FUSION ENERGY SCIENCES ADVISORY COMMITTEE
to the
U.S. DEPARTMENT OF ENERGY

PUBLIC MEETING MINUTES

Virtual Meeting via ZOOM
May 25, 2022

Fusion Energy Sciences Advisory Committee Meeting
May 25, 2022

The U.S. Department of Energy (DOE) Fusion Energy Sciences Advisory Committee (FESAC) convened on Wednesday, May 25, 2022 via videoconference from 10:30 a.m. - 3:45 p.m. Eastern Time. The meeting was open to the public and conducted in accordance with the requirements of the Federal Advisory Committee Act (FACA). Information about FESAC and this meeting can be found at https://science.osti.gov/fes/fesac.

Committee Members Present

Dr. Anne White (Chair), Massachusetts Institute of Technology (MIT)
Dr. Troy Carter, University of California, Los Angeles
Dr. Stephanie Hansen, Sandia National Laboratories (SNL)
Dr. Paul Humrickhouse, Oak Ridge National Laboratory (ORNL)
Dr. Charles Kessel, ORNL
Dr. Stephen Knowlton, Professor Emeritus, Auburn University
Dr. Carolyn Kuranz, University of Michigan
Dr. Tammy Ma, Lawrence Livermore National Laboratory (LLNL)
Dr. Richard Magee, TAE Technologies
Dr. Rajesh Maingi, Princeton Plasma Physics Laboratory (PPPL)
Dr. Simona Murph, Savannah River National Laboratory (SRNL)
Dr. Scott Parker, University of Colorado
Dr. Don Rej, Los Alamos National Laboratory (LANL)
Dr. Susana Reyes, SLAC National Accelerator Laboratory (SLAC)
Dr. Fred Skiff, University of Iowa
Dr. Philip Snyder, ORNL
Dr. Paul Terry, University of Wisconsin-Madison
Dr. Mitchell Walker, Georgia Institute of Technology
Dr. Brian Wirth, University of Tennessee

Committee Members Absent

Dr. Ralph Izzo, Public Service Enterprise

Group, Inc. (PSEG)
Dr. Lorin Matthews, Baylor University
Dr. Thomas Sunn Pedersen, Max-Planck Institute of Plasma Physics

Ex Officio Members Present

Dr. Paul Wilson, American Nuclear Society (ANS), Fusion Energy Division, University of Wisconsin-Madison
Dr. Denise Hinkel, American Physical Society (APS), Division of Plasma Physics (DPP), LLNL

Ex Officio Members Absent

Dr. John Verboncoeur, Institute of Electrical and Electronics Engineers, Nuclear and Plasma Sciences Society (IEEE NPSS), Michigan State University

DOE Personnel Present:

Dr. Stephen Binkley, Principal Deputy Director, DOE Office of Science (DOE SC)
Dr. James Van Dam, Associate Director, Fusion Energy Sciences (FES), DOE SC
Dr. Sam Barish, Designated Federal Officer, FES, DOE SC

Approximately 237 individuals were present for all or part of the meeting.

Wednesday, May 25, 2022

Welcome and Opening Remarks, Dr. Anne White, Chair, Massachusetts Institute of Technology and Dr. Sam Barish, Designated Federal Officer, Fusion Energy Sciences

Dr. Barish convened the meeting at 10:32 a.m., thanked Dr. Rej for his six years of service as FESAC Chair, and introduced Dr. White as the new Chair.

Dr. White welcomed attendees, highlighted recent events and reports relevant to FES activities, and reviewed upcoming changes to FESAC membership on June 2, 2022.

Introduction of the Under Secretary for Science and Innovation, Dr. Stephen Binkley, Principal Deputy Director, Office of Science

Dr. Binkley introduced Dr. Geraldine Richmond.

News from the Under Secretary for Science and Innovation, Dr. Geraldine Richmond, Under Secretary for Science and Innovation (pre-recorded remarks)

Dr. Richmond thanked FESAC members for their service and acknowledged the passing of Dr. Bernard Bigot, head of the ITER project.

Fusion energy is a major priority for this Administration and DOE leadership. To realize net-zero carbon dioxide emission goals by 2050, all clean energy avenues must be explored, including fusion. The White House Fusion Summit held in March 2022 celebrated fusion research and development (R&D) progress thanks to sustained bipartisan Congressional support over the past decades. Operations are transitioning to a new era where fast growing private sector interest is underpinned by fundamental science and technology research efforts. FESAC's 2020 Long-Range Plan (LRP), entitled *Powering the Future: Fusion & Plasmas,* was produced in concert with the fusion and plasma science community and is guiding the program direction. Also, the National Academies of Sciences, Engineering, and Medicine (NASEM) report on *Bringing Fusion to the U.S. Grid* was the subject of one of the first briefings given to the President's Council of Advisors on Science and Technology (PCAST) in 2021. Both reports recommend harnessing public-private partnerships (PPPs) to accelerate fusion energy development.

All must work together to overcome fusion energy's remaining challenges, including fostering a community representative of this country's diversity. Fusion commercialization will require a creative research enterprise with the private sector accompanied by public engagement to develop acceptance. Led by Dr. Richmond's office, DOE has established a new fusion cross-cutting team. Future budget requests will be coordinated across the entire department to support fusion's bold decadal vision. A DOE-funded workshop focused on PPP development will be hosted in June 2022 with participation from DOE, national laboratories, universities, the private sector, and other public partners. Congress has appropriated fiscal year (FY) 2022 funding to launch a fusion development program.

Today, FESAC will receive an SC charge on international benchmarking and collaborations in the field of fusion. The fusion community has collaborated internationally for decades, and the U.S. and Japan recently issued a report describing 40 years of bilateral activities. The U.S. also collaborates with six other international partners on ITER. The charge encourages consideration of international collaboration towards fusion energy's decadal vision while assessing U.S. leadership in an international arena.

Award Conferral, Dr. Stephen Binkley, Principal Deputy Director, Office of Science

Dr. Binkley conferred a Secretary of Energy Appreciation Award to **Dr. Rej** for his tenure and service as FESAC chair from 2016 - 2022. FESAC members offered their thanks.

FES Perspective, Dr. James Van Dam, Associate Director, Fusion Energy Sciences

The White House Fusion Summit held on March 17, 2022 included stakeholders from government, private sector, energy justice, and non-profit communities. More than 1200 individuals live-streamed the meeting. The U.S. is committed to leading development of commercial fusion energy in partnership with the private sector with concomitant needs for sustainable, carbon-neutral energy; energy justice; and diversity, equity, and inclusion (DEI) in the fusion workforce. Pursuit of a bold decadal fusion energy mission will be supported by in-depth stakeholder engagement to define metrics and technology roadmaps for PPPs. Dr. Scott Hsu has been appointed the Lead Fusion Coordinator of the new fusion crosscutting team in the Office of the Undersecretary for Science and Innovation (S4) with the White House Office of Science and Technology Policy (OSTP). Future budget requests will be coordinated across the DOE, and a funding opportunity announcement (FOA) for a milestone-based cost-share program is being prepared.

The enacted FY2022 FES budget totals $713M, with $308.23M allocated to Research; $125.27M to Facility Operations; $278M to Projects; and $1.5M to Other Activities. Within this budget, $25M is dedicated to starting the milestone-based cost-share program.

The FY2023 Request seeks $723.222M, with $337.722M dedicated to Research; $129M to Facility Operations; $255 to Projects; and $1.5M to Other Activities.

In FY2023, FES will participate in all SC cross-cutting initiatives with the exception of the Accelerator Science and Technology initiative for which FES has completed its obligations. The Request allocates $2M for Advanced Computing; $11M for Artificial Intelligence and Machine Learning (AI/ ML); $3M for Fundamental Science to Transform Advanced Manufacturing; $5M for Microelectronics; $10M for Quantum Information Science (QIS); $6M for Reaching a New Energy Sciences Workforce (RENEW); $2M for the new Funding for Accelerated Inclusive Research (FAIR) initiative; and $6M for the new Accelerate Innovations in Emerging Technologies initiative. Within the FY2023 Request, $25M is again sought for the milestone-based cost-share program, bringing the total funding level across FY2022 and FY2023 to $50M and slightly surpassing the LRP's recommended level of $45M. The FY2023 Request also budgets for an Inertial Fusion Energy program.

The FY2024 Budget Request is under preparation in the context of the LRP recommendations, the White House Summit's bold decadal vision, and Congressional authorizations pointing future opportunities.

Applications are under review for the Opportunities in Frontier Plasma Science and Collaborative Research on International and Domestic Spherical Tokamaks FOAs. Full applications for Collaborative Research in Magnetic Fusion Energy Sciences on International Tokamaks are due June 2, 2022. Award selection is in progress for High Energy Density Laboratory Plasma Science and National Science Foundation (NSF)/ DOE Partnership in Basic Plasma Science and Engineering. SC will soon publicly announce selected awardees for the SC Early Career Research Program (ECRP). The forthcoming FES RENEW FOA will fund ~20 projects targeted to increase the research participation and retention of underrepresented groups.

The U.S. ITER Subproject-1 is 67% complete. Subproject-2 will be re-baselined in September 2023. The international ITER project is 73% complete towards First Plasma. To date, 93% of fabrication awards for the U.S. ITER project remain in the U.S; as of June 2021, funds spent in the U.S. totaled ~$1.4B, with ~$729M, ~$26M, and ~$506M awarded to industry, universities, and national laboratories, respectively. Senator Joe Manchin visited ITER in March 2022. The 11th ITER International School will be held July 25-29, 2022 and focus on ITER Plasma Scenarios and Control.

The third Computational Physics School for Fusion Research is scheduled for August 22-27, 2022. The 33rd International Union of Pure and Applied Physics (IUPAP) conference in Computational Physics will be held July 31-August 4, 2022 and will include a session on plasma and fusion physics.

The DIII-D National Fusion Facility (DIII-D) at General Atomics is pursuing a two-year, 40-week research program through FY2022-FY2023. The FY2022 program is 23% complete. FES and General Atomics are improving DIII-D user agreements to allow private industry to use facilities for non-proprietary and proprietary purposes.

In Spherical Tokamak research, toroidal field bundle replacement will delay National Spherical Torus Experiment Upgrade (NSTX-U) Recovery completion by more than a year. A new cost and schedule baseline is planned for this summer. Record temperatures were achieved in the compact Spherical Tokamak 40 (ST40). A final report identifies areas of consensus across DIII-D, Joint European Torus (JET), and Korea Superconducting Tokamak Advanced Research (KSTAR) studies of shattered pellet injection for ITER disruption mitigation.

MPEX currently resides at critical decision 3A (CD-3A); an Energy System Acquisition Advisory Board (ESAAB) review for CD2/3 is planned for September 2022. Project completion (CD-4) is anticipated in January 2028 at an estimated total project cost (TPC) of $183M. MEC-U is currently holding CD-1 with CD-4 anticipated in FY2029 at an estimated TPC of $264M-$461M.

Now in its fourth year, the Innovation Network for Fusion Energy (INFUSE) program, has issued 47 awards totaling $9.3M to nine DOE national labs in collaboration with 17 fusion companies. A pilot program for university participation was launched in FY2022. Selections for the FY2022 First Round Request for Assistance call will be announced shortly.

The *Special Report on the Occasion of the 40th Anniversary of the Japan/ U.S. Fusion Research Collaboration* summarizes cooperation spanning 2011-2020.

In Theory and Simulation, the nine FES multi-institutional Scientific Discovery through Advanced Computing (SciDAC) partnerships are being extended for a sixth year. Portfolio re-competition is scheduled for FY2023; work will expand from whole device to whole facility modeling towards a fusion pilot plant (FPP).

AI/ML FY2022 efforts will consider a data center, and FY2023 plans will begin a new three-year award cycle. FES has supported six one-year pilot studies in randomized methods, plasma pulse design, stellarator optimization, detached divertor models, inertial confinement fusion, and physics-informed neural networks for disruption prediction. New ML descriptors have improved the accuracy of atomistic materials simulations. In QIS, new quantum algorithms have finally cracked nonlinear equations which will support the study of fusion plasmas.

The Energy Science Network (ESnet) conducted an FES Network Requirements Review in FY2021. A final report is expected soon.

The third LaserNetUS Users meeting is scheduled for August 2022. The University of Michigan recently left the network, and the University of Central Florida joined. In total

LaserNetUS has more than 1200 members representing 123 institutions of which 88 are in the U.S. The network is pursuing a memorandum of understanding (MOU) with LaserLabEU. Two relatively new research networks recommended by the LRP have been formed. MagNetUS is a network of magnetized plasma experimental facilities for basic plasma science established in 2021. The second Annual Users Meeting is scheduled for June 2022. ZNetUS is a consortium of universities, labs, and industry for pulsed power Z-pinch science and technology research formed in 2020. The second ZNetUS Workshop was held in April 2022.

Three FES Basic Research Needs (BRN) workshops, pending DOE approval, will address: 1) Inertial Fusion Energy (June 2022); US ITER Research (July 2022); and Plasma Science for Microelectronics Fabrication (August 2022).

The International Atomic Energy Agency (IAEA) Department of Nuclear Energy is seeking a nuclear expert to lead fusion reactor technology activities and coordinate collaborative projects within and outside of the United Nations as part of the Peaceful Uses Initiative.

PPPL's virtual 2022 Young Women's Conference in Science, Technology, Engineering, and Mathematics, held in May 2022, engaged ~300 seventh-to-tenth-grade students.

SC released a report from a 2021 Roundtable entitled *Supply Chain Risk Mitigation for Scientific Facilities and Tools.*

The U.S. Fusion Energy website (https://usfusionenergy.org/) was organized and designed by the U.S. fusion community in alignment with the LRP. The site provides the fusion community and the general public with an introduction to and general education on fusion and plasma science; current news and events; sciences supported by government and industry; and student engagement and research opportunities.

FES has scheduled a briefing with Dr. Asmeret Berhe, the SC Director as of May 2022.

Discussion

Dr. Carter asked about the new milestone-based cost-share program and the MOU for an NSF/DOE partnership. **Dr. Van Dam** said meetings addressing the PPP program are ongoing, and an FOA will be released. Congress and the White House Office of Management and Budget (OMB) have given FES a special exception to disburse FOA funds in early FY2023. The MOU is in progress, and NSF is organizing a workshop.

Dr. Kuranz inquired about the FY2022 MEC-U budget which has decreased by $10M relative to that of FY2021. This project promises great science. However, European X-ray Free Electron Laser (XFEL) activities suggest the U.S. has already lost leadership in this important area. Hopefully, the U.S. can resume leadership. **Dr. Van Dam** confirmed the budget places MEC-U on pause. FES had to operate within FY2023 budget confines, and MEC-U costs have increased due to the need for an underground chamber. There is fierce international competition in this area; the U.S. wants to remain the leader, but budget constraints are real. There is potential for a partnership with the National Nuclear Security Agency (NNSA). SC leadership is aware of this situation and is working with SLAC, LLNL and the University of Rochester. Every year, FES generates three budget scenarios: target, decrement, and growth in the budget preparation process. FES is focusing attention on a growth scenario for FY2024.

The Path Forward after the White House Summit on Fusion, Dr. Scott Hsu, Senior Advisor and Lead Fusion Coordinator, Office of the Under Secretary for Science and Innovation

The White House Fusion Summit pointed to decadal steps to fusion commercialization, with net energy gain developments in the 2020s; materials, fuel cycle, and enabling technology

advancements from the 2020s to the mid-2030s; launch of FPP(s) and first-of-a-kind (FOAK) plant(s) from the 2030s to 2040; and aggressive commercial deployment from the mid-2030s towards 2050. Growth in private funding, which significantly exceeded DOE FES funding for the first time in 2021, signals a strong market pull and fusion's technical readiness to move forward with development and demonstration. Strategies for PPPs and government investment are being guided by the 2021 NASEM report and other models of successful PPPs. Resultant PPPs will focus on the LRP's highest R&D priorities. Plans align with enacted legislation, including the Energy Act of 2020 and Division D of the FY2022 Appropriations Act.

A DOE Workshop on Fusion Energy Development via Public-Private Partnerships is scheduled for June 1-3, 2022. This meeting will bring together R&D and commercialization stakeholders to (1) outline policy or legislative actions to clear the path to commercialization; (2) align public- and private-sector fusion R&D activities; and (3) advance plans for the milestone-based fusion-development program in partnership with the private sector.

In addition to representation from S4 (Dr. Scott Hsu), the new Fusion Crosscut Team includes leadership from FES (Dr. James Van Dam) and Advanced Research Projects Agency-Energy (ARPA-E, Dr. Sam Wurzel). Other represented offices include: NNSA (NA-113 Inertial Confinement Fusion); the SC offices of Basic Energy Sciences (BES) and Advanced Scientific Computing Research (ASCR); the Office of Nuclear Energy (NE); the Office of Economic Impact and Diversity (ED); and the Office of Environmental Management at the Savannah River Site (SRS). Engagement of additional offices may involve the Office of Technology Transitions (OTT), the Organization for Economic Co-operation and Development (OCED), NNSA (NA-20 Nonproliferation); and the Office of Cybersecurity, Energy Security, and Emergency Response (CESER). Immediate team priorities include facilitation of the milestone-based fusion-development program via use of Other Transaction Authority (OTA) for desired flexibilities; launch of the Fusion Crosscut Team for development of a DOE-wide strategy; coordination of the FY2024 budget request; development of sustainable programmatic models for labs and universities to contribute to FPP RD&D in partnership with the private sector, DEI and energy justice initiatives; and external partnerships.

Discussion

Dr. Ma asked if the upcoming PPP workshop will be recorded or accessible via a public webinar. The Inertial Fusion Energy BRN will be interested. **Dr. Hsu** explained the difficult decision was made not to record or live stream the workshop to ensure those present will speak freely and candidly. A publicly available summary will be posted after the workshop.

Dr. Magee called attention to language citing FPPs, noting the LRP timeline typically includes one FPP. **Dr. Hsu** relayed that language surrounding FPPs is guided by the NASEM report which calls for solicitation and selection of multiple teams. The federal government is recommended to support teams as long as they make progress towards milestones, and targeted federal investments continue to attract needed private sector investments. The number of FPPs supported through PPPs should not be predetermined but rather limited by federal budgets and appropriations. All paths to FPPs will be driven by PPPs.

Dr. Carter commented that OTA is a heavy lift but is important to enable the decadal timeline. **Dr. Hsu** remarked that the recent QIS FOA included provisions for the OTA mechanism, though none were ultimately needed. Work is currently focused on exploring whether OTA can be included in the FOA language. Promises cannot be made at the moment.

The U.S. Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) are providing mentorship, though their authorities differ from the DOE's.

Dr. Walker observed PPPs are a great way to accelerate progress as seen with NASA. However, there is typically a mass extraction of government talent to accelerate private progress. **Dr. Hsu** acknowledged immediate challenges of workforce limits. In the long term, the situation will hopefully not be viewed as the private sector stealing from the government sector, and people going from the public to private sector will be seen as positive. The work pipeline must be grown aggressively in R&D as well as for engineers and technicians. Recruitment must include vocational schools and retraining of workers affected by the energy transition. Efforts are already leveraging SC programs and considering new ones.

Dr. Terry voiced concerns that science and physics that do not naturally fit within milestone-based initiatives and may fall by the wayside. Essential activities are already under stress. Going forward, obstacles may not be surmounted unless a developed, underlying understanding enables solutions. **Dr. Hsu** came to this position from the fundamental plasma science side of the portfolio and will work closely with FES on this issue. A broad base of ideas is needed, and discovery science and foundational fusion science and enabling technology activities must continue. Identifying which parts of fusion science and technology activities are foundational without attached timelines or milestones may be more challenging than for discovery science. How to structure efforts are topics for discussion at next week's workshop as well as ongoing dialogue with FES. There is recognition that R&D challenges must be solved; this is not merely an engineering problem. New innovations are needed for an economically viable FPP.

Discussion

Dr. Snyder inquired about the transition to PPPs and ensuring concepts championed by the public program are not lost. **Dr. Hsu** indicated the best ideas from the public sector are needed. However, future efforts may focus less on the public sector pushing a specific concept and more on finding ways for the best public sector ideas to support the private sector. Private teams may be stood up around ideas like a sustained stellarator or laser inertial fusion energy. Or, the best ideas from the public sector may integrate into leading private sector paths. Partnering is important to realizing the decadal FPP vision enabled by private capital.

Dr. Reyes questioned how R&D investments will be prioritized without clearly defined end products. **Dr. Hsu** referred to the NASEM report which advised selecting two to four teams, each with a defined end product and technology roadmap. The technology roadmaps from selected teams will be prioritized, and the areas with technology overlap will receive the highest priority. NASEM's vision does not delineate a single endpoint. The private sector will define the market product.

Dr. White dismissed the meeting at 12:19 p.m. for lunch and reconvened at 1:00 p.m.

Exascale Computing Project, Dr. Douglas Kothe, Director, Exascale Computing Project, Oak Ridge National Laboratory

The $1.8B Exascale Computing Project (ECP) is a critical component of the broader U.S. Exascale Computing Initiative involving more than 80 R&D teams from six core DOE national laboratories, universities, and industry. The ECP Council engages members from five federal agencies and efforts includes industry. The ECP has launched a series of HPC systems at DOE

national laboratories, beginning with Titan at ORNL in 2016 and moving to delivery of the ~1.5-exaflop Frontier system at ORNL in 2022. Two additional exascale systems, Aurora and El Capitan, are scheduled for access in 2023 at ANL and 2024 at LLNL, respectively. Each HPC system has enabled progression of the ECP's three core teams. Application Development (AD) has stood up six co-design centers and generated 24 applications spanning a broad range of science, engineering, security, and health domains critical to the DOE's mission. Potential outcomes are far reaching, and many of these applications directly relate to fusion science and technology. Software Integration (SI) has created 70 unique products comprising a vertically integrated software stack. Hardware and Integration (HI) has engaged six U.S. vendors in continuous testing and delivery of ECP products at leading DOE HPC facilities.

As a milestone-based DOE Order 413.3B project, each ECP team is required to meet Key Performance Parameters (KPPs). KPP-1 and KPP-2, respectively, address the success of ECP applications teams in demonstrating challenge problems on first-of-a-kind exascale systems designated as mission critical or broadening the reach of exascale science and mission capabilities. KPP-3 and KPP-4 address SI and HI evaluation, respectively. The Summit system delivered at ORNL in 2018 has served as the primary development platform for applications with Frontier acting as the target system for KPP demonstration. Summit performance of several KPP-1 applications has greatly exceeded expectations of a 50x improvement. Most increases in performance are attributable to changes in algorithms, data structures and software architectures.

The AD team has targeted 13 application motifs representing common patterns of computation and communication: (1) Dense linear algebra; (2) Sparse linear algebra; (3) Spectral methods; (4) N-body methods (particles); (5) Structured grids; (6) Unstructured grids; (7) Monte Carlo; (8) Combinatorial logic; (9) Graph traversal; (10) Graphical models; (11) Finite state machines; (12) Dynamic programming; and (13) Backtrack and branch-and-bound. Additionally, seven computational functions have emerged as vital enablers of massive data analysis: (1) Basic statistics; (2) Generalized N-body problem; (3) Graph-theoretic computations; (4) Linear algebraic computations; (5) Optimization; (6) Integration; and (``7) Alignment problems. ECP's six co-design centers are advancing motifs as well as ML and deep learning to augment workflows.

Science highlights featured select applications (WarpX, EXAALT, and WDMApp) applied to FES-relevant problems and examples of the ExaLearn Co-Design Center capabilities in addressing tokamak fusion.

ECP's Extreme-Scale Scientific Software Stack (E4S) packages the latest ECP software technology products in software development kits (SDKs). The most recent E4S quarterly release in February 2022 includes 100 products using the Spack package manager. E4S is advancing the ECP's goal of a sustainable, reusable software ecosystem that lowers barriers to new technology adoption and porting to advanced hardware.

ECP's dependency database tracks internal and external dependencies.

The multipronged ECP Broader Engagement Initiative will expand the pipeline and workforce for DOE HPC. Efforts will engage talented people from underrepresented groups, influence DOE culture, and provide accessible introductory HPC materials to the community. Actions will leverage ongoing activities via the Sustainable Horizons Institute, DOE-wide and laboratory-specific programs, and local and regional HPC communities. These engagement efforts are anticipated to continue through ASCR following the ECP's conclusion.

Discussion

Questions held for public comment.

The U.K. Fusion Programme and an Update on the Spherical Tokomak for Energy Production (STEP) Programme, Professor Ian Chapman, Chief Executive Officer, U.K. Atomic Energy Authority; Head, Culham Centre for Fusion Energy

The 2021 United Kingdom Atomic Energy Authority (UKAEA) strategy report, entitled *Towards Fusion Energy,* sets the overarching goals of (1) demonstrating the commercial viability of fusion by building a prototype fusion power plant in the U.K. that puts energy on the grid; and (2) building a world-leading fusion industry which can export fusion technology globally in the following decades. A subsequent 2021 Green Paper, *Regulatory Horizons Council Report on Fusion Energy*, outlines plans to form a fusion regulatory framework and supports a pro-innovative and internationally-collaborative approach. The recent Queen's speech supported these measures now incorporated in the Energy Security Bill.

JET set a new fusion power record in February 2022.

The Mega Amp Spherical Tokamak Upgrade (MAST-U) was completed in 2021 and received the Royal Academy of Engineers Major Project Award for that year. The first experimental results show that the Super-X divertor reduced heat by more than a factor of 10 as predicted.

The Materials Research Facility (MRF) allows irradiated materials testing at small scale. UKAEA is building an ~$35M magneto-thermal hydraulics test facility, the Combined Heating and Magnetic Research Apparatus (CHIMERA), to test components at the meter scale and under combinatorial loads. CHIMERA operations are projected for 2023.

A new 100-gram tritium research facility called Hydrogen-3 Advanced Technology (H3AT) is also under construction. The facility will accommodate storage, production, separation, and extraction techniques.

The Remote Applications in Challenging Environments (RACE) robotics facility supports fusion activities and adjacent areas. Its research aims to develop enabling technologies where there is no overlap with industry, like in-bore laser pipe cutting, welding and alignment for plant design, or in-vessel movers for blankets or divertors. Complementary control systems are under development.

The UKAEA has greatly expanded its training program for the next workforce generation. At present, ~35 universities and 13 Centres for Doctoral Training are supporting 150 PhDs. The UKAEA has also generated a multi-award-winning apprentice scheme that matches skilled individuals with more than 20 industrial partners. Currently, 280 apprentices are in training with funding secured to expand this number to 1000 by 2025.

STEP is taking a high-risk approach to delivering predictable net energy production for the grid at a lower capital cost than other fusion power plant designs by 2040. The £220M investment for concept design by 2024 is already a national endeavor involving 290 companies and more than 20 universities. The selected site announcement is expected in late 2022. STEP will harness at least three partners consisting of the UKAEA, a facility construction partner, and a technology and engineering partner. Delivery will be conveyed through a special purpose vehicle operating as a company limited by shares, subject to approval. There are opportunities for a closer U.S. relationship in the future.

Discussion

Dr. Carter expressed enthusiasm for future collaboration at new test facilities. **Dr. Chapman** is supportive of collaborations; the U.S. and the U.K. have a history of complementing each other to reduce duplication. The U.K. is open to discussion regarding access to its test facilities in return for access to U.S. facilities.

Dr. Reyes asked if FES has considered adopting a project structure similar to STEP's towards development of an FPP. **Dr. Van Dam** explained that the U.S. program differs from STEP because of greater U.S. private sector funding compared to U.K. levels. STEP is a PPP funded mostly by the public sector. However, the U.S. will pursue technology development roadmaps; the UKAEA is ahead in this domain. FES will meet with the UKAEA shortly.

Dr. Magee requested more information about STEP's PPP. **Dr. Chapman** commented that the UKAEA uses public funds to subcontract construction vendors and has collaboration agreements with industry. The Delivery Organization currently envisions a sweat equity model, potentially with cash investment in the future. Public procurement will run an open process for partner selection. As opposed to U.S. activities where private money is a prerequisite, the U.K. is prepared to use public funds to bankroll the FPP.

Dr. Maingi asked whether other international partners are interested in STEP. **Dr. Chapman** relayed that discussions with the U.S. are more advanced than with any other partner. STEP has had exploratory conversations with some European states and Asian ITER partners.

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FESAC Charge on Collaborations on International Fusion Facilities, Dr. Anne White, Chair, Massachusetts Institute of Technology

FESAC has been charged to form a subcommittee to conduct an international benchmarking exercise addressing FES's research, facilities, LRP, decadal vision, and workforce pipeline. The subcommittee will: (1) identify areas of research and facilities presenting U.S. opportunities over the next decade; (2) determine the potential of these facilities to address the LRP and NASEM report recommendations towards the Administration's decadal fusion vision and increase U.S. readiness for ITER operation; (3) evaluate whether existing modes of collaboration are adequate for maximizing the impact of international collaborations on the U.S. fusion program and objectives; (4) offer guidance on how the U.S. can take advantage of the growing fusion private sector in international engagements and cooperate with overseas PPPs; (5) identify FES-supported research areas and facility capabilities for fusion energy science and discovery plasma science where the U.S. is leading, where U.S. leadership is threatened in the near- and long-term, and where investments could offer significant leadership opportunities beneficial to U.S. goals and objectives; and (6) determine how the U.S. can 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.

Discussion

Dr. White called attention to the 2012 report entitled *Opportunities for and Modes of International Collaboration in Fusion Energy Sciences Research during the ITER Era.*

Dr. Van Dam relayed that FACA committees from BES, the Office of High Energy Physics (HEP), the Office of Biological and Environmental Research (BER), and ASCR have received similar charges. BES's report, completed last year, has already impacted Congress. **Dr. Maingi** requested more information on impacts. **Dr. Van Dam** stated that Congress is aware that

facility funding is restricted and resources became tighter during the pandemic. BES has many user facilities, and the report showcases which are leading and which need upgrades.

Dr. Carter emphasized the importance of considering how collaborations can enable future facilities. **Dr. White** agreed, pointing to charge language calling for identification of areas where U.S. leadership is threatened in the near- and long-term.

Dr. Kessel suggested strong emphasis on facilities and materials for fusion science, technology, and engineering. **Dr. White** acknowledged comments and invited suggestions for other topics to spotlight. **Dr. Van Dam** remarked that the charge addresses all FES portfolio areas, including discovery plasma science, high energy density research, and inertial fusion energy.

Dr. Kuranz sought clarification on subcommittee composition, including international participation, and recommended including individuals with XFEL or MEC expertise. Europe is investing heavily in high intensity lasers. This is an area where the U.S. is quickly falling behind. **Dr. White** explained that the subcommittee need not consist only of FESAC members. Nominations are welcome. **Dr. Van Dam** added that the subcommittee chair does not need to be a FESAC member. Selections can include incoming FESAC members. **Dr. Barish** said it remains to be determined if the subcommittee will mostly compromise U.S. nationals examining international context or if the subcommittee will seek international members to advise on the global arena.

After voicing support for inclusion of international subcommittee members, **Dr. Carter** called attention to charge language addressing U.S. cooperation with overseas PPPs. **Dr. Van Dam** observed that national efforts are now focused through the lens of PPPs, so international PPPs should also be considered. Though intellectual property introduces challenges, collaborations with private companies are possible. Examples include Cooperative Research and Development Agreements between Princeton University, ORNL, and Tokomak Energy. **Dr. John Mandrekas** (FES) led charge formulation. The charge asks how FES can cooperate with overseas PPPs. Cooperation is a key word. There has already been some discussion today with Dr. Ian Chapman.

Dr. Maingi asked whether the charge desires the subcommittee to investigate collaborating with other overseas models like STEP, or if the charge is asking about possible new connections from either U.S. public or private sectors to overseas public or private sectors. **Dr. Mandrekas** indicated the charge covers both possibilities. **Dr. Van Dam** noted that STEP is a premier example of an overseas PPP. FES held a bilateral meeting with Japan which is also moving towards PPPs. China is considering similar directions.

Dr. Terry cited charge language asking how the U.S. can take advantage of its fusion private sector in international engagements. The U.S. can offer compelling areas of collaboration to people and companies outside of the U.S. Hopefully, the subcommittee will interpret relevant text as encompassing the entire range of engagement possibilities and not those limited to PPPs. Including individuals from private companies on the subcommittee may assist with intellectual property issues. **Dr. Van Dam** observed that Dr. Chapman touched on a similar point. No matter what platform is under development, there are many shared facility and R&D needs. This is why the NASEM report was written to be concept agnostic. There are opportunities to leverage international efforts and piggyback on existing facilities to develop the needed capacities shared by different concepts.

Dr. Hansen suggested coordinating with NNSA to ensure boundaries are respected and asked whether codes are part of the charge. **Dr. Van Dam** remarked that many NNSA labs

possess both expertise and facilities useful to this effort. FES respects NNSA's mission but will work to leverage assets. For example, the National Ignition Facility (NIF) allocates a small but significant fraction of its time to general science experiments. The U.S. has many splendid codes as discussed by Dr. Kothe. For instance, PPPL supports other users of the TRANSP code without sharing source code information. This code was used by JET. Greater care is taken with sharing neutronics codes. **Dr. Mandrekas** stated that the charge was originally written with facilities in mind. International collaborations are traditionally justified by unique capabilities not present in the U.S. Though codes present intellectual property issues, if a there is a way to collaborate, then codes will be considered for the charge.

Dr. Parker advised that the U.S. needs to foster ties with larger international tokamaks to better understand power handing in the scrape-off layer (SOL) region. European graduate training is outstanding, especially in computation, and the U.S. is hiring many graduate students. The subcommittee might consider more innovative approaches such as internships to reduce barriers with international partners.

Dr. Maingi asked whether the subcommittee is expected to filter information regarding potential international collaborations based on challenges surrounding intellectual property and other concerns. These issues are more challenging for some countries like China. However, China is building a phenomenal technology program. **Dr. Van Dam** indicated that the subcommittee will focus recommendations on science. FES has a long-standing, productive relationship with China and other countries. Many Chinese scientists were trained in the U.S., and FES knows these individuals very well. Some aspects of the fusion program are not discussed between countries, and it is a win-win situation. Fusion is for the world, not just one country.

Dr. Carter highlighted discovery plasmas, especially low temperature plasmas. There are also opportunities to explore the role of thermal R&D in the context of international collaborations for microelectronics production. Finally, the portion of the charge addressing how the U.S. can take advantage of its growing fusion private sector in international engagements is not limited to facilities; thus, the charge's purview includes codes, especially if there is an international code ahead of those of the U.S. This can be called out in response to the portion of the charge addressing U.S. leadership.

Dr. Wilson said that there are many emerging collaboration opportunities for new codes, especially in the technology space. Including codes in the charge purview makes sense for evaluating existing capabilities, strengths, and weaknesses. Additionally, cementing formal partnerships will be important for avoiding effort duplication. **Dr. Van Dam** agreed that this topic is important for the subcommittee to examine and is also relevant to ITER. **Dr. White** summarized discussion, noting that the subcommittee can take an expansive approach to thinking about charge directives within necessary boundaries.

In reference to codes, **Dr. Snyder** agreed that ITER provides an obvious point of contact for organizing efforts. Additionally, the charge outlines assessment of both U.S. collaboration and leadership activities, and the relationship between these two areas is critical. International partners are seeking a balanced relationship; while the U.S. does not need to lead in every area, the U.S. must offer complementary leadership in key areas and facilities within the international arena. If the U.S. does not build recommended facilities from the LRP and NASEM reports, such as those related to confinement, it is unclear how the U.S. can position itself for stronger international collaborations.

Dr. Kuranz commented that Asia has made large investments in high intensity lasers. Is the charge's workforce lens focused solely internationally, or does it also encompass domestic activities to improve talent recruitment from underrepresented groups? **Dr. White** commented that in order for the U.S. workforce to be strong and competitive in the international arena, the U.S. workforce must be diverse. **Dr. Van Dam** agreed with this interpretation.

Dr. Maingi asked if ITER was outside the charge's scope. **Dr. Van Dam** confirmed that this is true.

Dr. Barish and Dr. Van Dam encouraged the subcommittee, once formed, to seek clarification on charge language from FES staff. It may be useful to seek advice from BES. **Dr. White** added that the subcommittee can reach out to a variety of outside experts

Dr. Maingi weighed report succinctness versus material depth. **Dr. Van Dam** replied that FES is looking for impact. **Dr. Carter** advised careful consideration of the audience which potentially includes Congress; keeping the focus narrow and picking a few main points creates impact. Select topics can have added depth. **Dr. Barish** commented that the report's deadline may guide the level of detail provided.

Dr. Magee asked if there are other active FES subcommittees. **Dr. Barish** said there are no other active subcommittees. The last subcommittee produced the LRP.

National QIS Research Centers, Professor Andrew Houck, Department of Electrical and Computer Engineering, Princeton University and Brookhaven National Laboratory

Five NQISRCs, each led by a national laboratory, were launched in 2020: Co-design Center for Quantum Advantage (C^2QA); Next Generation Quantum Science and Engineering (Q-NEXT); Quantum Systems Accelerator (QSA); Quantum Science Center (QSC); and Superconducting Quantum Materials and Systems Center (SQMS). Each Center represents a partnership of labs, universities and industry. NQISRCs take distinct but complementary approaches to tackling major challenges in advanced materials for quantum technologies; entanglement distribution networks; high-performance instruments and sensors; and full-stack quantum computation. Solutions address the entire QIS innovation chain for emerging technologies. An Executive Council coordinates activities across Centers.

The NQISRCs contribute to QIS ecosystem stewardship by (1) supporting workforce development programs aimed at broadening and diversifying the workforce; (2) engaging with industry partners to accelerate deployment of quantum-enabled technologies; and (3) creating new community synergies with DOE programs and user facilities. In their first year of operation, the Centers jointly conducted activities in technical coordination, facility instrumentation, workforce development, cross-center management, and outreach. Future plans will continue joint center support for ecosystem stewardship, instrumentation and facilities, and coordination across technical areas.

NQISRC science highlights include synthesis of tunable molecular color centers from Q-NEXT; investigation of a spin system's quantum phases using a programmable quantum simulator by QSA; discovery of room-temperature, single-photon emitters in SiN by QSC; generation of an efficient, fully-coherent Hamiltonian simulation by C^2QA; and discovery of niobium nanohydride precipitates in superconducting transmon qubits by SQMS.

Discussion

Dr. Carter requested more information about industry coordination. **Dr. Houck** commented that most NQISRCs fund industry partners to work in specific areas. For example, C^2QA collaborates with IBM on software and algorithms but steers away from materials collaboration because of proprietary concerns. Successful collaborations leverage complementary strengths while avoiding areas where collective effort may not work well.

Dr. Terry asked about Center interactions with academia. **Dr. Houck** remarked that it is difficult for academics to make progress if not part of a Center. Different NQISRCs have different degrees of academic focus. At C^2QA, the degree of openness and transdisciplinary collaboration is unparalleled. Primary investigators (PIs) and their students share unpublished data, skills, and samples. One cross-center collaborative effort brought the per qubit cost down to $2K from the usual $100K when using classical electronics. The field programmable gate array solution is now open-source hardware that is slowly being adopted.

Dr. Reyes observed that the ECP, STEP, and NQISRCs are well-organized efforts with defined technical goals, and the NQISRCs have diversified their efforts through five Centers that allow partnerships across labs, universities, and industry. FES may consider aspects of these technology development models as possible approaches for realizing an FPP.

Public Comment:

Dr. Bruno Coppi (MIT) stated that the scientific community at large faces difficult questions about proving the scientific feasibility of fusion. The community cannot wait for a magnetic confinement demonstration from ITER, which has tremendous engineering difficulties still requiring solutions. The U.S. only has one big inertial confinement experiment in California; there used to be several experiments throughout the country. Most theory-based codes were developed 40-50 years ago and are inadequate for fusion burning regimes. The community must accelerate efforts in both theory and experimentation.

Dr. White adjourned the meeting at 3:45 p.m.

Respectfully submitted
Holly Holt, PhD
Science Writer, Oak Ridge Institute for Science Education (ORISE)

Certified as Correct by:

Anne White

Professor Anne White
FESAC Chair
Date July 7th,2022