

Finding F2a-10: The 2019/2020 APS-DPP Community Planning Process and subsequent FESAC Long Range Plan identified the need for a Blanket Component Test Facility to perform integrated, non-nuclear testing of blanket prototypes in advance of fusion pilot plant construction, but it is presently unclear if construction and operation of this facility domestically are achievable on a decadal timeline in light of other facility priorities outlined in the FESAC long range plan.

> **Recommendation R2a-5:** Evaluate the suitability of the CHIMERA and H3AT facilities in the UK for testing US blanket concepts and ancillary systems. Pursue collaboration on these facilities if the evaluation is favorable, and if there is no clear path to construction and operation of a domestic facility on a decadal timescale.

IV.4. Technology

IV.4.1. Introduction

The establishment of fusion power plants will depend on multiple technologies beyond plasma physics and fusion physics. In particular, we will need radio-frequency (RF) actuator technology, neutral beam sources, magnetic technology, and related human capital for building and operating the facilities. The key knowledge repositories and related facilities to enable these technologies reside outside the US. Thus, the collaboration will be critical to the US efficiently integrating these technologies into functional power plants. The report lists key technologies that would benefit from international collaboration.

<u>Unique Issues</u>

The committee identified several unique issues related to the identification of key facilities to engage in international collaboration for technology development

1. Facilities that are not available for international collaboration due to prior commitments
2. Facilities that will not be operational at the time this report is released
3. Duplicative facility capability

IV.4.2. Narrative

<u>Background</u>

Radio-frequency (RF) and neutral beam injection (NBI) actuators are crucial for bulk plasma heating and plasma control. Current profile and pressure profile control allow access to regimes of improved plasma confinement and high bootstrap current fraction needed for steady-state operation of a tokamak-based FPP. Generally, electron cyclotron current drive (ECCD) can be used for suppression and control of Neoclassical Tearing Modes (NTM’s). Control of the plasma current profile control can be achieved through the use of ECCD and ion cyclotron range of frequency ICRF) fast wave current drive at $0 < r/a < 0.2$, neutral beam current (NBCD) at $0 < r/a$

< 0.5, helicon current drive at 0.4 < r/a < 0.6, and lower hybrid current drive (LHCD) at 0.6 < r/a < 0.8.

Depending on the specific FPP design and physics basis, a different complement of actuators will be needed. For example, in a high-field FPP design that utilizes High-Temperature Superconducting (HTS) magnet technology, the higher magnetic field improves the use of LHCD through improved LH wave accessibility, poses a challenge for ECRF because of higher source frequency requirements, and has minimal impact on ICRF and NBI. Several examples of the technologies used to heat and control plasmas in magnetic and inertial confinement fusion are shown in **Figure IV.4-1**.

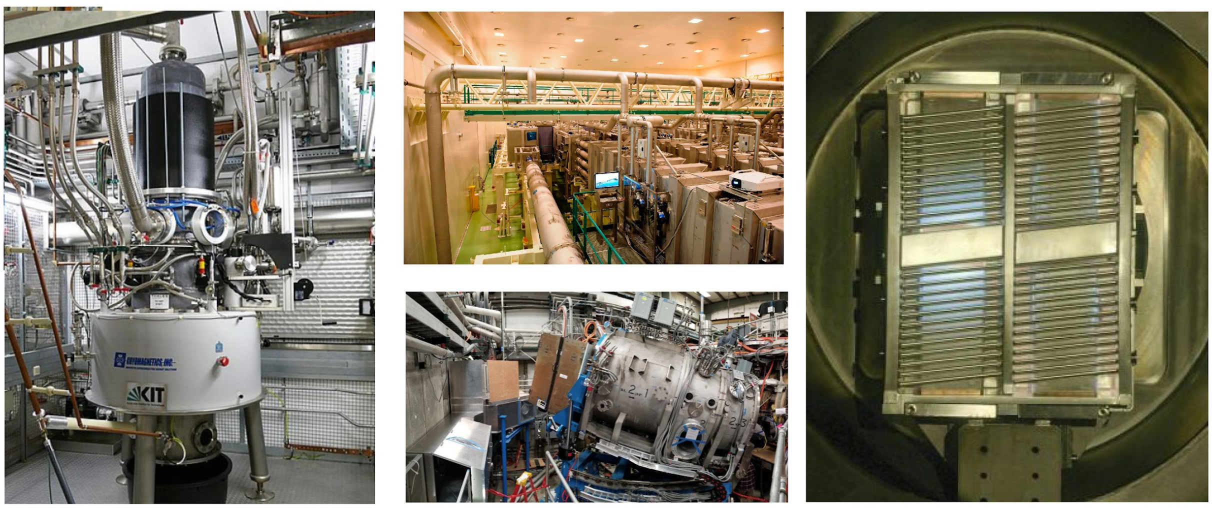

Figure IV.4-1: Examples of state-of-the-art technologies used to heat and control fusion plasmas. **Left**: W7-X 140 GHz gyrotron (reproduced from [Blank 2023]). **Middle-top**: The PETAL Laser and LMJ Bundle 2 [reproduced from https://www.asso-alp.fr/gallery/?album=312&album_ses=1#aigpl-album-gallery-]. **Middle-bottom**: The DIII-D tilted neutral beam injectors (reproduced from [Grierson 2020]). **Right**: The WEST ICRF antenna (reproduced from https://irfm.cea.fr/en/west/cube-masonry.php).

Research Needs:

The Community Planning Process [CPP 2020] identified gaps in the technology area under strategic objective F: "Innovate the magnet, heating, and current drive technology needed to reduce the pilot plant capital cost."

The "Plug-to-plasma" efficiency of RF systems is a constraint on an economical fusion plant and the limiting factor in all frequency ranges is source efficiency, which must be improved. Typical present-day RF source efficiencies are <70% (30 - 130 MHz) and <60% (130-200 MHz) for ICRF; <60% for Helicon (500 MHz - 2 GHz); <45% for Lower Hybrid (4-10 GHz); and <50% for ECRH/EBW (28-500 GHz) [Wukitch 2022].

There is also a need for higher gyrotron tube frequencies (beyond the 170 GHz) planned for ITER. These higher frequencies are needed in order to heat and drive current at the higher densities in a fusion pilot plant (FPP) where O-mode is cut-off, and X-mode launch is required. Also, in high-field FPP designs (~9-10 T), higher tube frequency is needed for O-mode launch.

Although not called out in the table below, the University of Fukui Facility in Japan has expertise in the development of very high-frequency sources, and the Fulgor Facility at the Karlsruhe Institute of Technology (KIT) has expertise in the development of high power / CW tubes relevant to FPP. Finally, ITER-India should also be considered as a possible collaborating test site, given that they have just completed acceptance tests for ITER high-power 170 GHz tubes.

Solid state (SS) amplifiers are beginning to compete with tetrodes in the f < 200 MHz frequency range, but power is limited. In order to reach the MW class, tolerance to reflected power of SS systems must be improved.

Supply chain issues for microwave sources are severely impeding development, especially with the removal of Russia from the international market.

The main issues for RF transmission line technology are developing materials and transmission line design for high power, high neutron flux, and high temperature (e.g., 700 °C), that have to be cooled with He. Currently, ORNL is developing transmission lines for ITER. ORNL has a Resonant Ring Test Stand to circulate high power (6 MW) for long pulse (1 hr) [Lamalle 2015].

The main challenge for neutral beam technology is to develop negative ion sources (for high energies) and long pulse beams. ITER will have two beams, 1 MeV, 16.5 MW, 16.5 A (40 amps negative ions), and 3600-s pulse length. These are scheduled for 2025, and the beams will be needed by 2031. This involves developing technology for cesium handling (cesium-coated grids are hard to maintain in steady state for long pulse beams), coupling of RF power in an ion source, and filtering co-extracted electrons. Also, there is currently no training program for students on NB technology in the US [Hopf 2021].

In the area of magnet technology, a leading problem is the cryogenic cooling of NB_3Tn SC magnet. This may be "solved" by using Rare Earth Barium Copper Oxide (REBCO) HTS magnets, which can be cooled with hydrogen. A bottleneck for the use of REBCO magnets is actually production capability and not the supply of rare earth material. South Korea, China, the US, and Germany are the main suppliers of REBCO tapes [Bruzzone 2018].

Roles of compelling collaborations in satisfying research needs:

Three major overseas facilities where RF plays a major role are JET, which has a workhorse ICRH system; however, that program is likely winding down and tritium exposure makes re-purposing unlikely. ASDEX-UG has a vibrant RF program plus powerful NBI (20 MW), making it possible to study RF-NBI interactions. In contrast, the WEST tokamak relies on RF for plasma sustainment.

In RF technology, research needs fall broadly into the areas of sources and transmission. Korea is an international leader in klystron development. Extensive gyrotron manufacture and development are carried out internationally with commercial suppliers of gyrotrons in Russia, Bulgaria, and Japan. Research centers for gyrotron research include the Karlsruhe Institute of Technology (KIT) - Karlsruhe, Germany; the EPFL - Lausanne, Switzerland; Research Center for Development of Far-Infrared Region, University of Fukui - Fukui, Japan; University of Tsukuba and Kyushu University (Japan); Institute of Electronics of the Bulgarian Academy of Sciences - Sofia, Bulgaria; National Key Laboratory of Science and Technology on Vacuum

Electronics - Beijing, China; Institute of Applied Physics, Nizhny Novgorod - Russia; Gycom Ltd, Nizhny Novgorod - Russia.

Transmission system development is carried out at CEA (French Alternative Energies and Atomic Energy Commission) where a vacuum resonant line is used for testing ICRH transmission line designs [Bernard 2011]. The Laboratory for Plasma Physics of the Ecole Royale Militaire (LPP/ERM-KMS) has developed a quarter-scale mock-up of the ITER ICRH antenna with a dummy load to develop a matching network [Messian 2016]. It is worth noting that the LPP/ERM-KMS facility capabilities overlap those of CEA West.

Neutral Beams

The R&D effort behind the ITER Neutral Beams has created a great opportunity for leveraging by the domestic program. While the facilities in Padova (MITICA, the full-scale prototype ITER beam, and SPIDER, the negative ion source test stand) are both at the time of this writing fully contracted by ITER, their predecessor facilities located in Garching, Germany (ELISE and BATMAN) are winding down their ITER obligations and the teams there have both the desire and bandwidth for developing new research partners in the areas of ion source development for long pulse negative ion beams.

The National Institute of Quantum Science and Technology (QST) in Chiba, Japan, is another center of excellence in the area of high energy neutral beam R&D and one that could greatly benefit the domestic program. While the IPP test stands are focused on the ion source, the QST team is building on their experience of developing high current beams for JT-60U and tackling the high voltage engineering of ion optics and beamline.

As the groups at IPP, Padova, and QST continue to push the boundaries of NB performance with R&D efforts to increase both energy and pulse duration, there are several groups around the world who have successfully deployed and operated systems that can be leveraged today.

For example, for positive ion sources, ASDEX-UG has a mature, well-diagnosed suite of neutral beams, both arc- and rf-based, which can serve the domestic program as a training ground for students.

On the negative ion source side, the Large Helical Device at the National Institute for Fusion Studies in Toki, Japan, has three high energy, negative ion neutral beams, each capable of producing 10 A of ion current at energies ranging from 130 to 190 kV for several seconds. These beams are currently in operation, so there is an opportunity for workforce development and technology exchange that may be of interest to domestic players today.

Magnets

Use of REBCO magnet technology is an area where the US should seek to lead since the rest of the world is locked into the use of NB_3Sn. FES investment in REBCO tapes could drop the price by factors of 10 - 100. HTS magnet development could lead to commercial fusion - ARC class fusion energy systems [see B. N. Sorbom et al., Fusion Engineering and Design Volume 100, November 2015, Pages 378-405].

Overseas collaboration opportunities exist in magnet technology at several Centers of Excellence. These include the high field magnet cable test facility at Sultan in EPFL (Switzerland), which is the reference facility for ITER; the High Field Laboratory for Superconducting Materials (HFLSM) at Tohoku University (Japan); the Robinson Research Institute at Victoria University of Wellington (New Zealand).

Lasers

The frontier of laser technology is pushing to higher intensities combined with high-repetition rate. This includes exercising Ti-sapphire laser capabilities to push to shorter pulses, and coupling diode-pumped lasers with better heat load management to achieve increased repetition rates. The US is leading the global community in laser design and building the laser architecture needed to achieve these goals. However, opportunities for US scientists to gain experience at domestic laser facilities to further optimize laser performance or advance strategic science applications is limited to non-existent.

Overseas collaboration opportunities which enable US scientists to exercise high-intensity and high-repetition rate testing (e.g., EPAC 100 J laser at 10 Hz) to work through thermal management challenges and exercise this technology is seen as an excellent learning opportunity. Advancements in high repetition rate laser diagnostics are also possible through collaborations at ELI, at AWE, and EuPRAXIA to provide opportunities to work with high-frequency, short-pulse systems.

Key Collaboration Opportunities

The subcommittee identified numerous high-quality facilities available for the development of fusion-related technologies. Numeric scoring of features of interest for each facility was used to select the ten facilities where an international collaboration would return the highest expected return on investment. In addition to the panel members, subject matter experts were interviewed to generate the numeric scores. Categories added to the assessment that are unique to the technologies area include technology relevance and key capability. An unweighted average of the numeric scores was used to select the most compelling opportunities for international collaboration.

The 2020 Community Planning Process [CPP 2020] identified gaps in technology including high-field magnets (SO-F.1) and cable technology SO-F.3), RF launchers (SO-F.4) and sources (SO-F.5), and heating/current drive scenarios (SO-F.6) (see **Table IV.4.2-1,** last column).

Table IV.4.2-1 shows the key compelling opportunities for collaboration identified by the committee. Experts consulted by panels, additional opportunities, and related details are included in Appendix A3.

Table IV.4.2-1. Key technology testing and development facilities for US international collaboration.

Facility	**Technology Relevance**	**Type**	**Key capability**	**US Goals/Gains from Collaboration**
ASDEX-UG	ICRH/ tokamak	Experimental	Flexible RF system for experimentation Phase controlled $k_{\parallel}$ spectrum 30.0, 36.5, 41.8 and 55.1 MHz ICRH, minority heating	Workforce development Alternative ion heating schemes Antenna design optimization to minimize PMI (SO-F.6)
CEA/WEST (TITAN)	ICRH transmission test stand	Experimental	Vacuum resonant line for ITER transmission line tests at CW All tungsten PFC's	RF engineering, high power, CW RF transmission Evaluate ICRF antenna performance in all metal (tungsten) device (SO-F.4, SO-F.6)
ELISE (IPP-Garching)	NB	Exp. (Testing)	½ scale ITER source Part-time ITER R&D, limited availability for collaboration	High-energy beams Long-pulse beams (SO-F.6)
BATMAN (IPP-Garching)	NB	Exp. (Testing)	⅛ scale ITER source Flexibility in aperture geometries, materials, magnetic fields Low burden for ITER work, available for collaboration Good for experimentation	High-energy beams Long-pulse beams General NB R&D Materials (SO-F.6)

QST	NB	Exp. (Development)	Voltage hold-offs, high energy beams	Very high-energy beams NB engineering (SO-F.6)
ASDEX-UG	NB	Exp. (Application)	Positive ion beams, arc, and RF Good training program for young scientists on NBs	Workforce development
Research Center for Development of Far-Infrared Region, University of Fukui - Fukui, Japan	ECRF	Technology Development	Develops advanced version of the Gyrotron and applies it to energy science. Frequency ranges up to ~400 GHz	Important for FPP at higher B-field (SO-F.6)
Sultan (EPFL)	Magnet	Exp. (Development)	Largest magnet facility in the world - reference for ITER Nb_3Tn SC's Made 18 kA HTS current leads for EPIDO Facility	Development and testing for HTS (SO-F.1)
HFLSM (Tohoku University	Magnet	Exp. (Development)	International COE of materials science in high magnetic fields. Offers varieties of research opportunities for overseas users.	Materials science, magnet testing (SO-F.1, SO-F.3)
Robinson Research Institute (New Zealand)	Magnet	Exp. (Development)	Coil technology portfolio includes HTS and LTS windings—using insulated conductors or with engineered resistivity between turns and high-current cables.	Coil design, commercialize HTS for use in domestic program (SO-F.1, SO-F.3)

			Core mission is to develop technology with partners and commercialize it.	
FULGOR (Karlsruhe Institute of Technology)	Gyrotron	Exp. (Development)	Will comprise a 10 MW CW power supply Equipped to test the conventional 1 MW or coaxial 2 MW gyrotrons	Gain expertise in the development and testing of high-power tubes. (SO-F.6)
JOYO (JP)	Materials Test-stand	Exp. (Development)	Fast spectrum materials and fuel test reactor (> MeV)	Testing of technology components in nuclear environment. Continue collaboration as it is a user facility through (existing US-Japan programs); Could pursue student work-exchange programs. (SO-F.4, SO-F.6)

IV.4.3. Findings and Recommendations (Charges 1 and 2a in Technology)

Multiple technologies are required to transition plasma physics and fusion physics to practical fusion energy power plants. Efficient development and acquisition of these technologies can be aided by strategic collaborations between US and international entities.

Finding F1-26: Experimental data on ICRF antenna performance in all-metal environments is very limited but crucially needed for burning plasma due to the generation of impurities. The EU is the leader in this area and is pushing toward fusion energy system compatibility.

> **Recommendation R1-11:** Collaborate with CEA/WEST (all tungsten PFCs) to develop a knowledge base for ICRF impurity generation and mitigation in a device with tungsten PFC's, and collaborate on and utilize the CEA ICRF test stand facility (TITAN) to study more fusion energy system-relevant RF launchers such as the traveling wave antenna.

Finding F2a-11: Neutral Beams: Strategic Objective F.6 from the CPP LRP identifies the development of fusion energy system-relevant heating scenarios with neutral beam (NB) injection as a priority. CW, high-energy, negative ion NB technology needs to be developed for high-density tokamaks and alternative concepts. In particular, the challenges include long-pulse or steady-state operation, thermal degradation of cesium-coated grids on the time scale of minutes to hours, and RF coupling and related co-extraction of electrons.

> **Recommendation R2a-6:** Support collaborations with both IPP-Garching and QST since the US does not have facilities capable of developing long pulse, high energy neutral beam technology.

Finding F1-27: The US faces challenges in delivering high-temperature superconducting (HTS) technologies, for material manufacturing and testing, because it lacks the at-scale manufacturing capability and commensurate magnet test facilities for Rare-earth barium oxide (ReBCO) tapes.

> **Recommendation R2a-7:** Collaborate with HFLSM (Tohoku University) and the Robinson Institute (New Zealand) to develop the manufacturing techniques to advance at-scale domestic manufacturing capabilities for REBCO tape, and take advantage of large-scale test facilities such as Sultan (Switzerland).

Finding F1-28: There is a need for higher source frequencies (> 200 GHz for high field), higher tube efficiencies, and greater source reliability in the electron cyclotron range of frequencies (ECRF); the US lacks leadership in this area.

> **Recommendation R2a-8:** Support collaboration on the development of high-frequency (> 200 GHz) gyrotron sources with facilities such as the Research Center for Development of Far-Infrared Region (University of Fukui), and the Karlsruhe Institute of Technology (KIT).

Finding F1-29: The number of gyrotron vendors in the US is limited, and they face challenges with respect to long lead times and expenses with domestic component manufacturers. This problem is exacerbated by the fact that suppliers in Russia are now off-limits.

> **Recommendation R1-12:** Use reliable international suppliers of gyrotrons, such as those in Japan and Europe to supplement the supply chain, in order to overcome the limited capacity of the domestic market.

Finding F1-30: There is currently no solution for putting an RF launcher close to a burning plasma. Challenges include the survivability and propagation of an RF launcher in a nuclear environment. US progress in the development of advanced alloys (i.e., GRCop-84) and advanced manufacturing techniques can be evaluated and advanced by performing tests and leveraging collaboration with fast fission reactors (in alignment with **Recommendation R1-5** related to fast neutron needs for materials development).

Finding F1-31: The US is currently at the forefront of laser science, technology innovation, and development. However, leveraging this domestic skill to build local laser capabilities/facilities has been lacking. The US risks losing leadership in this area in the next few years.

Recommendation R1-13: Enable US scientists and engineers to access key international laser facilities (e.g., ELI) to exercise high repetition rate laser technologies and maintain currency with best practices. Support the foundational experimental and theory/simulation effort to continue advancing US laser technology for a wide range of applications.

IV.5. Fundamental Understanding of Plasmas

IV.5.1 Introduction

Discovery Plasma Science (DPS) and High Energy Density (HED) science are incredibly diverse fields of research, spanning a range of density and temperature conditions, from near-vacuum trapped ion plasmas at micro-Kelvin temperatures, to high energy density plasmas inside stars, at several times solid density and tens of millions of degrees. Throughout this range of conditions, advances in DPS and HED science and technology contribute to answering fundamental questions in science – from the evolution of the universe, astrophysical phenomena and radiation fields, to how material and plasma properties can control and be controlled while at extremes of pressure, temperature and density. A characteristic of these discoveries is that they often enable rapid development of new technologies. Plasma science has provided a major impetus to multi-billion-dollar twentieth-century technologies such as microelectronics and lighting, and it continues to drive twenty-first-century technologies in ignition, manufacturing, medicine, agriculture, decarbonization, and national security. There is also a synergistic interplay between science and technology advancements, improving foundational and applied theory/physics models and simulations, with the design and access to cutting-edge experimental facilities. There is a clear trend in facilities across the globe to achieve higher pulse energy and high average power, as well as co-locate these facilities with a suite of experimental probes and capabilities. Internationally, a unique and key facet of understanding foundational plasma science is the clear link to students and early career researchers/engineers. This connection is inextricable from establishing a diverse workforce and workforce development by virtue of the fact that a large component of this work is done at educational institutions, universities, colleges, and government-sponsored laboratories with close ties to educational institutions. Though this is a clear component of Panel 5 considerations due to the nature of the topics, scope and recommendations toward workforce development will be covered in *Section VIII Workforce Development and Recruitment from Underrepresented Groups.* The following sections will discuss the compelling collaborations recommended by this Panel to promote frontier work in fundamental plasma science.

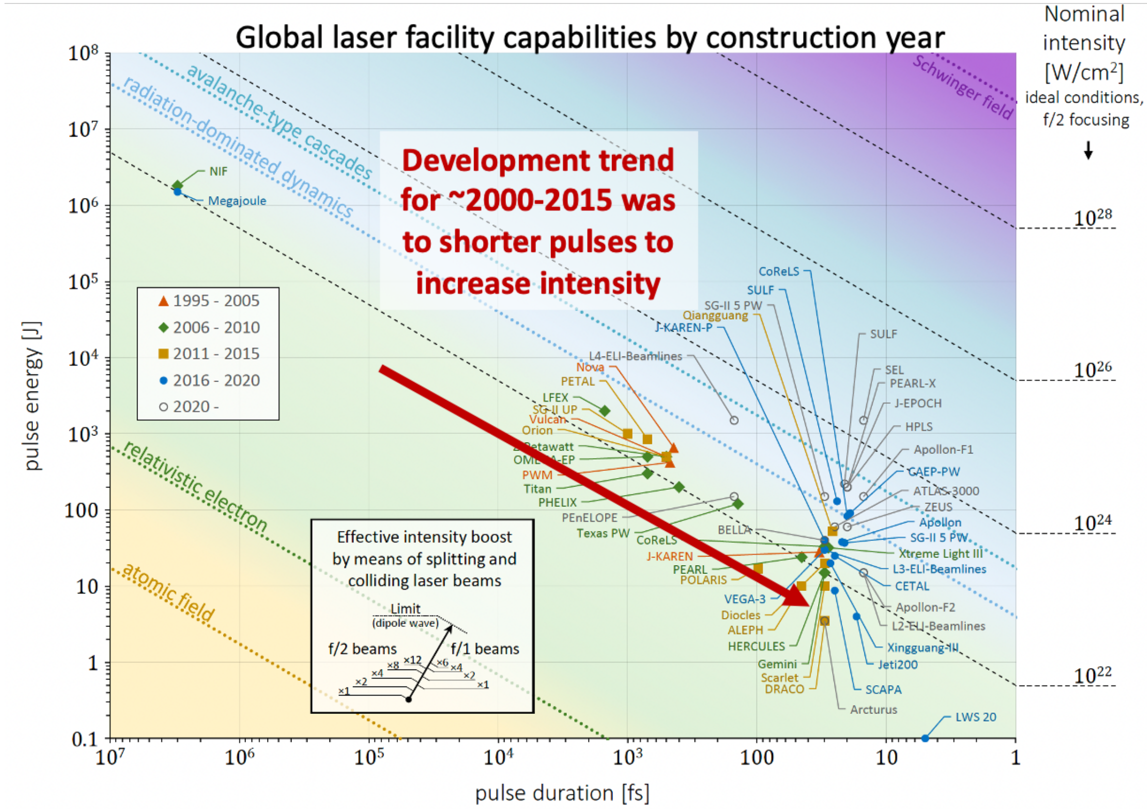

Figure IV.5-1. Expanding laser capabilities across the globe with an emphasis on discovery plasma and HED science and technology [Figure reproduced from Gonoskov *et al,* Rev Mod Phys **94** 045001 (2022)].

IV.5.2 Narrative

The scope of international collaborations needed to advance the many topical areas covered in Fundamental Plasma Science is spread into the following general science categories (which largely mirror Priority Research Opportunities outlined in the FES LRP [FESAC 2020] and the APS DPP CPP [CPP 2020] Reports, as well as the recent IFE BRN Report [IFE-BRN 2022]: 1) Laboratory Astrophysics, 2) Dusty Plasmas, 3) Warm Dense Matter & Plasmas, 4) Laser-Plasma Interaction Science, 5) Ignition Science, 6) Quantum Electrodynamics, 7) Foundational Materials Science, 8) Agricultural Plasma Science, 9) Plasma Medicine, and 10) Space Propulsion. A key theme of strategic international collaborations should include access to and use of high repetition rate, high-intensity laser architecture and co-location of probes is needed for scientific discovery across many/most of these science categories. The 2020 Community Planning Process [CPP 2020] identified gaps in IFE under alternative concepts in strategic objective H "Develop alternative approaches to fusion that could lead to a lower cost fusion pilot plant, utilizing partnerships with private industry and interagency collaboration." Relevant gaps identified included: IFE program (SO-H.1) and drivers (SO-H.2). Discovery science gaps identified included "Explore the Frontiers of Plasma Science" (DSP-1), "Understand how intense light couples its energy to matter" (DSP-A), "Develop plasma-based technologies that improve the physical well-being of society" (DSP-K), and "Develop plasma-based technologies that provide secondary sources and other new capabilities, to benefit fundamental science, industry, and societal needs" (DSP-L) (see **Table**

IV.5.2-1, last column). In particular, the use of low temperature plasmas is essential to the manufacture of devices in the global semiconductor industry, from the creation of extreme ultraviolet photons used in the most advanced lithography to thin film etching, deposition, and surface modification [FES 2023]. Plasma-surface interaction research is an area of needed investment and innovation to regain a strong US standing in this technology, among robust and expanding international competition (e.g., compared to the EU and China). Utility of laser-driven EUV/XUV plasma sources for 3 nm – scale device features is a key industrial microelectronics achievement enabled by plasma science and the associated materials/surface science. New semiconductor materials including silicon carbide, GaN, Diamond, and others require development of science and technology to manage the new properties for plasma-based fabrication processes. Establishing US expertise in handling these specific plasma-surface interactions, also through international collaborations, will ensure a competitive advantage in this area and be a key economic and capability enabler.

Key Collaborations

Specific facility collaborations are recommended which include critical opportunities for US scientists to gain hands-on experience with high repetition rate, high-intensity lasers, e.g., ELI Beamlines and ELI NP Facilities, DiPOLE at EuXFEL, and EPAC. The numerous scientific thrusts outlined in the APS-DPP-CPP report, the LRP Report, the NASEM Report, and articulated in the BDV can be addressed through these collaborations. For instance, collaborations with ELI Facilities may enable US scientists to accelerate the development of high repetition rate capabilities. Here, these key collaborations will serve to provide the framework and large enough pool of people and information to compare novel results to help vet/validate/refine physics-models, enable accuracy and correctness, and establish/test/optimize workflow. This is all critical as these science scopes move into a regime of high data repetition rate at 1 Hz or greater. We recommend key partnerships and collaborations to exercise know-how and provide experience running experiments at this rate, especially at multiple mid- to large-laser facilities internationally (see **Fig. IV.5-1**).

Following metric application to the areas in fundamental science assessed, we arrive at the following key international collaboration opportunities, grouped by region and topical areas (**Table IV.5.2-1**).

Table IV.5.2-1: Key International Collaboration Opportunities for Fundamental Plasma Science

Facilities	Characteristics/ Capabilities	Research Focus	US Goals & Status	Gains from Collaboration

L3/L4-ELI Beamlimes @ Czech republic	PW coupled to kJ at 1 shot/min	Laser-plasma interaction; ignition science; lab astro, Whole Device Modeling (WDM) & plasma science; foundational materials science	Nothing comparable (until MEC-U)	Ability to exercise high repetition rate + high intensity laser facilities where a strategic collaboration enables US scientists/engineers to gain hands on experience (DPS-1, DPS-A, SO-H.2)
ELI NP @ Romania	high intensity 10 PW	Laser-plasma interaction; ignition science; lab astro, dusty plasmas, WDM & plasma science; quantum electro dynamics science	Nothing comparable	Ability to exercise high repetition rate + high intensity laser facilities where a strategic collaboration enables US scientists/engineers to gain hands on experience (DPS-1, DPS-A, SO-H.2)
DiPOLE, EuXFEL @ Germany	100 J, 10Hz laser + XFEL	ignition science; lab astro, dusty plasmas, WDM & plasma science; foundational materials science	Nothing comparable (until MEC-U)	Ability to exercise high repetition rate and provide student training opportunities (DPS-1, DPS-A, SO-H.2)
FAIR @ Germany	(low energy) ns and ps lasers coupled with ion accelerator	ignition science; lab astro, dusty plasmas, WDM & plasma science	Nothing comparable	Address foundational and applied physics knowledge gaps and provide student training opportunities (DPS-1, DPS-A, SO-H.2)

Apollon @ France	1 PW laser (upgrading to 10 PW 2025)	Laser-plasma interaction; lab astro, WDM & plasma science	Nothing comparable (until Zeus, Michigan)	Address foundational and applied physics knowledge gaps (DPS-1, DPS-A, SO-H.2)
LMJ @ France	350 kJ (upgrading to 1 MJ in 2027)	Laser-plasma interaction; ignition science	mini-NIF	Address foundational and applied physics knowledge gaps (DPS-1, DPS-A, SO-H.1, SO-H.2)
LULI, LULI2000 @ France	kJ class laser + sub PW	lab astro, WDM & plasma science; quantum electro dynamics science, foundational materials science	similar to Omega, LLE / JLF	Address foundational and applied physics knowledge gaps and provide student training opportunities (DPS-1, DPS-A, SO-H.2)
CORELS @ S. Korea	multi-PW at 0.1 Hz	Laser-plasma interaction; lab astro, WDM & plasma science	Nothing comparable (until Zeus, Michigan)	Ability to exercise high repetition rate (DPS-1, DPS-A, SO-H.2)
RAL @ UK	sub PW laser + kJ laser (upgrade soon to 20 PW + 20 kJ)	Laser-plasma interaction; ignition science; lab astro, WDM & plasma science	similar characteristics to LLE / Texas PW / JLF	Address foundational and applied physics knowledge gaps and provide student training opportunities (DPS-1, DPS-A, SO-H.2)
Orion @ AWE	2 x SP + 10x LP	Laser-plasma interaction; ignition science; lab astro, WDM & plasma science; foundational materials science	similar to Omega EP/Omega	Address foundational and applied physics knowledge gaps (DPS-1, DPS-A, SO-H.2)

EPAC @ UK	1 PW at 10 Hz (available in 2025)	Laser-plasma interaction; lab astro, WDM & plasma science	similar to Zeus, Michigan	Address foundational and applied physics knowledge gaps and provide student training opportunities (DPS-1, DPS-A, SO-H.2)
Gekko XII + LFEX @ Japan	1 x SP + 12 x LP	Laser-plasma interaction; ignition science; lab astro, WDM & plasma science; foundational materials science	similar to Omega EP/Omega	Address foundational and applied physics knowledge gaps and provide student training opportunities (DPS-1, DPS-A, SO-H.2)
RT-1 @ University of Toyko, Japan	Levitated (internal, superconducting) Dipole	Lab astro; High-beta plasmas; Turbulent transport	Nothing comparable	Address foundational and applied physics knowledge gaps and provide student training opportunities; Model validation & verification (DPS-1)
CIEL (Ctr. for Innov. Excellence in Livestock, UK)	Livestock research farms; Agri-Tech Ctrs	agricultural plasma science	Similar research topics @NC State; Agr. Res. Service, PA	Part of AgriPlas research collaboration CIEL/IGFS; study plasma-animal applications (DPS-1, DPS-K, DPS-L)
IGFS (Inst. for Global Food Security; Belfast)	Plasma-plant research farms; Agri-Tech Ctrs	agricultural plasma science	Similar research topics @NC State; Agr. Res. Service, PA	Part of AgriPlas research collaboration CIEL/IGFS; study plasma-animal applications (DPS-1, DPS-K, DPS-L)

INP Greifswald (Leibniz Inst. Pl. SciTech)	plasma redox, atmosphere plasma sources	plasma medicine/science; plasma medical devices	Similar to Drexel U. PEAB	Atmospheric pressure plasma sources, plasma-tissue interactions (DPS-1, DPS-K)

In the context of **Table IV.5.2-1** we observe additionally that:

- China is pursuing the Station of Extreme Light (SEL) facility, a 100 PW-class laser system that will be co-located with an XFEL. This facility is anticipated to be nearly identical in performance to the domestic LCLS-II-HE, and to operate by 2025. There will be nothing comparable in performance characteristics and capabilities in the US or internationally in the foreseeable future. The US may inevitably face a challenge in maintaining leadership in foundational DPS and HED areas needed to support ignition science and national security areas given this context.
- The EU Technology for High-Repetition-Rate Intense Laser Laboratories (THRILL) is planned for completion in 2026, and will provide a joint capability of a kJ-class laser coupled to the European XFEL (EuXFEL). Since there is nothing comparable in the US or planned in the foreseeable future, this is an excellent opportunity for collaboration and partnership.

High repetition rate, high-intensity laser research and technology are taking center stage for transformative advancements in: 1) Laboratory Astrophysics, 2) Warm Dense Matter & Plasmas, 3) Laser-Plasma Interaction Science, 4) Quantum electrodynamics, and 5) Ignition Science. There are several science areas where this Panel found the US is already leading and/or strategic international facility partnerships were identified, but due to metric assessment considerations were not listed in **Table IV.5.2-1**. These include: 1) Space Propulsion/Plasma Acceleration (US is already leading and no international partnerships/collaborations could be identified), 2) some areas of Low Temperature Plasma Science, 3) Dusty Plasma Science, and 4) Plasma Materials Processing. In Low Temperature and Dusty Plasma Science for cosmology research, continued close collaboration with: the European Southern Observatory, CERN, the International Space Station, and domestic/international satellite arrays and space probes providing geoplasma data are clearly critical for maintaining US leadership in these areas. We also note the near-future opportunities in controlling or influencing the plasma state in the immediate geospace environment, in order to assure the uninterrupted functioning of space assets (e.g., civilian or military satellites, etc.). As such, US-international cooperation (between EU, Japan, etc.) must continue around frontier space plasma physics.

Regarding workforce development in this area, key breakthroughs in foundational plasma science will occur with cross-pollination of plasma theorists and modelers with domestic and international experimentalists. Bolstering student exchange with legacy, international HEDLP, plasma science, Warm Dense Matter (WDM), and condensed matter international institutions (see above list in Charge 5 response) is strategic. Increased areas of effort should include a focus on code sharing and vetting against experiments in the areas of multi-scale 3D radiation hydrodynamics, and high-intensity laser-matter/plasma interaction simulations is recommended. Beyond investment in student and early career workforce growth, bringing more connectivity between communities in fusion is important. A vehicle for increased connectivity is via Networking. This could be done by seeding New International Networks, and/or augmenting existing Network Joint/Cooperative Programs with an international chapter. For instance, in theory or experiments, we recommend dedicated collaborative efforts to help develop networks in geographic regions presently with a low/small footprint, e.g., similar to LaserNetUS, or LaserLabEurope, or X-lites Network. Here, using LaserNetUS or X-lites Network as a model or template, we could work with key institutions in South America to develop their own 'LaserNetSouthAmerica'. This would also serve to expand diversity and inclusion in the workforce. The second stage could be coordinated proposal calls across domestic and international Networks, e.g., joint calls for addressing certain science scopes (say IF-relevant work on both LaserNetUS and LaserLabEurope, and requirements for international teaming in both experiment and theory). Essentially this could be regarded as an augmentation /adaptation of existing Networks in the US, e.g., PlasmaPy Project, LaserNetUS, to have an International Chapter or complementary capability, i.e., experiment vs theory.

IV.5.3 Findings and Recommendations (Charges 1 and 2a in Fundamental Understanding of Plasmas)

Finding F1-32: The US is currently in a leadership role for laser technology development supporting a range of science areas mentioned above. However, US domestic experimental facilities are non-existent/limited, and access is needed to ensure future science leadership and technology innovation, particularly in high repetition rate science.

> **Recommendation R1-14:** Establish international collaborations at key laser facilities including ELI Beamlines/NP, DiPOLE, Fair, Apollon, CORELS, RT-1, to develop US expertise in high repetition rate science, and establish corresponding data workflows.

Finding F1-33: Fundamental plasma understanding has a direct bearing on several critical application areas: 1) Plasma Medicine, 2) Agricultural Plasma Science, 3) Space Propulsion, and 4) Geospatial control of space assets. Though there is a history of strong collaborations with the European Space Agency and the Japan Aerospace Exploration Agency, recent political events have extinguished all long-term collaborations of nearly 30 years with Russia; i.e., Fakel, Moscow Aviation Institute, and TsNIIMash. Maintaining expertise in these application areas is available through collaborations with (including, but not limited to the following): CIEL, IGFS for Agricultural Plasma Science; INP for Plasma Medicine; DLR of Germany, CNRS of France, and JAXA for Space Propulsion.

Finding F1-34: Both domestically and internationally, experimental and modeling communities are not always interconnected in the most efficient/effective ways.

Finding F1-35: Materials and plasma properties data are needed across a wide range of conditions, time- and length-scales to support studies which underpin fusion energy science and technology. No one domestic or international facility can provide all the requisite datasets. Progress toward dataset completeness across P-T-rho regimes and uniformity of data architecture (enabling more streamlined workflows for AI/ML compute) is available through collaborations with a full set of international facilities, e.g., ELI, LULI, DiPOLE, Gekko, and Orion, to build up needed materials/plasma properties databases, and push towards homogenization of data archiving and formatting and workflows.

> **Recommendation R1-15:** Support and utilize US-international networks (similar to, e.g., LaserNetUS, or X-lites) for improved connectivity, as well as exchange of both research opportunities and workforce.

IV.6. Theory, Algorithms, and Computation

IV.6.1 Introduction

The fields of theory, modeling, simulation, computational physics, control mathematics, design, advanced algorithms, machine learning (ML), and artificial intelligence (AI) are related through their high reliance on computational algorithms and platforms, and are cross-cutting through the topical research areas described elsewhere in Sec. IV. These fields complement and support the facility-based and experimental aspects of fusion science, and provide the crucial mechanism for extrapolating scientific understanding to device designs and specific solutions to realize the BDV and LRP. They play an indispensable role in the interpretation of experimental data, and advancement of scientific understanding itself. They enable creation of high-confidence operational solutions, including control algorithms and models that can be used in real-time for synthetic diagnostics, system monitoring, and fault prevention purposes. While many collaborations in these fields are highlighted elsewhere in Sec. IV where they support relevant topical research and goals, many international institutions offer important opportunities for collaboration focused on theory, algorithms and computational goals themselves, and are therefore separately identified in this section.

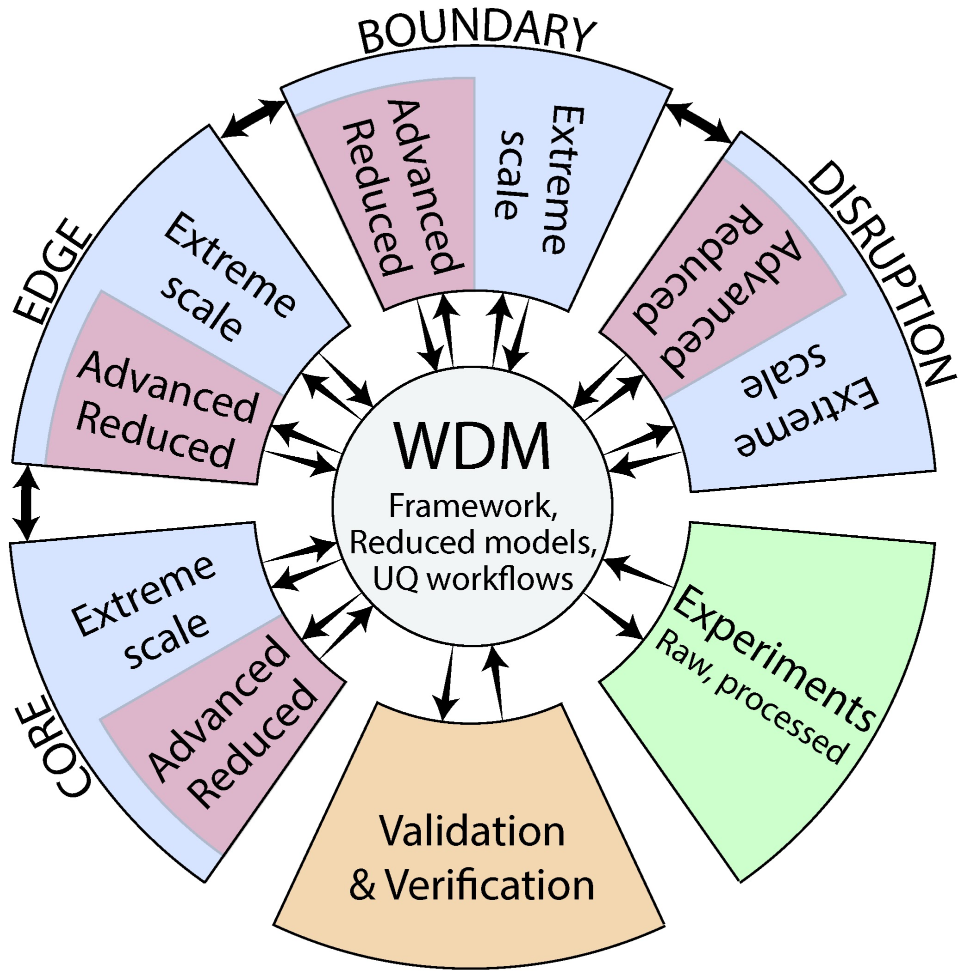

Figure IV.6-1. Theoretical models and simulations can require integration of many multi-physics modules. International collaboration can access important sources for sharing of modules, and provide unique opportunities for cross-code verification and validation (reproduced from [IntSim 2016]).

IV.6.2 Narrative

While the US leads in high-performance computing at the exascale level (for example the Scientific Discovery Through Advanced Computing Initiatives), as well as in general ML/AI and its enabling massively parallel hardware and software, the international fusion community has made many advances and established research institutions with strong potential to complement and accelerate US fusion efforts in theory and computational physics-related areas. These areas are critical to the success of the present BDV and the realization of commercial fusion power, since the extrapolation and design efforts required depend on theory and algorithmic/computational tools. In addition, since the cost of building many experimental facilities to develop and demonstrate solutions directly is deemed to be prohibitive, the importance of theory and computational analysis is amplified by the need to accomplish such extrapolation with a limited number of experimental facilities.

The roles of theory, algorithmic, and computational research can be broadly divided into three areas: 1) theory, simulation, modeling, and computational physics (including algorithmic advancement towards the exascale, and use of surrogate models for process acceleration); 2) control mathematics, algorithms, and ML/AI data-driven models and analysis; and 3) device and subsystem design. While the US possesses world-class to world-leading resources and expertise in these areas, there are strong benefits to international collaboration in each of them. Collaborations with institutions such as CEA/IRFM and the Max-Planck Institute for Plasma Physics can provide important cross-code validation to enhance confidence and accuracy of theoretical and computational models [Budny 2012, Bonoli 2014, Falchetto 2019, Oikawa 2008]. Collaborations for joint development of software modules with multi-machine validation involving such institutions, along with (for example) EU device experimental data, can expand the breadth and power of complex US multiphysics and whole device simulations. Collaborations with institutions such as UKAEA can enable joint development of design suites, for example, making use of the PROCESS and BLUEPRINT design codes. Although there are various design codes and suites developed and presently in use by US laboratories and private industry, these tools are in rapid flux at the moment, and would benefit from validation and enhancement through international collaboration to meet the needs of BDV-supporting design efforts. Collaborations with institutions such as CREATE, DIFFER, and EPFL focused on control mathematics and design efforts, as well as ML/AI methods for incorporating data-driven inference in operations algorithms, can provide enrichment and expansion of US tools for control and operations. In addition, US control and other operational algorithms can be better validated and certified in the context of international standards through such collaborations, a key advantage when deploying commercial power plants. Joint efforts with these and similar institutions involving ITER and other international devices have already demonstrated the value of such approaches and collaborations [Humphreys 2015, Snipes 2017].

US capabilities in these research areas can benefit particularly well from collaboration with international institutions. Unlike facility-sharing in experimental collaborations, joint development of software and algorithms can provide essential opportunities for cross-validation and checking, increasing the credibility of and confidence in US models, results, and products. This validation and metric-based certification will be essential for performance acceptance and licensing in a wide range of results derived from such activities. Integration of US resources into international processes increases their level of acceptance for both domestic and international use in mission-critical and commercial fusion energy systems. Many collaborations are currently supported through ITPA activities, an important framework and mechanism for coordinating such efforts for ITER application. These activities should continue, and indeed require strengthening as ITER operation approaches. However, further collaborations are needed beyond the ITPA framework to enable work on non-ITER burning plasma preparations. **Table IV.6-1** lists some key opportunities for international collaboration in these areas, and highlights the relevant research focus and alignment with US goals for each. The 2020 Community Planning Process [CPP 2020] identified gap area Cross-Cut objective TC: "Theory and Computation," which provides the basis for interpreting experimental observations and transforming those observations into physical understanding. The last column of **Table IV.6-1** reflects the connection between given international collaborations and this cross-cutting objective.

Table IV.6-1. Key opportunities for international collaboration in theory, simulation, computational physics, control mathematics, design, advanced algorithms, ML/AI.

Institution	Type	Characteristics/ Capabilities	Research Focus	US Goals/Gains from Collaboration
CEA/IRFM	Theory, Computation, Simulation	LUKE, C3PO for LHRF wave-particle interactions; QuaLiKiz for quasilinear gyrokinetics; CRONOS code suite for integrated modeling	Whole device modeling, transport & stability theory, RF modeling	Cross-validation of theory models and codes; sharing of software modules and algorithms (CC-TC)
Max-Planck IPP	Theory, Computation, Simulation	GENE for gyrokinetics; TORIC for ICRF full-wave & RAPLICASOL for ICRF sheaths	Whole device modeling, transport & stability theory, RF modeling	Cross-validation of theory models and codes; sharing of software modules and algorithms (CC-TC)
EuroFusion/ IPP	Fusion power plant design	Design of the EU-DEMO fusion energy system	Tokamak demo power plant design	Joint development of tools and solutions; accelerate tokamak fusion energy system design (CC-TC)
QST	Fusion power plant design	Design of the JA-DEMO fusion energy system	Tokamak demo power plant design	Joint development of tools and solutions; accelerate tokamak fusion energy system design (CC-TC)
KFE	Fusion power plant design	Design of the K-DEMO fusion energy system	Tokamak demo power plant design	Joint development of tools and solutions; accelerate tokamak fusion energy system design (CC-TC)
LPP-ERM / KMS	Theory, Computation, Simulation	ICRF antenna codes (ANTITER suite)	ICRF antenna design (especially ITER)	Cross-validation of theory models and codes; sharing of software modules and algorithms (CC-TC)
UKAEA	Theory, Computation, Simulation	Comprehensive advanced computing program	Part of UK's flagship ExCALIBUR (Exascale Computing: ALgorithms and Infrastructures	Benefit from advances made in advanced computing in the UK (CC-TC)

			Benefiting UK Research) Programme	
UKAEA	Simulation, Design	PROCESS/BLUEPRINT tokamak design suite	ST-based fusion energy system design, interpretation of ST experiments	Joint development of tools and solutions; accelerate tokamak design (CC-TC)
CREATE	Control, Design, Simulation	General control design, CREATE-L/NL, CARMa suite	Design of operational control solutions for ITER, etc…	Joint development of tools and solutions; accelerate control design; workforce expansion (CC-TC)
DIFFER	Control, Design, ML/AI	General control design, ML/AI	Research and applications of integrated and advanced control; ML/AI research	Joint development of tools and solutions; accelerate control design; workforce expansion (CC-TC)
EPFL/SPC	Control, Design, ML/AI	General control design, ML/AI; RAPTOR	Control algorithm development and experimental study on TCV; ML/AI, esp. Reinforcement Learning	Joint development of tools and solutions; accelerate control design; workforce expansion (CC-TC)
University of York	Theory, Computation, Simulation	Transport physics (GS2, BOUT++, EPOCH.)	Broad program includes transport & stability theory, RF modeling - York Plasma Institute	Cross-validation of theory models and codes; sharing of software modules and algorithms (CC-TC)

IV.6.3. Findings and Recommendations (Charges 1 and 2a in Theory, Algorithms, and Computation)

Finding F2a-12: International opportunities for collaborations based on theory, simulation, computational physics, and modeling and design research offer strong potential for enhancement and acceleration of US efforts toward the LRP/BDV. These collaborations will rely heavily on fundamental capabilities to validate theoretical models and extrapolate to burning plasma regimes and power plant operational environments, as well as high confidence design of fusion devices and key subsystems.

Recommendation R2a-9: Pursue international collaborations with CEA/IRFM, the Max-Planck Institute for Plasma Physics, and CCFE to develop/validate theoretical/computational models, as well as with UKAEA, Eurofusion/IPP (EU-DEMO), KFE (K-DEMO), QST (JA-DEMO) to jointly advance fusion device modeling and design capabilities.

Finding F2a-13: International opportunities for collaborations based on control mathematics and ML/AI models and research offer strong potential for enhancement and acceleration of US efforts toward the LRP/BDV, which will rely heavily on US capabilities to inform device designs by control performance constraints, and develop and deploy effective control algorithms with high confidence.

> **Recommendation R2a-10:** Pursue international collaborations in control and ML/AI with CREATE, DIFFER, and EPFL/SPC to complement and accelerate development of fundamental control mathematics and machine learning capabilities in US programs through joint research, and to help the US prepare for ITER operation.

Finding F1-36: ITPA is a very effective and important framework for international collaboration, focused on ITER needs and preparations, but enabling broader research collaboration as well. It is in fact one of the most effective presently existing mechanisms enabling large-scale international collaboration on a wide array of fusion topics and devices.

> **Recommendation R1-16:** Continue and expand US participation in ITPA as a framework for collaboration in joint experiments, theory, computational physics, and control. Support ITPA involvement beyond present "voluntary" effort to enhance the accessibility of ITPA participation for US institutions.

Finding F1-37: The rise of high-repetition-rate laser facilities results in vastly larger amounts of data and changes the paradigm of how experiments are done. AI & ML techniques are required to automate and improve data processing and analysis. In the future, such techniques are crucial for the operations of IFE power plants which will require multi-Hz repetition rates. Multiple international facilities are more efficient to standardize, and the international community has many resources in ML/AI to share.

> **Recommendation R1-17:** Facilitate collaboration on machine learning and artificial intelligence linked to world-leading laser facilities (both high and low repetition rate), and develop common interoperable metadata standards with international collaborators.

V. Maximizing Impact of International Collaboration

Charge 2b: "Please assess whether the existing modes of collaboration are adequate for maximizing the impact of international collaborations on the US fusion program and objectives."

International collaborative activities involve unique characteristics relative to non-collaborative research and domestic collaborations. The impact of international research collaborations can be maximized by taking these unique aspects into account in general approaches and specific procedures, while also incorporating good general practices common to all kinds of collaborations. Existing modes of international collaboration incorporate a wide range of practices with varying impact. In response to charge 2b, we identify modes and practices to maximize the impact of collaborations in general, including practices specific to different types of collaboration.

V.1 General Best Practices to Maximize Impact of Collaborations

Critical best practices to ensure effective collaborations (Charge 2b) begin with strong frameworks for the team effort, including documentation of the team structure and roles, and mechanisms to run the collaboration like a true project, with all communication and project control needs met. Specific features that maximize the impact of international collaborations in general include:

- Inclusion of strong technical contributions and participation/support (ideally balanced) from personnel of both on-site host and collaborating parties.
- Common depository for collaboration documents, resources, tracking tools
- Collaboration formation document providing description of project, names, people, contacts, project schedule, and key milestones. Clear specification of the collaborative project goals and responsibilities is essential for effective execution.
- Regular meetings with key collaboration team personnel; optimized mix of whole-team meetings and sub-project team meetings
- Clear expression and agreement between host and collaborators on responsibilities for all aspects of the collaboration products: experiments, analysis, paper preparation, conference presentation, intellectual property disposition
- Effort to align research goals of the US in collaboration with values and research priorities of host institutions. The best collaborations occur when both host and collaborator strongly value the goals of the collaboration, and support the execution of the related work.
- Effort to integrate international collaborators into reciprocal or complementary research at domestic facilities. International expert participation in US fusion facilities, experiments, and technology development can enrich and benefit collaborations at international sites, as well as the advancement of domestic US fusion research.

V.2 Experimental Collaborations

Collaborations primarily focused on joint experimental work tend to require additional and specific practices to extract maximum value. This is because an experimental device schedule tends to be potentially fluid, depending on operational realities, faults, and need for dynamic re-assignment of teams and topics. These realities drive further requirements for maximum productivity of a collaboration involving experiments:

- Clear understanding of approvals and constraints on experimental facility use, granted by the collaborating institution for purposes of the project
- Clear understanding and training in safety procedures appropriate to on-site experimental participation
- Note that on-site collaboration tends to have lower efficiency for the traveling participant in some ways (e.g. due to the costs and impacts of travel), but high impact in the experimental effort (due to the direct contact with experimental operations). Conversely, remote participation with strong supporting infrastructure tends to be very efficient for the remote participant, but often with reduced effectiveness and impact of the effort relative to on-site participation.
- Exploitation of beneficial tradeoffs to optimize the mix of remote and on-site participation, maximizing overall efficiency and effectiveness during experimental campaigns. The ability to achieve scientific goals through remote operation and participation in experiments can also be important under conditions in which travel is limited (e.g. due to health and safety concerns).
- Strong leadership roles for collaborators in experiment planning and execution
- Tight communication and planning connections between collaborators and host team
- Experimental design and goals well-aligned with the capabilities and mission of the target device and operational conditions
- Tight coordination with the ebb and flow of a device’s status through an experimental campaign, to enable flexible adaptation to changing conditions
- In many cases it will prove optimal to have personnel onsite when there is hardware involved (diagnostics, etc)
- Integration of international collaborators into synergistic or complementary research at domestic experimental facilities can enrich and benefit collaboration efforts at international sites, and help advance the progress of domestic US fusion research.

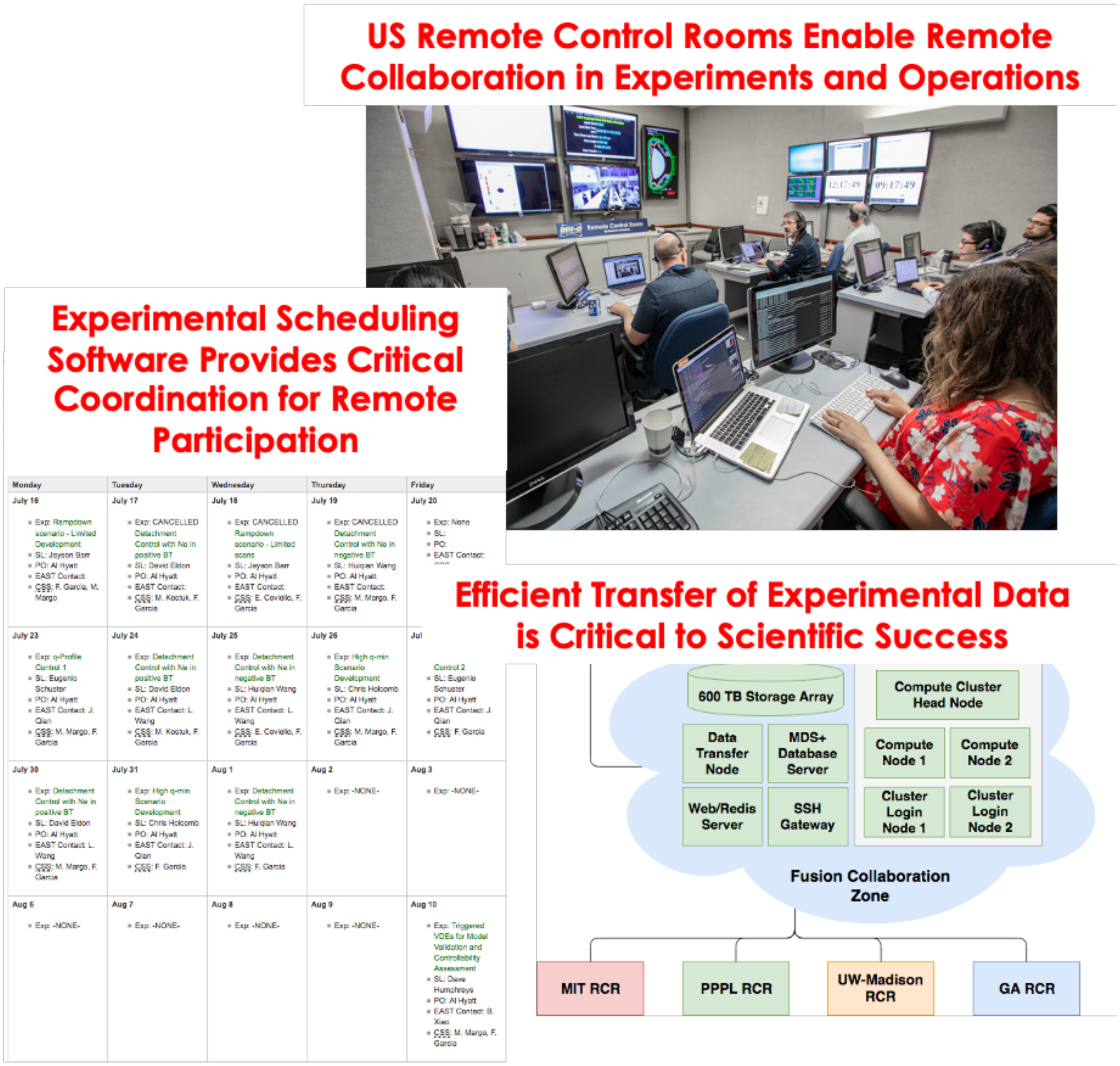

Figure V-1. Remote operation and experimental participation can significantly enhance impact of international collaborations involving experiment execution and facility operations. Remote Control Rooms (RCR) can facilitate such collaborations by reproducing the environment of domestic experimental facility control rooms. (Images courtesy of General Atomics)

V.3. Technology Collaborations

Collaborations primarily focused on technology R&D tend to require unique approaches. Technology *development* collaborations are further distinct from technology *testing* collaborations, owing to the higher level of intellectual contributions and information flow involved in development relative to testing. In addition to the General Best Practices identified in Sec. V.1, these realities drive further requirements for maximum productivity of a collaboration involving technology development or testing:

- Clear and complete planning for all stages of technology collaborative activity, with clear specification of roles, schedules, and deliverables, including hardware and other preparation results
- Technology *development* collaborations in particular require strong attention to intellectual property identification and invention provenance
- Technology *testing* collaborations in particular (including testing stages of a technology development collaboration) require strong coordination among a collaborative team, and often specific training to ensure competence in safety and use procedures for a test facility
- Much like experimental collaborations, technology operations and testing activities often require careful scheduling and coordination with local facility operations constraints

V.4. Theory/Computational/Mathematics Collaborations

Collaborations primarily focused on theory, computational physics, mathematics, control, machine learning, data-intensive workflows, and other algorithmically-based fields, tend to have unique features. Such collaborations tend to feature high intensities of both direct human intellectual exchange and computational or algorithmic information exchange. These realities drive further requirements for maximum productivity of a collaboration involving these areas. Several important aspects of these types of collaboration include:

- Low administrative barriers to cyber access (while maintaining sufficient security) are particularly important.
- High bandwidth, low latency communication links are essential.
- Collaborations involving sharing, benchmarking, and development of codes, algorithm development, and data analysis are especially well-suited to remote modes.
- Modern approaches for workflows and code coupling, performance portability, software productivity, and software engineering will greatly enhance the success of collaborations involving code sharing and development.

V.5. Foundational and Discovery Science Collaborations

Collaborations primarily focused on foundational science study, particularly in the areas highlighted most strongly in the Panel 5 assessment (see Sec. IV.5), share certain distinct characteristics with additional implications for achieving maximum impact. These include sharing of highly-subscribed research resources, as well as modes of research that require (or benefit substantially from) on-site participation. Several important aspects that can maximize the impact of these types of collaborations include:

- Establishment of international networks for small- to mid-size facilities.
- International agreements are important for beamtime allocations in addressing grand challenge science goals, and to accomplish closure of knowledge gaps, knowledge sharing, and experiment-modeling-theory exchange. An example of such agreements could take the form of a union of LaserNetUS + LaserLabEurope for key science goals.

- Maximize co-location and onboarding process of research team participants, visiting experimentalists and modelers, for extended periods. Often enabled by strategic international networks, even short periods of on-site collaboration can dramatically enhance the productivity of international collaboration in discovery science with resulting advances in understanding.

V.6. Findings and Recommendations (Charge 2b)

Finding F2b-1: Existing modes of international collaboration incorporate a wide range of practices with varying effectiveness and impact on the US fusion program, some viewed as adequate, and some less so. The most useful guidance in response to Charge 2b is therefore to identify the modes and practices that maximize the effectiveness and impact of collaborations in general, as well as practices specific to different types of collaboration.

> Note that this finding relates to the subcommittee process, so no corresponding action is recommended.

Finding F2b-2: Effective collaborations in general benefit from strong frameworks that support the functioning and communication needs of the collaborative team.

> **Recommendation R2b-1:** Construct strong frameworks for collaboration at time of initiation to include documentation of goals, team structure and roles, and mechanisms to run the collaboration that provide the needed communication and information flows.

Finding F2b-3: Collaborations primarily focused on joint experimental work benefit from additional and specific practices to extract maximum value, primarily driven by the fluidity of experimental device schedules, impacts of operational uncertainties and faults, and the need for dynamic re-assignment of teams and topics. Experimental collaborations benefit from a clear understanding of expectations on facility use from the collaborating institution, a well-considered mix of on-site and remote experimental participation, strong leadership roles for collaborators in experiment planning and execution with tight communication between collaborators and host team, and experimental design and goals well-aligned with the capabilities and mission of the target facilities, experimental programs and related operational conditions.

> **Recommendation R2b-2:** Ensure that *experimental* collaborations have clear coordination with the hosting institution at every level of collaboration and team, and a well-considered mix of on-site and remote experimental participation where appropriate. Where possible and beneficial, invite participation of international researchers in synergistic or complementary domestic experiments.

Finding F2b-4: Collaborations primarily focused on technology R&D tend to require unique approaches. Technology *development* collaborations are further distinct from technology *testing* collaborations, owing to the higher level of intellectual contributions and information flow involved in development relative to testing.

> **Recommendation R2b-3:** Ensure that *technology* collaborations have clear and complete planning for all stages of the collaborative activity, including clear specification of roles, schedules, and deliverables, and explicit handling of intellectual property identification and invention provenance. They should include specific training to ensure competence in safety and procedures.

Finding F2b-5: Collaborations primarily focused on theory, computational physics, mathematics, control, machine learning, data-intensive workflows, and other algorithmically-based fields, have unique features. Such collaborations are characterized by high intensities of both direct human intellectual exchange and computational or algorithmic information exchange. Activities of these types that involve sharing, benchmarking, and development of codes, algorithm development, and data analysis are especially well-suited to remote collaboration modes.

> **Recommendation R2b-4:** Ensure that collaborations focused on *theory, computational physics, mathematics, control, machine learning, algorithms, and data-intensive workflows* have low administrative barriers to cyber access while maintaining sufficient security, high bandwidth, and low latency communication links, and employ modern tools and best practices to manage software development workflows and code coupling.

Finding F2b-6: Although individual-to-individual collaborations have been common in the past, such relationships are now less frequent and often difficult to achieve. Such small-scale collaborations have proven extremely valuable in the past for establishing the foundation on which to build larger collaborations.

> **Recommendation R2b-5:** Broaden support for international collaboration beyond present focus on multi-year, many-person, to include smaller-scale (down to person-to-person), short timescale (down to one year), and smaller-scope (down to single topic) collaborations.

Finding F2b-7: Collaborations primarily focused on foundational and discovery plasma science have unique features. Such collaborations are characterized by sharing of highly-subscribed research resources, as well as modes of research that frequently require or benefit substantially from on-site participation in unique ways.

> **Recommendation R2b-6:** Establish and exploit international networks and agreements for collaborations focused on foundational and discovery plasma science for small- to mid-size facilities (e.g., a union of LaserNetUS + LaserLabEurope for key science goals), and maximize colocation of research team participants and visiting experimentalists and modelers for extended periods.

VI. Public-Private Engagement

Charge 3: "How can the US take advantage of its considerable and growing fusion private sector in international engagements, and how can we cooperate with overseas public-private partnership programs that focus on accelerating the development of commercial fusion?"

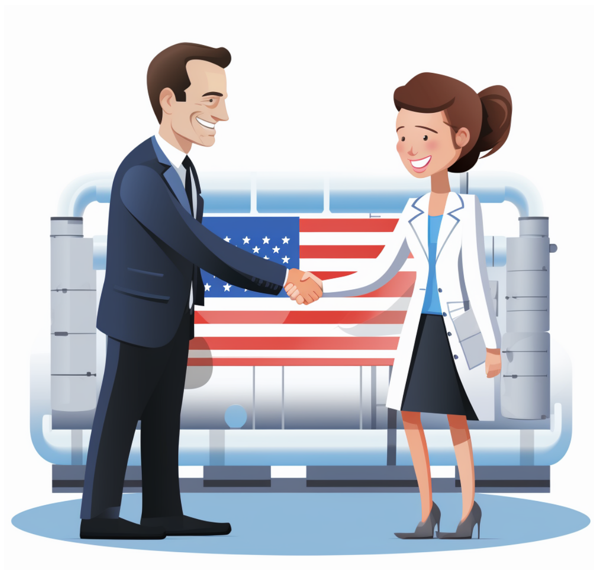

Figure VI-1. Partnerships between the public and private sectors can accelerate the development of fusion energy. *Image generated by MidJourney©*

A confluence of three interrelated factors has reinvigorated interest in utilizing public-private partnerships to develop and commercialize fusion energy. First, recent record-breaking results in both magnetic and inertial fusion energy - record fusion energy production of 59 megajoules at JET in December 2021 and record Q of 1.5 at the NIF in December 2022 - have catalyzed interest in fusion generally. Second, an explosion in investment in private fusion companies has resulted in an inversion in which the capital in the private sector now exceeds that of the federally funded program by more than a factor of two. Third, there is renewed political will, evinced by the announcement of the White House's Bold Decadal Vision to develop fusion energy and the launch of the DOE's Milestone-based Fusion Development Program - a competitive program to allocate government funds for private companies to deliver plans for a fusion pilot plant in 5 years.

In this context, we address Charge 3 to recommend ways in which the US can leverage this momentum and a sizable private sector in international engagements to accelerate the development of fusion energy.

VI.1 Magnetic Fusion Energy in the Private Sector

While the path to fusion as laid out by the FESAC LRP identifies the tokamak as the most advanced concept on which to base a pilot plant, with the stellarator serving as a secondary, both the LRP and the NASEM report strive to be concept-agnostic. Relative to decades of MFE research in which the tokamak was the explicit frontrunner, this position represents a shift in direction driven in large part by the emergence of a private sector where tokamaks and stellarators constitute a minority of concepts, approximately 30% according to the Fusion Industry Association's 2023 report [FIA 2023]. While alternative magnetic confinement concepts tend to lag behind the tokamak and stellarator in terms of plasma performance, they have the potential to leapfrog them if the engineering challenges of building a power plant prove to be lower for these concepts.

In the spirit of the federal government supporting the private effort, it is critical that these companies have access to complementary alternative confinement experiments (see Section IV above) and facilities for developing and testing enabling technologies. If those resources do not exist domestically, it is in the interest of the federal government to facilitate private-public partnership abroad. Advances in the development of fusion which accelerate commercialization align with the goals of the BDV, whether they occur in the public or private sector.

VI.2 Inertial Fusion Energy in the Private Sector

The recent demonstration of ignition at the NIF has further established the United States as the world leader in inertial confinement fusion. The longstanding public expertise is bolstered by the ongoing DOE NNSA ICF and HED program, which has sustained R&D with substantial funding over several decades in many science and technology areas that are synergistic with IFE needs.

Multiple IFE companies have been recently established, and are either internationally-based (roughly half of IFE startups to date) or have both a US and international presence (balance of startups), exploring a multitude of approaches and technology development paths.

Currently, there is no dedicated IFE facility anywhere worldwide, and the only large-scale ICF facilities with availability for open experimentation reside in the US, so private companies are seeking to collaborate with the US public sector on these US facilities. IFE private companies may begin construction of testbed or demonstration facilities in short order. However, sustained operations and full or optimal utilization of such facilities may be a challenge, and one where the US public sector could help in providing expertise or jointly operating. Many private companies are also looking to the US national labs for help with simulations, target design, target manufacturing, laser development, materials, and more.

Presently, many of the required IFE technologies are still at low technology readiness levels (TRL), and the foundation for many of these needed capabilities reside currently in government funded national labs, selected universities, and industry designed to support the US ICF and HED programs. These technologies can and should be leveraged for accelerating IFE research, development, and deployment. Well-formed, mutually beneficial public-private partnerships are a necessary tool to support the development of these technologies and to transition them to application space and commercialization.

VI.3 Scope and Constraints

There are at least three ways in which private companies may seek to leverage international collaboration. First, as private companies often have their limited experimental resources focused on their primary research channel, they need access to other facilities to test components or major subsystems (e.g., neutral beams, RF heating, magnet technology), develop plasma diagnostics, and/or benchmark simulations. Second, private companies often seek to answer technical questions with a binary outcome. These are usually well-defined, short-term, and limited in scope, making them ideal projects for collaboration. Finally, the rapid growth of private companies is creating a huge demand for trained physicists, engineers, and technicians that might be in part addressed by collaboration.

It should be noted that the scope of these collaborations is wide ranging, and includes connecting a variety of stakeholders from government, academia or industry, i.e., regulators, public interest groups, suppliers, national laboratories, private fusion companies, universities and specialty schools, etc.

We should also consider the constraints under which such collaborations would need to operate in order to be attractive to both the private and public sectors. Private companies value maintaining and growing intellectual property over the open publication of scientific results at this stage of fusion development. It is therefore critical that appropriate protections are put in place, including non-disclosure agreements and contracts that clearly delineate IP and data ownership at the start and throughout collaborations. It is also critical that collaborations benefit both parties, implying that the needs of the public sector should be addressed as well. At least a portion of the knowledge generated by a partnership should be made open to the public for all to use.

It should also be noted that there exists significant expertise within the public sector already that can be leveraged or licensed by the private companies - in some cases those capabilities are not well-known to the private sector, so effort needs to be put in to make those capabilities known and available, in a mutually beneficial manner.

VI.4 Leveraging the private sector

The sizable US private sector has introduced new opportunities for international collaboration to advance both commercial and public goals. It remains to be seen if the world's first fusion plant will be designed, built and operated by a private company, by a private company supported with federal funds, or largely by the federal government itself. However, current trends point toward significant roles for both public and private sectors, both of which can benefit from international collaboration. As the goal of the DOE is to deliver commercial fusion energy to the market as quickly and efficiently as possible, it should remain agnostic to the funding structure employed to reach that goal, but should broadly support collaborative opportunities to benefit US commercial fusion energy development. In many instances, the private sector can provide unique opportunities for connections with international facilities that are especially mission-driven and potentially more focused and effective than public research collaborations.

The diversity and size of the growing private fusion sector implies intellectual property challenges that are complex and potentially unique to specific technical approaches, particularly when applied across international lines. To most effectively leverage these investments through international collaboration, DOE should establish methods for efficiently vetting the feasibility of technical approaches and financial viability of the project, as well as sufficiently broad methods for managing their IP challenges.

VI.5 Findings and Recommendations (Charge 3)

Finding F3-1: While there are numerous mechanisms to facilitate public-private partnerships within the United States (e.g., ARPA-E, INFUSE, others), there are extensive and sometimes unique resources outside of the United States (e.g., this report) which could accelerate the technological development of fusion if opened to the private sector.

Finding F3-2: Private companies primarily have an interest in limited scope collaboration on topics such as the development of supporting technology (e.g., neutral beams, RF, magnets) and diagnostics and simulation benchmarking.

Finding F3-3: While the private sector typically seeks to minimize disclosure requirements and maximize IP protection when entering into partnerships, the public sector seeks to maximize the contribution to public knowledge and the federal program. There are model agreements that have been used successfully in other programs (e.g., the INFUSE CRADA).

> **Recommendation R3-1:** Create a program that facilitates targeted collaboration between domestic private companies and international institutions engaged in fusion development which strikes a balance between openness and IP protection.

Finding F3-4: There also exist counter-streaming opportunities, in which international private companies seek to utilize resources from the federal program, especially in inertial fusion energy.

> **Recommendation R3-2:** Create opportunities for private companies from abroad to collaborate in the US, while ensuring all activities stay consistent with DOE/government regulations for protecting assets as necessary.

Finding F3-5: In addition to the vibrant US private fusion sector, there exists a burgeoning international private sector effort pursuing the development of supporting technology (e.g., blankets, balance-of-plant, materials, etc.) relevant to the US fusion energy mission and is keenly interested in collaboration with US entities.

Finding F3-6: The US fusion private sector can benefit from engagement with international foundational and discovery science institutions, which can help address outstanding challenges to private industry goals while also supporting expansion of the private workforce.

> **Recommendation R3-3**: Encourage US fusion community engagement with international companies primarily focused on fusion energy system goals, and also with international plasma science and technology companies with supporting technology goals.

VII. Role of International Collaboration in US Leadership

Charge 4: “Within the Fusion Energy Science-supported research areas and facility capabilities for fusion energy science and discovery plasma science, what are the areas where the US is leading, the areas where US leadership is threatened in the near- and long-term, and the areas in which US is not leading at present but where investing resources could offer significant opportunities for leadership that would be beneficial to the US fusion program goals and objectives?”

VII.1. Introduction

The establishment of international collaborations can maintain and enhance US leadership in key areas required to deliver an operational fusion power plant. The US enjoys a range of leadership levels that vary widely across the many fields that comprise fusion energy and plasma science. The US leads in many areas, notably aspects of short pulse magnetic fusion and inertial fusion energy science, as well as key technology and fundamental plasma science areas. US leadership in these areas is not significantly threatened at present. However, there are critical areas in which the US is at parity with the international community, and in which the US is not leading. The section following presents an assessment and discussion of the general status of US leadership in key fusion fields. **Table VII-1** summarizes the results of this assessment, comprising key topical areas in fusion development and plasma science. The content of the table consolidates the analysis performed in the earlier sections of the report. **Figure VII-1** provides a high-level illustration of these results, grouping topical areas together by color depending on whether the US is leading (i.e. US essentially dominates the field), the US is at approximate parity with international parties, or the US is not leading. Topical areas are then further grouped via discipline corresponding to Physics, Technology, and Computation & Algorithms

VII.2. US Leadership Status in Fusion Energy and Science

The US leads in many aspects of tokamak physics, including high-performance scenarios with demonstration in short pulse, disruption avoidance and mitigation physics/control, and core-edge integration. However, the US only has access to superconducting tokamaks through international collaborations to study long pulse performance, and burning plasma experiments have been led by JET. This range of leadership levels in tokamak physics areas leads to a net assessment of rough parity, and represents a key opportunity for investment of resources to enhance US leadership through collaboration.

The US leads in the areas of stellarator disruption physics and optimization in large part because of US expertise in theory and simulation in these fields. The lack of domestic stellarator experiments leaves the US behind Japan and the EU in core and divertor physics.

As demonstrated by the recent ignition achievement, the US is the international leader in ICF now, but in order for the US to grow and maintain its leadership in ICF/IFE, it is important to keep science open as much as possible for international collaboration while still retaining and protecting US intellectual property and ensuring critical technologies adhere to export control policies.

The US is on parity with international parties in the area of neutron testing where both lack facilities for producing fusion-level neutron energies, but possess neutron sources with varying useful characteristics for testing. In the area of plasma facing materials research the US is not leading; international devices have deployed multiple types of wall materials including Be, W, Mo, and C, whereas US devices have been more limited. The US leads in computational modeling for fusion materials research because of its exascale computing capabilities and data storage facilities.

Three balance of plant topical areas were identified in which the US is not leading. These are tritium breeding blankets where there are significantly larger investments in ITER TBM and DEMO blanket development activities in the EU, Japan, Korea, and China; tritium handling and fuel cycle where significant US capabilities exist in the non-fusion-focused area but fusion-focused facilities are lacking; and in ancillary systems where significantly larger investment in ITER TBM and DEMO blanket ancillary systems have been made in the EU, Japan, Korea, and China.

Two key technology areas in which the US is not leading and could benefit from international collaborations are gyrotron source development and high-repetition rate laser construction and experiments. The US was also found to lag in neutral beam technology and development where NNBI and large-scale beam testing facilities exist only abroad. Although the US is leading in HTS magnet development, it lags in manufacturing capability. In ICRF systems the US is generally on parity with the international community in antenna design while international entities lead in source and transmission line development.

In the field of Fundamental Plasma Science, the US is leading in HEDP where it has a few single-shot facilities capable of experimentally achieving the highest energy density plasmas worldwide, as well as premier codes. In ignition science, the US presently has the only ignition-capable laser facility (NIF) in the world. Although the US leads in the knowledge base of technology, design, and architecture of advanced laser systems, and is at parity for the supporting capabilities for these facilities (diagnostics, targets, control systems), it lags behind the international community in the construction, hosting, and access to the next-generation high-repetition-rate and high intensity laser facilities.

The US is clearly world-leading in theory and HPC-based modeling and simulation and is at parity with international efforts in integrated modeling, control mathematics, advanced algorithms, and ML/AI. The US is not world leading in fusion systems design in general, where many international DEMO/fusion energy system design teams exist (the exception is in inertial fusion). However, US design capabilities are rapidly increasing in this area.

Table VII-1. Assessment of high-level US leadership status in selected key topical areas in fusion development and plasma science.

Topic	Subtopic	US Leadership Status	Context, Implications, US Capabilities
Fusion Core			

	Tokamak: Burning plasma	Parity	US pursuing many burning plasma FPP configurations, but presently lacks a burning plasma device. JET experiments with DT provide leading experimental experience; several nations lead the US in producing highly mature DEMO device designs
	Tokamak: Divertor and Core-Edge Integration	Parity	US experimental and modeling capabilities comparable to international teams; DIII-D leads world in high heat flux and detachment physics; NSTX-U will augment capability, add liquid metal divertor; MAST-U leads in advanced divertors; several international tokamaks lead with W-divertors
	Tokamak: Scenarios	Parity	US experimental and modeling capabilities comparable to international short pulse tokamaks; US has no long pulse superconducting devices; only JT-60SA has same potential or betaN > 4 as DIII-D and NSTX-U
	Tokamak: Disruptions	Leading	US experimental and simulation expertise leads in disruption avoidance and mitigation physics/control
	Stellarator: Optimization	Leading	US leads in optimization tools, however EU and Japan lead in stellarator facility design and deployment (often using US-developed tools)
	Stellarator: Core physics	Not Leading	EU and Japan lead in stellarator experiments and core physics understanding (W-7X, LHD, TJ-2); US lacks stellarator facilities
	Stellarator: Divertor	Not Leading	EU and Japan lead in stellarator experiments and diverter solutions (W-7X, TJ-2); US lacks stellarator facilities
	Alternative magnetic configurations	Parity	US pursuing many alternative magnetic configurations as part of BDV, but international devices (e.g. RFX, EXTRAP-T2R, Gamma-10) provide competitive study opportunities
	IFE	Leading	US is clear leader in ICF/IFE experimental physics and modeling
	Fusion Energy System-compatible sensors	Parity	Limited capability available worldwide; US at similar level to international parties, with development in various DOE-funded laboratories (fission and fusion)
Materials/PMI			

	Irradiation testing	Parity	Both US and international parties lack fusion-level neutron energies, but possess neutron and similar sources with varying useful characteristics for testing
	Plasma facing materials	Not Leading	International devices have deployed multiple types of wall materials including Be, W, Mo, and C; US devices have been more limited: e.g. DIII-D DiMES (existing), WITS (planned) material testing facilities
	Computational modeling for Materials	Leading	US exascale computing capabilities and data storage facilities for fusion materials research lead the world.
Balance of Plant			
	Tritium breeding blankets	Not leading	Significantly larger investment in ITER TBM and DEMO blanket development activities in the EU, Japan, Korea, and China relative to US. UKAEA, EU pursuing blanket test facilities (e.g. CHIMERA)
	Tritium handling and fuel cycle	Not leading	Significant US capabilities are defense, not fusion-focused. US lacks fusion-focused tritium handling facilities.
	Ancillary systems	Not leading	Significantly larger investment in ITER TBM and DEMO blanket ancillary systems in the EU, Japan, Korea, and China relative to US. Remote handling led by e.g. JET, EU development for DEMO; EU and JA deploying blanket advanced cooling systems.
Technology			
	Gyrotron R&D	Not leading	US lacks gyrotron development programs and manufacturing facilities. Many international industrial parties dominate ECH source development and deployment
	ICRF technology	Parity	US has parity in antenna design; ORNL operates ICRF test facility; international entities lead in source and transmission line development
	Neutral beams	Not leading	NNBI and large scale beam testing facilities leading abroad; DIII-D and NSTX-U PNBI; US lacks NNBI facility
	HTS magnets	Leading	US leads in development, lags in manufacturing capability
	High repetition rate	Leading	US leads in technology, design, architecture,

	lasers		but lags in deployment
	Radiation-hardened sensors & actuators	Parity	Limited capability available worldwide; US at similar level to international parties
Fundamental Understanding of Plasmas			
	HEDP	Leading	US has highest energy density plasma facilities worldwide
	Ignition science	Leading	US has only presently ignition-capable laser facility (NIF) worldwide
	Laser driven experimental fundamental plasma facilities	Not leading	US leads in technology, design, architecture, but lags in domestic facility capability relative to international
Theory, Algorithms, & Computation			
	Theory, Simulation, Computational Physics	Leading	US leads the world in theory, HPC-based modeling and simulation, exascale facilities
	Integrated modeling	Parity	US integrated modeling capabilities (SciDAC-funded programs, TRANSP, etc…) on par with international resources (CEA/IRFM, UKAEA, etc…)
	Fusion system design	Not leading	Although there are many international DEMO/fusion energy system design teams, US design capabilities are rapidly increasing
	Control mathematics, advanced algorithms, ML/AI	Parity	US control mathematics expertise (Lehigh Univ., Princeton Univ., General Atomics, etc…) at parity with international capabilities (DIFFER, CREATE, EPFL/SPC, etc…)

Key: Leading = US leading (i.e. dominates the field); Parity = US is competitive, at approximate parity with international parties; Not Leading = US not leading;

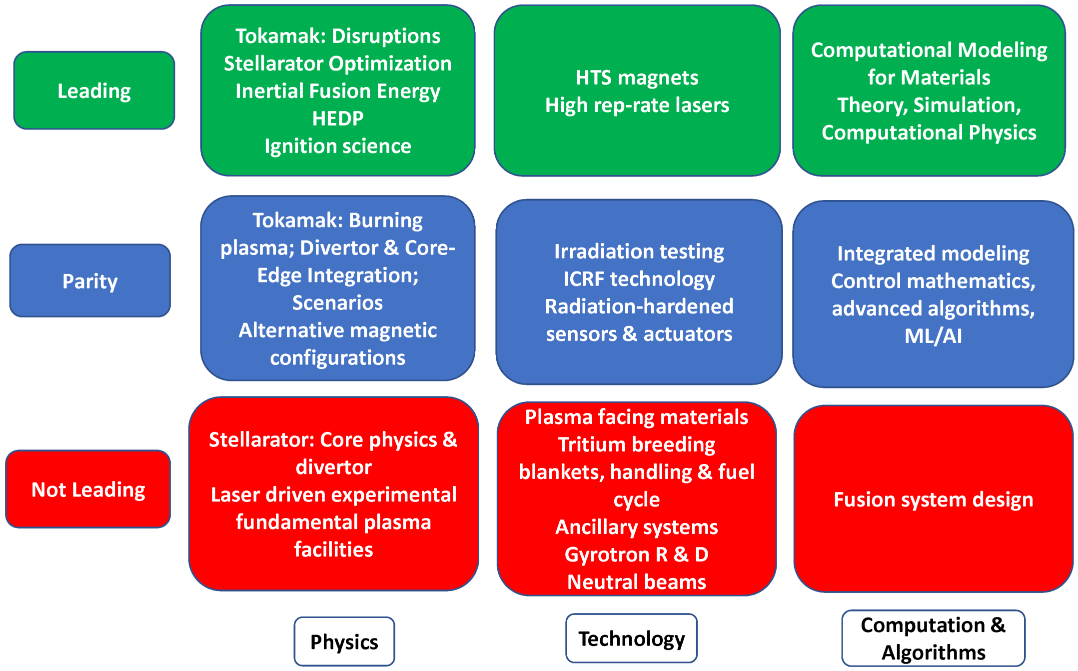

Figure VII-1: Summary of topical areas from **Table VII-1** grouped horizontally by color in which the US is leading and dominates the field (green); the US is competitive, at approximate parity with international parties (blue); or the US is not leading (red). Topical areas are further grouped into columns by discipline corresponding to Physics, Technology, and Computation & Algorithms.

VII.3. Strategic Planning to Enhance US Leadership

Several high-level strategic steps can be taken to make best use of international collaborations to enhance US leadership in the gap areas identified above. Distinct from the practices that maximize the effectiveness of collaborations (Charge 2b, Sec. V), these steps apply to broader strategic planning of the US international collaboration portfolio, and include:

- Establishment of a national strategy for leadership priorities in fusion, including identification of the specific roles for international collaboration, significantly drawn from the gap areas highlighted in this section and Sec. IV above.
- Tailoring of international collaborations to specifically contribute to enhancing US leadership where appropriate, including maximizing the degree of open science while protecting IP interests of US companies and institutions, and creating collaborative project plans that will advance US leadership goals while mutually benefiting collaborative partners
- Applying sufficient priority to accessing large-scale facilities in particular, to enable expansion of relevant US operations experience with such facilities
- Incorporation of workforce development goals into strategic collaboration planning, ensuring that each collaboration program proposal includes strong workforce elements (identified in Sec. VIII)

- Incorporation of US private company goals, and their roles in a national strategy, into planning of private-private and private-public collaborations abroad (see Sec. VI)
- Broader coordination across federal agencies and integration of DOE efforts and goals with other federal science international collaborations

The unique role of private capital and private sector contributions to the BDV implies important roles in maintaining and enhancing US leadership in fusion in the coming decade. In some cases, significant portions of US leadership are derived from the investment and activity of the private sector. In general, US private companies need a source of domestic private capital to maintain their participation in government programs and funding opportunities. It is also critical that while contributing to US leadership advancement through these activities, IP not be restricted in a way that delays/prevents/inhibits progress.

Significant quantities of private capital can be focused on science investigation and technology development by leveraging the interests of private industry with the appropriate incentives. In many cases, the private investments can be orders of magnitude larger than the budgets of existing government programs. These investments can greatly accelerate scientific and technical progress as well as identify go/no-go metrics for the next phase of activities and eventual system deployment. Unfortunately, after public investments are made in private ventures, it is often difficult, if not impossible, to control the direction and ownership of the results. Due to the pressures of cash flow and expectations of returns to investors, private companies often do not have US strategic interests in mind as they make decisions on where to purchase components or where to site facilities. Furthermore, private entities often evolve over time and may transition the intellectual property to new entities (by getting acquired) as well as adding international investments to their portfolio. There are multiple opportunities for the fusion community to learn from the best practices of other communities on approaches to leveraging private industry. The most recent and visible example is the effort by NASA and the DOD to develop low-cost access to space, i.e., SpaceX and Blue Origin. Thus, there is a need for whole-of-government and whole-of-nation strategic planning to avoid repeating past mistakes.

Leveraging private investments to accelerate scientific progress and technology development, advancing the national leadership position, is not new to the US government. It is however relatively new to the fusion community, and would benefit from strategic coordination.

VII.4. Findings and Recommendations (Charge 4)

Finding F4-1: In the areas where the US presently leads, that leadership is not significantly threatened. The focus of international collaborations in this environment is most effectively directed to maintaining such leadership, as well as gaining in key areas lacking current leadership. However, while benefiting all participating parties, it is particularly important that US-funded international collaborations satisfy US national goals for technical advancement and leadership.

Recommendation R4-1: Clearly identify the anticipated roles in international collaborations in satisfying US national goals as part of a national strategy for technical advancement and leadership.

Finding F4-2: Benefiting from decades of investment in ICF, and as demonstrated by the recent ignition achievement, the US is the international leader in ICF now. ICF was declassified in 1970, and there has been an enormous benefit to utilizing the international community to advance the science and provide peer-review. The transition from the NIF science performance demo (the 210808 single shot) to the required re-rated platform needed for IFE to FPP demo requires laser technology investment. This is an area where the US has ported its most valuable capabilities overseas (in ELI) and creates an opportunity to collaborate with ELI to train our scientists, engineers and future workforce on their repetition-rated laser infrastructure.

Recommendation R4-2: Keep the scientific process in ICF/IFE programs open as much as possible for international collaboration, and pursue collaboration with ELI to grow US repetition-rated laser expertise for ICF/IFE applications.

Finding F4-3: Long-term public and private leadership status and goals are important considerations to usefully inform public grants/investments.

Recommendation R4-3: Review best practices in other industries and apply them to obtain the best return on public investment when supporting public-private partnerships and international collaborations for maintaining or establishing leadership.

Finding F4-4: The US lacks a sufficient number of large facilities to maintain leadership in construction and operation of large fusion facilities.

Recommendation R4-4: Leverage international collaborations to facilitate access to large-scale fusion facilities in order to improve the US level of expertise in the areas of construction and operation, consistent with the needs of the BDV, as well as to obtain good scientific output from such facilities.

VIII. Workforce Development and Recruitment from Underrepresented Groups

Charge 5: "How can the US ensure the availability of a highly trained and internationally competitive workforce in fusion science and technology and related areas, including the recruitment of talent from traditionally underrepresented groups within the US?"

VIII.1. Introduction and General Observations for Workforce Expansion

The need for workforce expansion in the US fusion community to enable realization of the Bold Decadal Vision is tremendous and spans virtually all fields. It is likely one of the greatest challenges to near-term success in fusion power commercialization, since US public and private, as well as international parties, are all competing for a limited supply of domain-specialized expertise. The need extends well beyond plasma physicists, who have long been heavily-engaged in the fusion community in the US, to include materials scientists, engineers in nuclear, mechanical, electrical, and other specialties, mathematicians, computer scientists and computational algorithm experts, system engineers, software engineers, project managers, CAD designers, and technicians of all backgrounds.

The US fusion community has potential need for unprecedented growth in the coming decade, as private companies and publicly-funded laboratories expand to fulfill target milestones toward design, development, and deployment of fusion power plants of various scales [FIA 2023]. Because the efforts underway are for the most part First Of A Kind (FOAK), there is limited basis for estimating the overall cost and labor demand for such projects. Nevertheless, the various design and construction phases of ITER, and estimates for various DEMO programs, provide some guidance. For example, the Engineering Design Activity and Construction Phase of ITER have required roughly 500 and 1000 dedicated staff, respectively (and thousands of contractors during construction) [ITER 2021]. The EU DEMO project has already engaged hundreds of scientists and engineers for nearly a decade, and is estimated to require hundreds of dedicated advanced degree-level staff to be added per year for engineering design through construction [DEMO 2017, EURoadmap 2018]. It is likely that hundreds more dedicated professionals of varying less-advanced degree levels will be required per year in this effort as well.

If tens of companies and public laboratories experience persistent design, development, and construction activities toward power plant-scale devices in parallel, the experience of ITER and estimates from the EU DEMO program suggest that many thousands of new staff personnel will be needed to enter the US fusion-dedicated workforce in the coming decade (in addition to the much larger number of contractors that will be needed, particularly for final construction).

In the section following, we provide general observations for crafting a diverse Science, Technology, Engineering, and Mathematics (STEM) workforce in the US, including opportunities for leveraging domestic and international sources via direct support to educational institutions and use of collaborations in fusion science and technology, with a few specific examples.

VIII.2. Domestic Workforce Expansion

Dedicated efforts will be required to expand workforce development domestically, including support for collegiate students at all levels and in many fields of engineering, science, mathematics, computer science, and beyond, to enter fusion. Such support should include scholarships for undergraduate and graduate students, and funding of fellowships for post-doctoral students and early career researchers, in fusion-relevant areas. Internship programs for high school students and undergraduates, e.g., the present Science Undergraduate Laboratory Internships Program (SULI) summer internship program, can also be effective but must provide specific additional funding to host institution personnel in order to enable sufficient mentorship support for the interns. The multidisciplinary aspect of foundational and discovery plasma science, as well as plasma applications, is beneficial for workforce expansion due to the high pedagogical impact and access to education science facilities with hands-on activities, e.g., experiments and simulations in topical areas of laser-plasma interactions, ignition science, laboratory astrophysics, quantum electrodynamics, warm dense material science, plasma medicine, space propulsion, and agricultural plasma science. As the world's undergraduate and graduate students continue to reach unprecedented levels of advanced academic theoretical education never thought possible centuries ago, these scholars must also be nurtured and inspired to think creatively in an applied environment. Domestic programs to connect students to research facilities (e.g., small-scale academic, mid- to large-scale at national laboratories and labs in private industry) and provide experiential learning opportunities will help to encourage engagement with the fusion community of collegiate students at all levels, i.e., undergraduate, graduate, technical apprenticeship, and post-doctoral levels. It will also create tangible career pathways and employment opportunities. Graduate and undergraduate practicums available at US National Laboratories can supplement college and university programs, maximizing the growth of student populations in applied fields of fusion. National Laboratories' commitment to fostering and integrating underserved disciplines and populations can further ensure unparalleled advancements in scientific discovery. It is imperative to address a broad pipeline to grow the workforce – and this must include vigorous engagement at the undergraduate level and with participation from Minority Serving Institutions (MSIs), MSI-Faculty, women-only, and other institutions with underrepresented population focus. National laboratory and DOE programs (e.g. FAIR and RENEW) can focus students in underrepresented segments of the scientific community at the early onset of applicants' undergraduate and graduate careers. This ensures student awareness of the opportunities in fusion, and through some programs, offers accessibility for minority populations to these fields. Continued advancements in the ability to create relationships among a vast array of traditionally underrepresented minority populations of the scientific community are essential to an influx of creativity, discovery, and advancement in fusion innovation. Engagement at the secondary school level can also be effective, particularly through specific internship and outreach programs that connect high school students with research institutions and laboratories with sufficient funding for mentors and program support.

Establishment of US regional Hubs in IFE/MFE is another clear engagement opportunity for workforce development in fusion science and technology. 'Hubs' are consortia that include combined, coordinated efforts among academia (e.g., R1, MSI, and community colleges), private sector and National Laboratories, all located in a geographically similar region or part of the country, and can vary in size; not unlike this EDA, DOC NOFO [NOFO 2023]. Hubs are most effective when situated in and serving a geographically localized area, e.g., a Metropolitan Statistical Area [USCensus 2020]. Hubs can be 'regional,' i.e. incorporating multiple states [ClimateHub 2023]. A regional Fusion Hub is also effective when addressing a specific topical area, e.g. tritium handling or materials design, characterization and testing, magnet technology, laser-plasma interaction and control. Another example of effective Hub design is to organize around an existing National Laboratory/University. Such Hubs will have access to specialized staff or faculty expertise, infrastructure, experimental, or simulation capabilities which can be leveraged for student recruitment and retention in their topical areas. For example, a Southeast Regional Fusion Hub representing such a national lab-centered approach could consist of SRNL and ORNL, ~4-6 R1 academic institutions (including local Historically Black Colleges and Universities - HBCUs - in South Carolina and Tennessee, MSIs and community colleges). This Hub might naturally address topical areas including tritium handling and materials innovation for radiation and extreme environments. Such a Hub design could also support a strategy to broaden topical field diversity and leverage Hub-local-to-MSI engagement (including community colleges, universities geographically near the Hub). Moreover, this provides an opportunity for dedicated coursework at local R1 academic and HBCUs to be deployed to specifically prepare for work to be performed at ORNL and SRNL, and/or at participating private companies.

A number of augmented engagement activities are needed with MSIs to enhance diversity while accomplishing BDV goals. Fusion science and technology efforts through DOE and other agencies could provide an increased level of support of MSIs in several ways. For example, there could be increased support for curriculum and technology development/enhancement through instrumentation, and computing assistance. This is also synergistic with the 'regional Hubs concept' mentioned above. Modification of existing MSI courses and curricula, designed for fusion science and technology, could deepen learning and teaching. Professional development for students and faculty members through sabbaticals, internships, capstone projects, job-shadowing activities, tours, summer schools, and graduate studies, would also be advantageous. Connection of such activities to Regional Fusion Hubs can amplify their effectiveness in workforce development. Professional readiness and information dissemination assistance, e.g. travel costs, accommodations, visits to facilities, technical symposia/conferences, will benefit from explicit support. An additional vehicle of student connectivity is provided by Summer Internship Programs. Existing programs like SULI, Community College Internships (CCI), DOE National Lab summer internship programs, with a topical area emphasis in fusion science and technology, are also important, and would benefit from additional support for mentors being provided intrinsically to the program design.

Summer schools (or similar dedicated short-duration schools) can provide an important means of attracting or developing students and junior researchers into fusion-relevant areas. The ITER International School [ITERSS 2023], for example, has been highly effective in drawing students into ITER-focused areas and providing them with basic scaffolding to begin addressing ITER problems. Many other topical areas for summer schools have been successful in augmenting student engagement and preparation, including computer science/machine learning (e.g., [BMM 2023]), high energy density physics (e.g., [HEDSSS 2023]) and extreme matter (e.g., [EMSS 2023]).

Additionally, domestic public-private partnerships are areas where discovery science tools and technology development, often cultivated in the academia with connectivity to a diverse workforce, can transform and/or establish new industries, e.g., EUV-based lithography, plasma medicine, agriculture, plasma-mediated device construction, propulsion, and IFE. There are a number of exchange program formats and opportunities which could be advantageous to build connectivity and experiences leading to workforce development. Examples of such programs include Student Exchange Programs (6-12 month duration, potential for course credits, often set up between academic institutions at the undergraduate or graduate level, focused on topical areas relevant to FES); Detailee Programs: (1-2 year duration, postdoc or early career researcher can engage/participate in a government office/agency, e.g., Program Office for FES or ASCR, and then return to home institution with the benefit of being exposed to the inner workings and protocols of the government-related agency); Internship Programs: (duration is variable, depending on the facility, department or group – summer only, to 6 or 12 months, open to graduate/undergraduate or early career & postdocs, could be at National Labs, and/or academic institution or private industry strategically aligned with topical science and application areas); Apprenticeship Programs: (duration and type similar to internships, emphasis on learning a technical trade or engineering relevant to fusion science and technology).

Through the combination of well-prepared undergraduates and graduates in academic settings, enhanced by applied internships that spark creativity and discoveries, we will be well equipped to provide the key fusion advancements required to fulfill the BDV and beyond.

VIII.3. Workforce Expansion through International Collaboration

International collaborations have long provided access to additional personnel beyond the US-resident population, as well as opportunities for development of relationships and enhanced training of US personnel (e.g., see Finding 5-1). Leveraging international collaboration can provide opportunities to enhance training of students into a fusion domain of expertise, training of students by international experts, transfer of senior personnel from a non-fusion domain to a fusion domain of expertise (US resident or international personnel), and transfer of senior fusion-domain personnel from international sites to the US. Access to state-of-the-art user facility centers for high impact, advanced research studies, and testing of integrated technologies bolsters workforce development in basic and applied research. International collaborations often provide enhanced opportunities for diverse personnel to join US efforts and institutions. For example, many recent studies have identified that women in the US represent ~20% of particle physics Ph.D's, ~15-20% of physics Ph.D's, ~30% of physical science Ph.D's, ~20% of engineering Ph.D's (e.g. [Cabay 2018]). By comparison, > 40% of employed scientists and engineers outside the US are women (e.g. [SheFigures 2021]). Extending workforce acquisition to such international pools, as well as beyond physics communities to engineering and computer science, will intrinsically increase the diversity of the US fusion workforce. Improving the efficient availability of long-term visas and permanent resident status is likely to be essential to increasing the rate of acquisition and retention of international experts for the domestic workforce.

Similar to above mentioned domestic public-private partnerships, there are opportunities for international partnerships as well, e.g., Student Exchange Programs with international fusion companies, or receipt of class/course credits from international academic/lab institutions. Alignment of detailee assignments with international governmental program offices (equivalent to US FES or ASCR), or as part of the Fusion Program in the IAEA, could provide needed breadth and experience for a US career in this area as well.

Figure VIII-1 summarizes potential domestic (blue) and international (red) sources of fusion workforce expansion, including educational and government institutions, private industry, and non-fusion workforce sectors. Sourcing personnel from international STEM communities, and from outside fusion communities, will increase diversity naturally due to the greater diversity of those source populations.

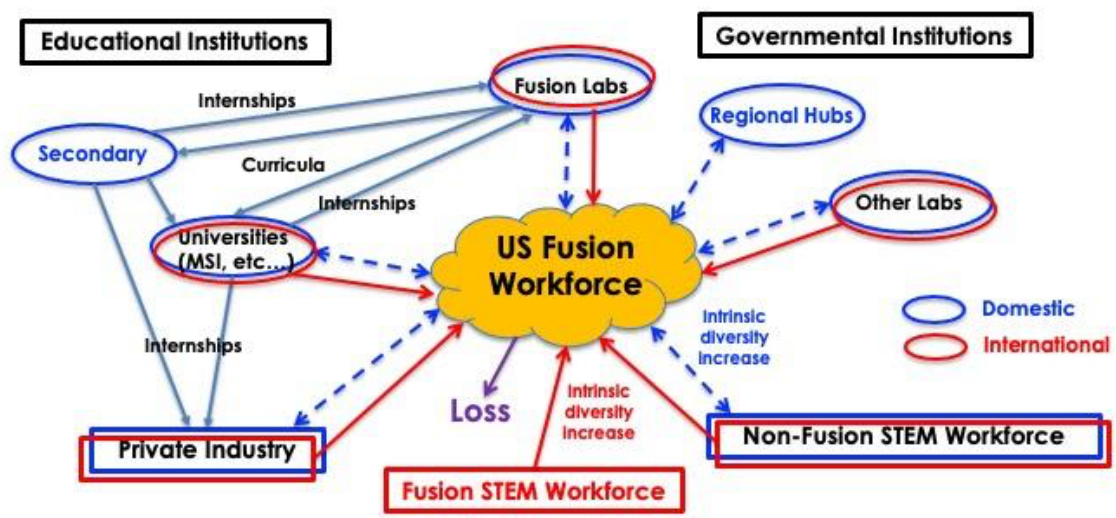

Figure VIII-1. Domestic and international sources of expansion for the US fusion workforce. Critically-needed expansion of the fusion workforce will be accomplished by leveraging many sources, including domestic and international universities, government laboratories, private industry internships and apprenticeships, and non-fusion STEM sources both domestic and international. Accessing new personnel from both in-fusion and non-fusion international sources, as well as domestic non-fusion sources, will naturally increase diversity in the US fusion community.

VIII.4. Findings & Recommendations (Charge 5)

Finding F5-1: Domestic workforce expansion in STEM areas is critically needed to support the requirements of the BDV, yet the American Physical Society (APS) - Division of Plasma Physics (DPP) has the lowest percentage of female participation [APS-DPP 2021]. The US workforce needs, and will benefit from, growth in diversity to achieve goals and timeline of the BDV. Sourcing new personnel from institutions with focus on underrepresented populations can provide key opportunities to improve workforce diversity (e.g. MSI's, and women-only schools).

Recommendation R5-1: Expand domestic support for students at all levels of engineering, science, mathematics, and computer science, in order to help grow the fusion workforce by many thousands of new dedicated staff in these areas over the coming decade. Provide a corresponding increase in the number of fusion undergraduate internships (e.g. SULI), graduate research opportunities (e.g. SCGSRs) and FES Postdoctoral Researcher Awards.

Recommendation R5-2: Provide sustained investments in increasing research capacities at MSIs and women-only academic institutions, e.g., by leveraging key DOE programs (FAIR and RENEW), and introducing dedicated international fellowship programs to MSIs. Support US-led community networks for expanding e.g. gender and ethnic, socio-economic, and learning-style diversity.

Finding F5-2: The student pipeline for fusion workforce development, beginning with the undergraduate level, is presently inadequate to address the requirements of the BDV.

Recommendation R5-3: Invest in undergraduate curriculum, practicum, and technology development/enhancement in fusion and plasma science, including providing relevant laboratory infrastructure and instrumentation, computing assistance, and faculty professional development at targeted institutions including MSI's. Support holding topical summer schools to attract and prepare students for participation in fusion areas.

Finding F5-3: Foundational, discovery science and technology are a clear vehicle to attract the next generation students for workforce enrichment, development and expansion. Both domestic and international educational and research institutions can contribute to this approach, in areas including HEDLP, plasma science, WDM, condensed matter international institutions.

Recommendation R5-4: Enhance educational opportunities in discovery science programs in academia and national laboratories to grow the STEM workforce. Establish and support faculty and student exchange programs among domestic and international universities including MSIs, as well as research laboratories, over multi-year timescales.

Finding F5-4: Domestic and international public-private partnerships include discovery/applied science and technology development, often cultivated in academia with connectivity to a diverse community, and can transform and/or establish new industries, e.g., EUV-based lithography, plasma medicine, agriculture, plasma-mediated device construction, propulsion, and IFE.

Recommendation R5-5: Support enabling collaborative participation of US students and early career researchers with domestic and international private industry and public-program facilities via exchanges, internships, and detailee programs.

Finding F5-5: Domestic workforce needs dramatic expansion in the skill areas of manufacturing, engineering, and technician work to fulfill the BDV. New US regional Hubs can support the needs of this expansion process.

Recommendation R5-6: Support US students and early career researcher programs for engagement in international tradesmanship/apprenticeships in manufacturing, engineering, and technician training, including those not requiring advanced degrees, and supported by the creation of new regional US hubs.

Finding F5-6: DOE funded research could offer opportunities for student and fusion professional development beyond post-doctoral positions, including undergraduate and graduate students, out-of-field researchers, and international experts. Acquiring and retaining international experts for the domestic workforce critically depends on efficient availability of long-term visas and permanent resident status.

> **Recommendation R5-7:** Incorporate and integrate domestic/international undergraduates, graduate students, out-of-field experts, in-field post-docs and international experts, into funded research opportunities in order to grow the domestic fusion workforce. Pursue mechanisms to maximize efficiency in obtaining long-term visas and permanent residency for international fusion workers.

IX. Summary, Conclusions, and List of Recommendations

IX.1 Subcommittee Process and Outcome Summary and Conclusions

The Fusion Energy Sciences Advisory Committee (FESAC) was charged by DOE in July 2022 to provide an updated benchmarking of US international collaborations for fusion energy development, fundamental plasma science, and related technology areas, in order to identify opportunities in the coming decade. A FESAC subcommittee was formed to answer the DOE charges focusing on the needs and context of the Bold Decadal Vision (BDV), and including assessment of international collaboration opportunities, identification of optimal modes of international collaboration, identification of ways to leverage the growing private sector in fusion, assessment of US leadership status in key areas of fusion research, and identification of strategies to address US workforce needs including recruitment from traditionally underrepresented groups. The subcommittee identified subpanels from among its membership, organized around topical areas derived from the Community Planning Process and FESAC Long Range Plan [FESAC 2020] reports (see Sec. III). These topical panels convened experts to inform the elements addressed in the charges, assessed the status and motivations for international collaboration opportunities, and produced a set of findings and recommendations covering the wide range of questions resulting from the charges.

Several assumptions were identified to guide the deliberations of the subcommittee. These included the context of the BDV and the existence of growing domestic and international private sectors for fusion development, continuation of US participation in ITER during the ITER Research Program extending through the lifetime of the device, and provision of adequate levels of government-to-government agreement mechanisms to formally enable and provide frameworks for international fusion collaboration. Guidance was provided for the subcommittee to exclude ITER-specific collaboration from its explicit assessments, although consideration of ITER context for other collaborations (e.g. ITPA-driven joint experiments) was included in the process.

US domestic programs and resources remain essential to support progress in fusion development and the BDV, and cannot be replaced by international collaborations in general. However, international collaboration remains important to the advancement of US plasma and fusion science and realization of the BDV, and can strongly complement domestic efforts. The value and impact of such international collaborations is generally maximized by the existence and engagement of strong domestic fusion science and R&D programs. Key international collaborative opportunities complementary to US efforts include experimental programs, materials science and development research, balance of plant research to support development of power-producing fusion energy systems, technology development needed to enable an economically attractive and operationally feasible power plant, fundamental plasma science, and collaborations focusing on theory, simulation, control mathematics, advanced algorithms, and machine learning. Both the BDV energy mission and foundational plasma science goals can benefit significantly from international collaboration.

IX.2 List of Recommendations

This section collects and summarizes full texts of all Recommendations made throughout the report (**Table IX.2-1**). Although the corresponding Findings are not summarized here, and Recommendations are written so as to stand alone as actionable statements, it is important to consult the Findings and supporting discussion in appropriate sections to identify the context in which the Recommendations are being made.

Table IX.2-1. List of Recommendations

Key to Charges: 1=Opportunities, 2a=Potential for LRP/BDV, 2b=Maximizing Impact, 3=Private/Public Engagement, 4=US Leadership, 5=Workforce Development

Charge #	R #	Recommendation
1	R1-1	Prioritize support for collaborations primarily on KSTAR, EAST, MAST-U, JT60-SA, DTT, and ST80-HTS to close key gaps in design and operation of divertors, operational scenarios, and disruption avoidance and mitigation in conditions not available in the US: long pulses with high beta, higher B-field, metal walls, and different divertor geometries at high heat flux.
	R1-2	Expand collaboration with W7-X, and the programs of HELIAS and FFHR, to maximize opportunities to study core confinement in optimized stellarator configurations, validate modeling capabilities, and improve exchange of design workflows and capabilities.
	R1-3	Support international collaborations on alternative magnetic confinement concepts between domestic partners (university, national lab, private sector) and institutions outside of the United States where the US has no comparable domestic facility (e.g., those listed in **Table IV.1.2-3**).
	R1-4	Leverage US leadership in ICF through collaboration on complementary international facilities to help realize IFE.
	R1-5	Strengthen ties with IFMIF-DONES to enable US researchers (including private sector) to access prototypical fusion neutrons when the facility comes online. Consider international triple-ion beam irradiation facilities as a bridge to fusion prototypic neutron irradiation testing. See also **Finding F1-30**.
	R1-6	Leverage international tokamaks using EAST (existing) or COMPASS-U

		(under construction) and DTT (planned) liquid metal PFCs to advance US expertise and experience with liquid metal PFC's until NSTX-U installs a liquid metal divertor.
	R1-7	Leverage international collaboration with existing solid metal wall tokamaks such as AUG, WEST, EAST to advance US capability in fusion-relevant solid PFC's. Explore collaborations with planned tokamaks as they approach operational readiness.
	R1-8	Work with international partners with critical irradiation testing facilities to facilitate rapid implementation of bilateral programs and design, and develop protocols for ease of transport of irradiated materials across international research programs.
	R1-9	Target international collaboration on tritium breeding blanket, fuel cycle, and balance of plant technologies to leverage the resources of international partners and offer additional opportunities for US leadership.
	R1-10	Pursue the programmatic collaborations outlined by the 2020 technical workshop with the EU, in the areas of safety assessment, nuclear design integration, tritium permeation and handling, MHD flow in blankets, and waste management.
	R1-11	Collaborate with CEA/WEST (all Tungsten PFC's) to develop a knowledge base for ICRF impurity generation and mitigation in a device with Tungsten PFC's, and collaborate on and utilize the CEA ICRF test stand facility (TITAN) to study more fusion energy system-relevant RF launchers such as the traveling wave antenna.
	R1-12	Use reliable international suppliers of gyrotrons, such as those in Japan and Europe to supplement the supply chain, in order to overcome the limited capacity of the domestic market.
	R1-13	Enable US scientists and engineers to access key international laser facilities, e.g., ELI, etc... to exercise high repetition rate laser technologies and maintain currency with best practices. Support the foundational experimental and theory/simulation effort to continue advancing US laser technology for a wide range of applications.
	R1-14	Establish international collaborations at key laser facilities including ELI Beamlines/NP, DiPOLE, Fair, Apollon, CORELS, RT-1, to develop US

		expertise in high repetition rate science, and establish corresponding data workflows.
	R1-15	Support and utilize US-international networks (similar to, e.g., LaserNetUS, or X-lites) for the exchange of research opportunities and workforce.
	R1-16	Continue and expand US participation in ITPA as a framework for collaboration in joint experiments, theory, computational physics, and control. Support ITPA involvement beyond present "voluntary" effort to enhance the accessibility of ITPA participation for US institutions.
	R1-17	Facilitate collaboration on machine learning and artificial intelligence linked to world-leading laser facilities (both high and low repetition rate), and develop common interoperable metadata standards with international collaborators.
2a	R2a-1	Pursue collaborations involving KSTAR, EAST, MAST-U, JT60-SA, DTT, JET (latter focused on database analysis), and ST80-HTS, with high potential to close many key burning plasma and MFE-based fusion energy system design gaps to achieve the BDV [FESAC 2020, NASEM 2021], and to help prepare for ITER operation.
	R2a-2	Expand collaboration with W7-X to maximize opportunities to study steady-state divertor solutions, including core-edge solutions. Explore ways to accelerate W7-X experimental capabilities to address operation in a tungsten PFC environment on a timescale consistent with the BDV.
	R2a-3	Pursue collaborative research on international high repetition rate laser facilities to advance IFE physics and technology. Partner with other countries that possess laser, optical, materials, and processing expertise (e.g. Germany or UK) to co-develop crucial pre-competitive technologies, which have high potential to help realize the BDV.
	R2a-4	Facilitate international collaborations (including the private sector) on Magnum-PSI to test materials at high heat flux until MPEX is ready.

	R2a-5	Evaluate the suitability of the CHIMERA and H3AT facilities in the UK for testing US blanket concepts and ancillary systems. Pursue collaboration on these facilities if the evaluation is favorable, and if there is no clear path to construction and operation of a domestic facility on a decadal timescale.
	R2a-6	Support collaborations with both IPP-Garching and QST since the US does not have facilities capable of developing long pulse, high energy neutral beam technology.
	R2a-7	Collaborate with HFLSM (Tohoku University) and the Robinson Institute (New Zealand) to develop the manufacturing techniques to advance at-scale domestic manufacturing capabilities for REBCO tape, and take advantage of large-scale test facilities such as Sultan (Switzerland).
	R2a-8	Support collaboration on the development of high-frequency (> 200 GHz) gyrotron sources with facilities such as the Research Center for Development of Far-Infrared Region (University of Fukui), and the Karlsruhe Institute of Technology (KIT).
	R2a-9	Pursue international collaborations with CEA/IRFM, the Max-Planck Institute for Plasma Physics, and CCFE to develop/validate theoretical/computational models, as well as with UKAEA, Eurofusion/IPP (EU-DEMO), KFE (K-DEMO), QST (JA-DEMO) to jointly advance fusion device modeling and design capabilities.
	R2a-10	Pursue international collaborations in control and ML/AI with CREATE, DIFFER, and EPFL/SPC to complement and accelerate development of fundamental control mathematics and machine learning capabilities in US programs through joint research, and to help the US prepare for ITER operation.
2b	R2b-1	Construct strong frameworks for collaboration at time of initiation to include documentation of goals, team structure and roles, and mechanisms to run the collaboration that provide the needed communication and information flows.
	R2b-2	Ensure that experimental collaborations have clear coordination with the hosting institution at every level of collaboration and team, and a well-considered mix of on-site and remote experimental participation where

		appropriate. Where possible and beneficial, invite participation of international researchers in synergistic or complementary domestic experiments.
	R2b-3	Ensure that technology collaborations have clear and complete planning for all stages of the collaborative activity, including clear specification of roles, schedules, and deliverables, and explicit handling of intellectual property identification and invention provenance. They should include specific training to ensure competence in safety and procedures.
	R2b-4	Ensure that collaborations focused on theory, computational physics, mathematics, control, machine learning, algorithms, and data-intensive workflows have low administrative barriers to cyber access while maintaining sufficient security, high bandwidth, and low latency communication links, and employ modern tools and best practices to manage software development workflows and code coupling.
	R2b-5	Broaden support for international collaboration beyond present focus on multi-year, many-person, to include smaller-scale (down to person-to-person), short timescale (down to one year), and smaller-scope (down to single topic) collaborations.
	R2b-6	Establish and exploit international networks and agreements for collaborations focused on foundational and discovery plasma science for small- to mid-size facilities (e.g., a union of LaserNetUS + LaserLabEurope for key science goals), and maximize colocation of research team participants and visiting experimentalists and modelers for extended periods.
3	R3-1	Create a program that facilitates targeted collaboration between domestic private companies and international institutions engaged in fusion development which strikes a balance between openness and IP protection.
	R3-2	Create opportunities for private companies from abroad to collaborate in the US, while ensuring all activities stay consistent with DOE/government regulations for protecting assets as necessary.
	R3-3	Encourage US fusion community engagement with international companies primarily focused on fusion energy system goals, and also with international plasma science and technology companies with supporting technology goals.

4	R4-1	Clearly identify the anticipated roles in international collaborations in satisfying US national goals as part of a national strategy for technical advancement and leadership.
	R4-2	Keep the scientific process in ICF/IFE programs open as much as possible for international collaboration, and pursue collaboration with ELI to grow US repetition-rated laser expertise for ICF/IFE applications.
	R4-3	Review best practices in other industries and apply them to obtain the best return on public investment when supporting public-private partnerships and international collaborations for maintaining or establishing leadership.
	R4-4	Leverage international collaborations to facilitate access to large-scale fusion facilities to develop and maintain leadership in construction and operation, as well as to obtain good scientific output from such facilities.
5	R5-1	Expand domestic support for students at all levels of engineering, science, mathematics, and computer science, in order to grow the fusion workforce by many thousands of new dedicated staff in these areas over the coming decade. Provide a corresponding increase in the number of fusion undergraduate internships (e.g. SULI), graduate research opportunities (e.g. SCGSRs) and FES Postdoctoral Researcher Awards.
	R5-2	Provide sustained investments in increasing research capacities at MSIs and women-only academic institutions, e.g., by leveraging key DOE programs (FAIR and RENEW), and introducing dedicated international fellowship programs to MSIs. Support US-led community networks for expanding gender and ethnic, socio-economic, and learning-style diversity.
	R5-3	Invest in undergraduate curriculum, practicum, and technology development/enhancement in fusion and plasma science, including providing relevant laboratory infrastructure and instrumentation, computing assistance, and faculty professional development at targeted institutions including MSI's. Support holding topical summer schools to attract and prepare students for participation in fusion areas.
	R5-4	Enhance educational opportunities in discovery science programs in academia and national laboratories to grow the STEM workforce. Establish and support faculty and student exchange programs among domestic and

		international universities including MSIs, as well as research laboratories, over multi-year timescales.
	R5-5	Support enabling collaborative participation of US students and early career researchers with domestic and international private industry and public-program facilities via exchanges, internships, and detailee programs.
	R5-6	Support US students and early career researcher programs for engagement in international tradesmanship/apprenticeships in manufacturing, engineering, and technician training, including those not requiring advanced degrees, and supported by the creation of new regional US hubs.
	R5-7	Incorporate and integrate domestic/international undergraduates, graduate students, out-of-field experts, in-field post-docs and international experts, into funded research opportunities in order to grow the domestic fusion workforce. Pursue mechanisms to maximize efficiency in obtaining long-term visas and permanent residency for international fusion workers.

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Appendix A1: Subcommittee and Panel Membership

In order to divide the effort and focus attention of small teams on specific topical areas of key importance to fusion energy advancement and fundamental plasma science, the subcommittee identified a set of five panel areas and sorted all members into these panels. Leads were identified for each panel, and subcommittee members were free to select more than one panel to participate in. Some adjustment was made to ensure balance and sufficient effort of participation in each topic. **Table A1-1** summarizes the subcommittee membership, and the panels in which each participated and/or led.

Table A1-1. Subcommittee and Panel Membership

Last Name	First Name	Institution	Panel 1: Fusion Core	Panel 2: Materials /PWI	Panel 3: Balance of Plant	Panel 4: Technologies	Panel 5: Fundamental Plasma Science
Bonoli	Paul	MIT					
Casali	Livia	U. Tenn.					
Ferraro	Nate	PPPL					
Field	Kevin	U. Mich.					
Gleason	Arianna	SLAC					
Holcomb	Chris	LLNL					
Humphreys	Dave	GA					
Humrickhouse	Paul	ORNL					
Ma	Tammy	LLNL					
Magee	Rich	TAE					
Marian	Jaime	UCLA					
Murph	Simona	Savannah River Natl Lab					
Paz-Soldan	Carlos	Columbia U.					
Walker	Mitchell	Georgia Tech.					

Key: Green = Panel Lead; Yellow = Panel Member

Appendix A2: Acronyms

AI = Artificial Intelligence

ASCR = Advanced Scientific Computing Research

BoP = Balance of Plant

BDV = Bold Decadal Vision

BES = Basic Energy Sciences

CHIMERA = Combined HeatIng and MagnEtic Research Apparatus

CORELS = Center fOr Relativistic Laser Science

CPP = Community Planning Process

CRADA = Cooperative Research And Development Agreements

CW = Continuous Wave

DiMES = Divertor Material Exposure System

DiPOLE = Diode-Pumped Optical Laser for Experiments

EC = Electron Cyclotron

ECH = Electron Cyclotron Heating

ECRF = Electron Cyclotron Range of Frequency (or Radio Frequency)

ELI = Extreme Light Infrastructure

ICRF = Ion Cyclotron Range of Frequency (or Radio Frequency)

FAIR = Funding for Accelerated, Inclusive Research or Findable, Accessible, Interoperable, Reusable (data)

FES = Fusion Energy Sciences

FESAC = Fusion Energy Sciences Advisory Committee

FFHR = Force-Free Helical Reactor

FMEA = Failure Mode Effects Analysis

FOAK = First Of A Kind

FPNS = Fusion Prototypical Neutron Source

FPP = Fusion Pilot Plant

FRC = Field-Reversed Configuration

HBCU = Historically Black Colleges and Universities.

H3AT = Hydrogen-3 Advanced Technology facility

HED = High Energy Density

HELIAS = HELIcal Advanced Stellarator

HEP = High Energy Physics

HIBP = Heavy Ion Beam Probe

HTS = High Temperature Superconductor

ICF = Inertial Confinement Fusion

ICRH = Ion Cyclotron Resonance Heating

IFE = Inertial Fusion Energy

IFMIF = International Fusion Materials Irradiation Facility

IFMIF-DONES = IFMIF DEMO Oriented Neutron Source

IP = Intellectual Property

ITPA = International Tokamak Physics Activity

LHCD = Lower Hybrid Current Drive

LHRF = Lower Hybrid Range of Frequency

LRP = Long Range Plan

LTS = Low Temperature Superconductor

MD = Molecular Dynamics

MFE = Magnetic Fusion Energy

ML = Machine Learning

MPEX = Material Plasma Exposure eXperiment

MSI = Minority Serving Institutions

MTF = Magnetized Target Fusion

NASEM = National Academies of Science, Engineering, and Medicine

NBI = Neutral Beam Injection

NNSA = National Nuclear Security Agency

PFC = Plasma Facing Components

PIC = Particle-in-Cell

PMI = Plasma-Material Interaction

PSI = Plasma-Surface Interaction

PW = Petawatt

PWI = Plasma-Wall Interaction

R1 = Highly-funded research university, top tier in Carnegie Classification of Institutions

RAMI = Reliability, Availability, Maintainability, and Inspectability

REBCO = Rare-Earth Barium Copper Oxide

RENEW = REaching a New Energy Sciences Workforce or REsearch NEeds Workshop

RF = Radio Frequency

RFP = Reversed-Field Pinch

SciDAC = Scientific Discovery through Advanced Computing

SCGSR = DOE Office of Science Graduate Student Research Program

SOL = Scrape-Off Layer

ST = Spherical Tokamak or Spherical Torus

STEM = Science, Technology, Engineering, and Mathematics

SULI = Science Undergraduate Laboratory Internships Program

TBR = Tritium Breeding Ratio

VNS = Volumetric Neutron Source

WDM = Warm Dense Matter or Whole Device Modeling

WITS = Wall Interaction Test Station

Appendix A3: Experts Consulted and Additional Panel/Topical Results

A3.1. Fusion Core

Experts Consulted Included:

Name of Expert	Affiliation	Topics Addressed
Jose Boedo	UC San Diego	TCV
Ted Biewer	ORNL	JET
Rejean Boivin	General Atomics	JT60-SA
Nick Eidietis	General Atomics	KSTAR, EAST, WEST
David Eldon	General Atomics	KSTAR
Ursel Frantz	Max-Planck-Institut	Negative Ion Beams
Andrea Garofalo	General Atomics	EAST
Arianna Gleason-Holbrook	Stanford	Materials - Lasers
Zach Hartwig	MIT	Superconducting Magnets
William Heidbrink	U. California, Irvine	Energetic particles in tokamaks and STs
Stan Kaye	PPPL	ST40
Cornwall Lau	ORNL	WEST
Tammy Ma	LLNL	IFE collaboration opportunities and recommendations
Piero Martin	U. Padova	DTT
Novimir Pablant	PPPL	W7-X and LHD
Thomas Sunn Pedersen	Type One Energy	International stellarator collaborations, including participation of private companies
Mario Podesta	PPPL	SMART

Roger Raman	U. Washington	QUEST
Jorge Rocca	Colorado State University	International IFE collaborations, including the participation of private companies
Stephen Wukitch	MIT	ICH/ECH

Additional Panel/Topical Results:

	HSX	**TJ-II**	**LHD**	**W7-X (Stage III)**	**W7-X (Stage IV)**	**CFQS**
Status	Operating	Operating	Operating	Operating		Under construction. No public timeline for operation.
Volume (m3)	0.44	<= 1	30	30		
Coils	Copper	Copper	NbTi	NbTi		Copper
Optimization Principle		QI		QI		QA
max(B) (T)	1.25					
<B> (T)		1		2.5		1
R (m)	1.2	1.5	3.7	5.5		1
Pulse Length (s)			> 1 hr at 3 MW	100	1800	
Heating (MW)		ECRH: 0.6 NBI: 1.2	NBI(+): 24 NBI(-): 16 ICRH: 4.5	ECRH: 10 ICRH: 1.5 NBI: 10	ECRH: 15 ICRH: 3.5 NBI: 20	ECRH: 0.45 NBI: 1
<beta>			4.8% [*]			Surfaces up to 1.2%; Mercier stable up to 2.0%
Divertor	C	Testing liquid metals	C	C	C	

Facilities	Type	Characteristics/ Capabilities	Research Focus	Unique US Goals/Gains from Collaboration
TJ-II	Stellarator	Lithium-coated PFCs Flexible configuration	Impurity transport PMI	Could provide testbed for validation of

				impurity transport in unoptimized stellarator, and some data on liquid metal.
LHD	Stellarator	Superconducting		Low potential for future collaborations on the facility. Expecting to be limited in field and power going forward. Establishing collaborations to model extant data might be most useful.
W7-X	Stellarator	Superconducting Quasi-isodynamic Island divertor Steady-state at high power	Testing optimization Steady-state, high-power operation	Strong existing collaboration. US leadership on diagnostics and modeling. High-power, steady-state testing of divertor materials and detachment control. Validating theory of transport in optimized configurations.
CFQS	Stellarator	Quasi-axisymmetric	Testing quasi-symmetry	Low potential for collaboration. Design is modest and the US is not involved. Schedule is uncertain.
L-2M	Stellarator			

A3.2. Materials/PMI

Experts Consulted Included:

Name of Expert	Affiliation	Topics Addressed
Jurgen Rapp	ORNL	Materials/PMI
Aaro Jarvinen	VTT (Finland)	Materials/PMI

A3.3. Balance of Plant

Experts Consulted Included:

Name of Expert	Affiliation	Topics Addressed
Tom Barrett	UKAEA	UK Balance of Plant facilities and research
Seungyon Cho	KFE	KO Balance of Plant facilities and research
Gianfranco Federici	F4E	EU Balance of Plant facilities and research
Satoshi Konishi	Kyoto Fusioneering	JA Balance of Plant facilities and research

A3.4. Technology

Experts Consulted Included:

Name of Expert	Affiliation	Topics Addressed
John Caughman	ORNL	ICRF Technology
Ursel Fantz	IPP-Garching	NB Research and Development
Richard Goulding	ORNL	ICRF Technology
Zach Hartwig	MIT	HTS Magnet Technology
Dennis Whyte	MIT	HTS Magnet Technology
Stephen Wukitch	MIT	RF Source and System Development

A3.5. Fundamental Plasma Science

Experts Consulted Included:

Name of Expert	Affiliation	Topics Addressed

Sebastien Le Pape	LULI, France	Foundational Plasma Physics/WDM/exp facilities
Jonathan Zuegel	LLE, USA	Foundational Plasma Physics/WDM/laser technology
Matthew Hill	LLNL/AWE	Foundational Plasma Physics/WDM/exp facilities
Louise Willingale	University of Michigan	Foundational Plasma Physics/WDM/exp facilities
Alex Zylstra	LLNL	Foundational Plasma Physics/WDM/IFE

Appendix A4: Charge Letter to FESAC

Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

May 18, 2022

Professor Anne White
Head, Nuclear Science and Engineering Department
School of Engineering Distinguished Professor of Engineering
Massachusetts Institute of Technology
77 Massachusetts Avenue, 24-107
Cambridge, Massachusetts 02139

Dear Professor White:

Thank you for agreeing to serve as the Chair of the Fusion Energy Sciences Advisory Committee (FESAC). This is an exciting time for the fusion program as the Office of Science (SC) has started to implement many of the recommendations in the recent FESAC Long-Range Plan (LRP) report "Powering the Future: Fusion & Plasmas"[1] and as the Administration is developing a bold decadal vision for commercial fusion energy in partnership with the private sector. Your leadership of FESAC during this critical time for the fusion program will be very important for accelerating the development of a fusion-based carbon-free energy source for the Nation and the world.

To fulfill this promise and ensure that the U. S. will be a leader in this emerging energy technology, we must maintain and develop world-leading capabilities in multiple science and technology areas. At the same time, with the recognition that international collaborations have been a hallmark of the fusion program since its beginning, targeted and mutually beneficial collaborative activities on overseas facilities with unique capabilities should continue.

FESAC is requested to assemble a subcommittee to address the following questions:

- Since the last time FESAC assessed the opportunities afforded to U.S. scientists by international fusion facilities with unique capabilities[2], a number of new facilities have come online, and existing facilities have undergone significant upgrades. In what areas of research and on which facilities are there compelling opportunities for U.S. researchers over the next 10 years?
- What is the potential of these facilities to help U.S. scientists address priorities and recommendations in the LRP and the National Academies report on "Bringing Fusion to the U.S. Grid"[3], contribute to the Administration's bold decadal vision for commercial fusion, and increase the U.S. readiness for ITER operation? In addition, please assess whether the existing modes of collaboration are adequate for maximizing the impact of international collaborations on the U.S. fusion program and objectives.

[1] https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf
[2] https://science.osti.gov/-/media/fes/pdf/workshop-reports/20120309/Intl_Collab_Final_SCSC-PRINT.pdf
[3] https://nap.nationalacademies.org/catalog/25991/bringing-fusion-to-the-us-grid

- How can the U.S. take advantage of its considerable and growing fusion private sector in international engagements, and how can we cooperate with overseas public-private partnership programs that focus on accelerating the development of commercial fusion?
- Within the Fusion Energy Science-supported research areas and facility capabilities for fusion energy science and discovery plasma science, what are the areas where the U.S. is leading, the areas where U.S. leadership is threatened in the near- and long-term, and the areas in which U.S. is not leading at present but where investing resources could offer significant opportunities for leadership that would be beneficial to the U.S. fusion program goals and objectives?
- How can the U.S. ensure the availability of a highly trained and internationally competitive workforce in fusion science and technology and related areas, including the recruitment of talent from traditionally underrepresented groups within the U.S.?

We would appreciate receiving a written report from FESAC by Spring 2023. Please contact Dr. James Van Dam, Associate Director of the Office of Science for Fusion Energy Sciences, if there is anything we can do to help you in this process.

I appreciate FESAC's willingness to undertake this important activity.

Sincerely,

JOHN BINKLEY

Digitally signed by JOHN BINKLEY
Date: 2022.05.18 17:00:10 -04'00'

J. Stephen Binkley
Acting Director
Office of Science