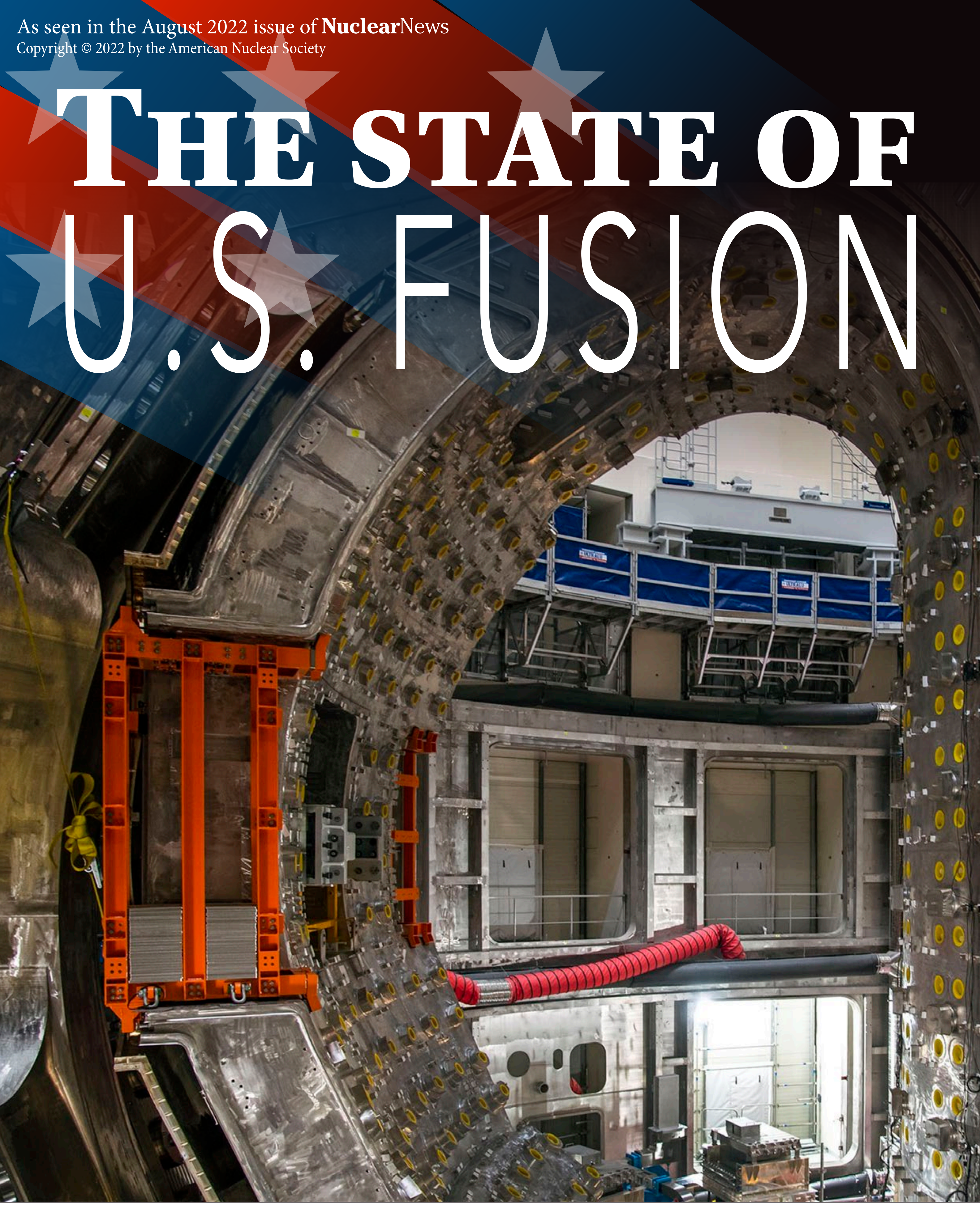
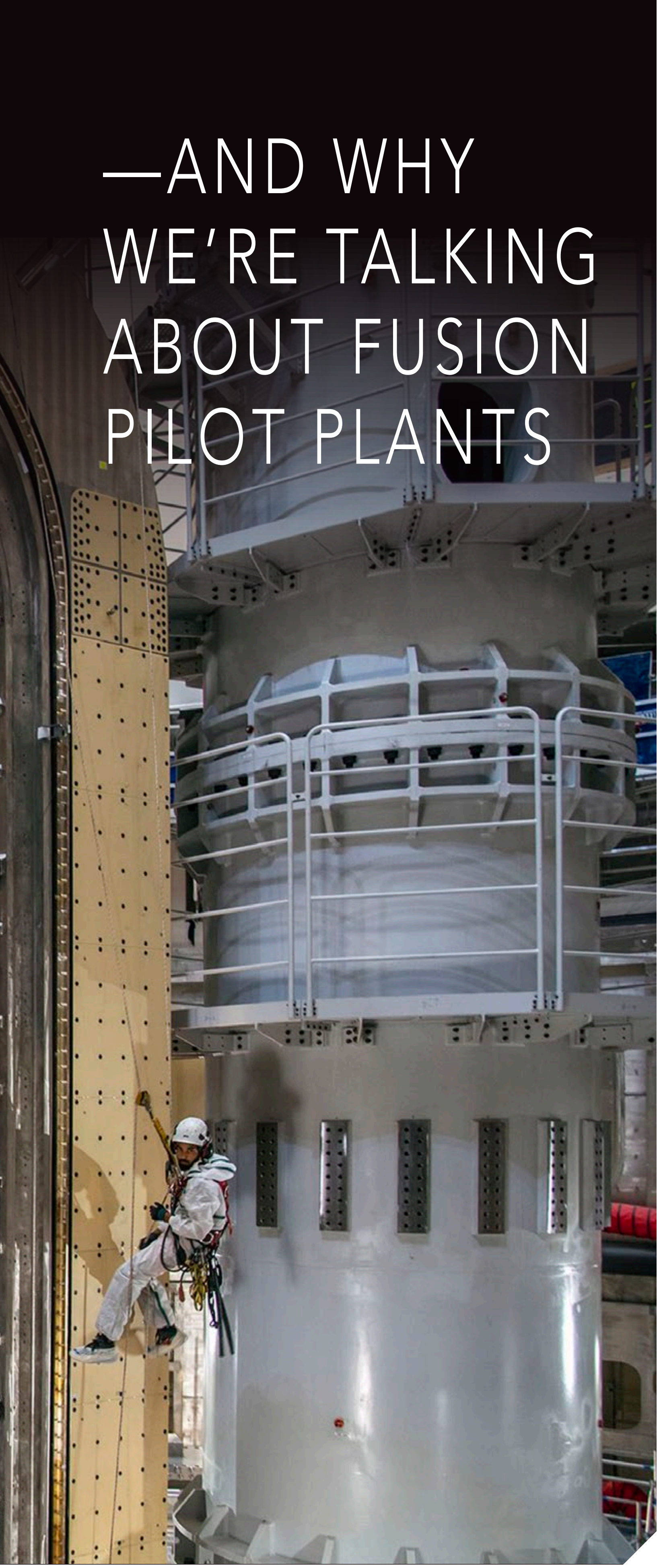
The State of U.S. Fusion



—AND WHY WE'RE TALKING ABOUT FUSION PILOT PLANTS



By Cami Collins

Delivery of electricity from fusion is considered by the National Academies of Engineering to be one of the grand challenges of the 21st century. The tremendous progress in fusion science and technology is underpinning efforts by nuclear experts and advocates to tackle many of the key challenges that must be addressed to construct a fusion pilot plant and make practical fusion possible.

As the globe reckons with the urgent need to reduce carbon emissions, the public and private sectors in the United States are working to expand carbon-free energy sources, including advanced fission and fusion. Across government, industries, and universities, there is strong support for an aggressive path to fusion energy that addresses the technical and scientific challenges and prepares fusion for the demands of delivering electricity to the grid.

Several key factors are contributing to this turning point in fusion: scientific discovery and applications of new technologies, consensus across the U.S. fusion community to focus on a path to commercialized fusion energy, substantial private investment in fusion industry, and new partnerships across public and private sectors.

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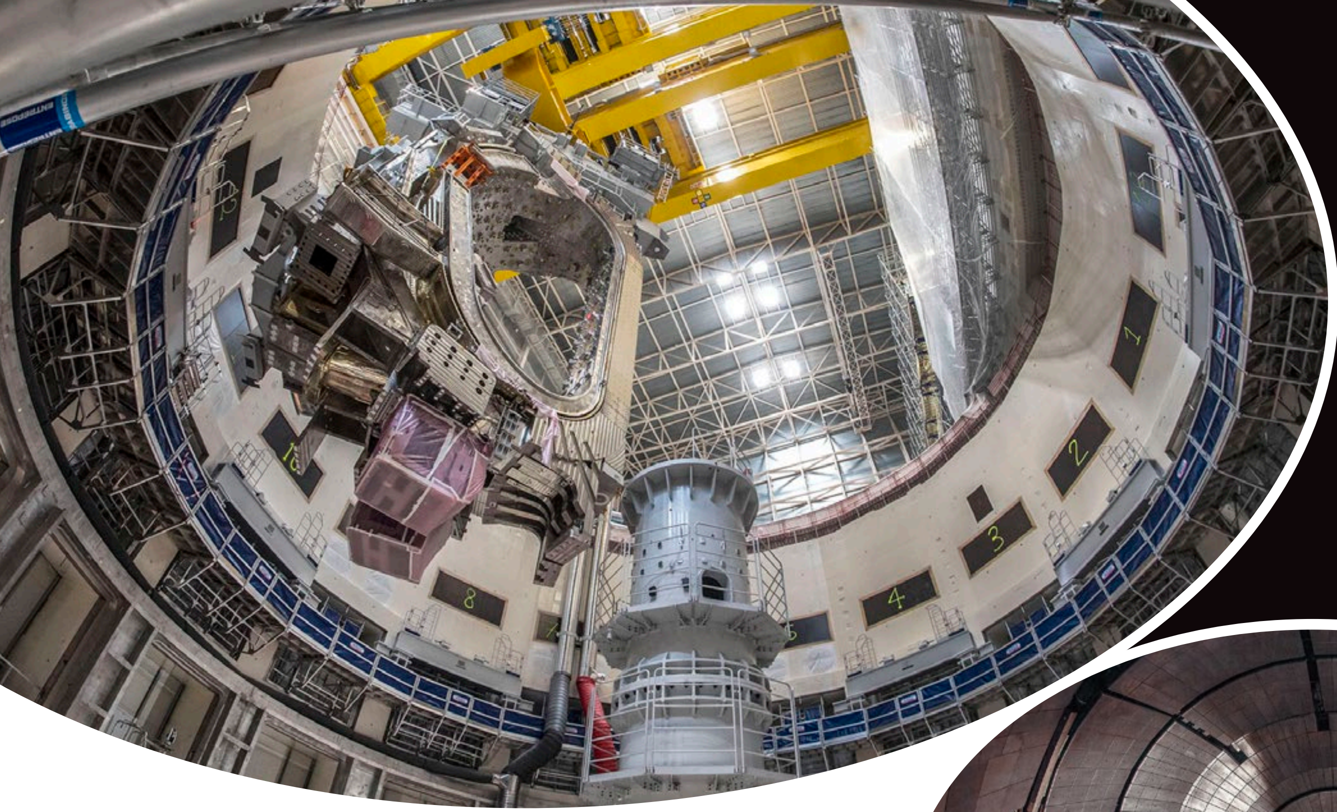
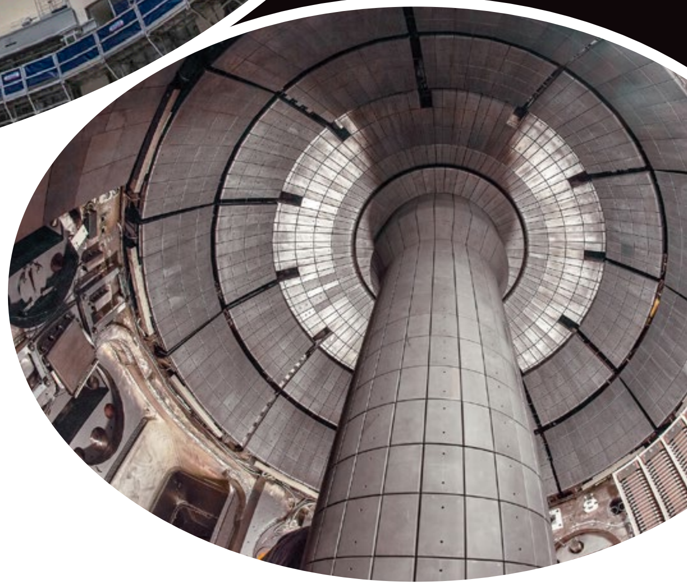
The first sector of the ITER vacuum vessel was placed in the assembly pit in May. Here, a technician positions targets on the surface of the component to be used in laser metrology. (Photo: ITER Organization)





Above: The first ITER vacuum vessel sector is lowered into the machine well. (Photo: ITER Organization)

Right: Inside the National Spherical Torus Experiment-Upgrade. (Photo: PPPL)

NEW DISCOVERIES AND TECHNOLOGIES

Significant advances have been made in fusion science and technology over the past two decades, many of which have been supported by public investment, through the Department of Energy national laboratories and user facilities and through university research supported by the DOE Office of Science. Magnetic confinement approaches to fusion, largely with donut-shaped tokamak machines, have been a prime focus of investment and research, resulting in deep experience and improved understanding. Other fusion confinement approaches have also made advances, typically through private investment.

The international ITER project, which receives support and participation from the U.S. government, is a multidecade effort that has yielded impacts across science and engineering. Tokamak assembly began in 2020, and the site and components are now more than 75 percent complete for first plasma operations. ITER is designed to produce a self-sustaining "burning plasma" that will operate for approximately 300 seconds and demonstrate 500 MW of fusion power. ITER has grown a fusion workforce and transformed the fusion supply chain, engaging industry, laboratories, and universities around the world. Every day, first-of-a-kind engineering achievements are accomplished at the project site and by ITER partners around the world, from the manufacture of superconducting magnets and leading-edge plasma heating technologies to the assembly of airplane-sized components with millimeter precision. Designing and fabricating qualified components for ITER provides the United States with practical fusion engineering and construction experience at reactor scale. In 2022, the U.S. fusion community prepared a draft report detailing many critical products and lessons to be learned through each upcoming ITER phase, spanning physics to engineering, diagnostics, and control of a large, nuclear, long-pulse facility. The report forms a plan to maximize the return of U.S.

The DIII-D National Fusion Facility tokamak interior. (Photo: General Atomics)

investment in ITER and ensure U.S. research on ITER strengthens and accelerates the development of a domestic fusion pilot plant.

Princeton Plasma Physics Laboratory has long been a leader in magnetic confinement fusion and plasma science. PPPL was home to the world record–setting Tokamak Fusion Test Reactor, which entered service in 1982 and was shut down in 1997. It was the first fusion device in the world to use 50/50 mixtures of deuterium and tritium as fuel and produced 10 MW of fusion power in 1997. Today, PPPL hosts the National Spherical Torus Experiment-Upgrade and is engaged in expanding its impact on fusion applications, including microelectronics and nanotechnology. The lab is also an active contributor to theoretical and advanced computing research focused on fusion.

The DIII-D National Fusion Facility, operated by General Atomics in San Diego, Calif., on behalf of the DOE, has been home to magnetic fusion research since the mid-1980s. Today, the facility has over 100 participating institutions and a research team of more than 600 people. The facility's D-shaped cross-section design has influenced fusion devices around the world, including KSTAR (Korea) and EAST (China). DIII-D is regarded as the most comprehensively diagnosed tokamak in the world, and its research and model validation has been especially important for ITER, both in early design periods and now in preparation for research operations. Key discoveries aided by DIII-D include understanding of plasma confinement during "H mode," or high-confinement operation; development of plasma control techniques; establishment of steady-state "advanced tokamak" plasma scenarios; and development of techniques for avoiding and mitigating plasma disruptions and undesirable transient plasma events called edge-localized modes.

Oak Ridge National Laboratory has over 50 years of fusion experience spanning many devices, national and global collaborations, and technologies. Today, ORNL is building the Materials Plasma Exposure eXperiment (MPEX) to support study of materials for fusion applications. The lab manages the U.S. hardware

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contributions for ITER while continuing to advance burning plasma science and fusion technology for public and private projects around the world. ORNL is also a leader in integrated modeling of fusion systems. Capabilities at ORNL include understanding both the plasma physics in the fusion core and the materials and engineering constraints of the surrounding components. Scientists and engineers are now applying this expertise toward developing reference designs for fusion pilot plants.

Lawrence Livermore, Los Alamos, and Sandia national laboratories also have a long history with fusion, tied to their national defense mission, and have played an important role in investigating fusion approaches other than magnetic plasma confinement. The National Ignition Facility at LLNL achieved a fusion milestone for inertial confinement fusion in August 2021, with a 25-fold increase in energy yield compared with the earlier record set in 2018. This facility uses high-energy lasers to put tiny hydrogen fuel pellets under extreme temperature and pressure. For a fraction of a second, the fusion reaction was driven primarily by the heat from other fusion reactions, approaching the threshold for ignition. For a practical inertial fusion energy system, higher energy yield and much greater driver efficiency and repetition rates would be required. Still, the achievement is a positive sign of the impact of expanded support for inertial confinement fusion research.

Universities are also critical contributors to fusion efforts, providing the central foundation to continuously develop the multidisciplinary workforce and bring essential talent, skills, and fresh perspectives to the fusion effort. Universities are training technical fusion experts; making discoveries; and building simulation tools, diagnostics, and technology innovations. Some institutions also host their own facilities or test stands for fusion development. The Massachusetts Institute of Technology, a longtime host of DOE-funded research and devices, is now partnering with the private fusion company Commonwealth Fusion Systems (CFS) to develop a compact, high-field fusion device that will take advantage of high-temperature superconducting (HTS)magnets. The University Fusion Association advocates for fusion research at universities. The need for increased coordination, opportunities, and pathways for engagement between university students, researchers, and professors with national laboratories and private industry has been identified in multiple fusion community reports.

Several factors have helped the national laboratories and universities accelerate their achievements in the

Plasma in the prototype of the Material Plasma Exposure eXperiment. (Photo: ORNL)

An HTS magnet designed and built by Commonwealth Fusion Systems and MIT's Plasma Science and Fusion Center. (Photo: Gretchen Ertl; CFS/MIT-PSFC, 2021)

past decade. High-performance computing has enabled high-fidelity modeling and simulation of fusion plasmas and devices. The richness of these simulations permits researchers to rapidly explore device and component design impacts, minimizing the number of test facilities that need to be built. Simulations and modeling are also key for preparing for high-confinement, high-power plasma operations that will be required in new devices, such as ITER, and ultimately for pilot plants and power plants.

Next-generation plasma diagnostics are also making a difference for fusion. Improved resolutions, techniques, and integration with high-performance computing enable measurements that were not even possible 10 years ago. U.S. experts contributed to diagnostics that helped measure a new fusion record in February 2022 at the Joint European Torus (JET), where researchers documented generation of 59 megajoules of sustained fusion energy, more than doubling the device's previous 1997 record. The high-power plasma phase lasted about 5 seconds and was hailed as the clearest demonstration to date of a viable path to carbon-free fusion energy.

In the future, the impacts of advanced manufacturing, integrated sensors, and artificial intelligence are expected to contribute to fusion development, including accelerated design and deployment of certified components and the optimization of operations.

In short, diverse contributors and sustained government investment in fusion and facilities have yielded new understandings of plasmas, new achievements in fusion performance, and new engineering capabilities relevant for preparing for practical fusion energy.

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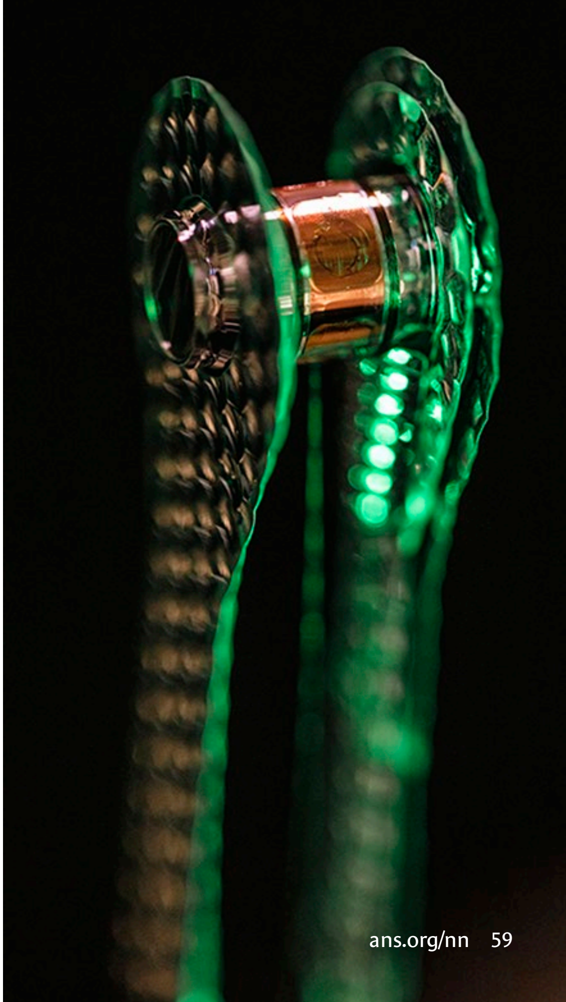
A National Ignition Facility cryogenic target. (Photo: LLNL)



POISED TO ADVANCE FUSION ENERGY

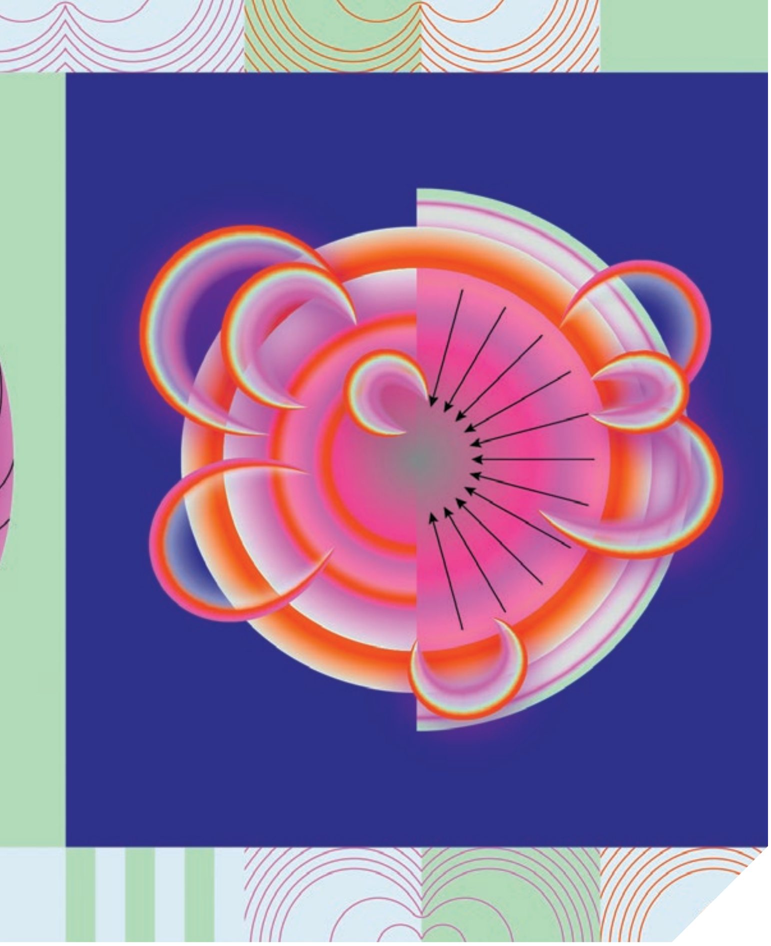
Members of the U.S. fusion research community, which spans the fields of plasma physics, nuclear engineering, and fusion technology, among others, are aligned with the pursuit of fusion for energy. There is an urgent need to address and solve specific challenges to achieve practical fusion, however.

In 2020, the final report of the American Physical Society Division of Plasma Physics (APS-DPP) community planning process, *A Community Plan for Fusion Energy and Discovery Plasma Sciences*, was made available. U.S. experts engaged in months of exchanges and discussions that culminated in this consensus report, which emphasized the equal importance of both fusion science and technology and discovery plasma science. The report conveys that preparation for a fusion pilot plant should be a prime organizing goal for fusion science and technology investments and outlined a prioritized set of strategic objectives needed to achieve this mission. This stands in contrast to past DOE-funded efforts, which have focused largely on plasma science.

The community plan specifically notes that research efforts should focus on further advancing the burning plasma physics basis necessary for a fusion pilot plant. In addition, further investment in fusion materials and technology is recommended. It urges innovation to drive the achievement of economically viable fusion—whether that be in transformative science, technologies, or coordination and integration of impacts from other fields.

Following the release of the community consensus report, the DOE Fusion Energy Sciences Advisory Committee issued a long-range planning report, *Powering the Future: Fusion & Plasmas*, in 2020. The executive summary opens with this statement: "Now is the time to move aggressively toward the deployment of fusion energy, which could substantially power modern society while mitigating climate change." The report articulates how investment in fusion and plasma research is changing the world—in energy and other sectors—and that unique international and public-private partnerships are situating the United States to accelerate the development of fusion energy. In concert with the community plan, this report notes that there are areas of fusion technology development that require serious attention now to address critical gaps between present fusion capabilities and the requirements for a pilot plant and, ultimately, fusion power plants.

In 2020, the DOE asked the National Academies of Sciences, Engineering, and Medicine to identify key goals and innovations needed to support the



(Image: Ana Kova for U.S. Fusion Outreach)

development of a U.S. fusion pilot plant. The resulting 2021 report, *Bringing Fusion to the U.S. Grid*, presents a strategic plan for the design, construction, and operation of a fusion pilot plant. The report contributors conclude that the DOE should move forward now to foster the creation of national teams, including public-private partnerships, that will develop conceptual pilot plant designs and technology roadmaps, leading to an engineering design of a pilot plant that will ultimately bring fusion to commercial viability. The contributors note that a time frame of 2035–2040 for a fusion pilot plant, dictated by the goal of making an impact on the transition to a low-carbon-emission electrical system by 2050, requires immediate and urgent investments by both the DOE and private industry in order to solve the remaining technical and scientific issues and design, construct, and commission a pilot plant.

One of the first achievements to emerge from the APS-DPP community plan was the November 2021 launch of a website, usfusionenergy.org, designed and hosted by members of the U.S. Fusion Outreach Team. The website is a centralized resource for all audiences, featuring jobs and internship opportunities, a "fusioneer" portal with resources for anyone working to get fusion energy on the grid, K–12 educational materials and events, curated news stories, and media resources.

URGENT CHALLENGES AHEAD

Despite all the current advances, there remain significant scientific and technical challenges to resolve and economic risks to manage. None of these are trivial or guaranteed to yield a successful outcome; however, much is possible with the continued shared focus, investment, and determined effort of the fusion community and government sector.

Fusion's appeal as an energy source is rooted in nuclear science: Fusion reactions release even more energy per unit mass than fission reactions, and fusion reactors use fuel that is potentially abundant. Plus, the by-products of a deuterium-tritium reaction, helium plus an energetic neutron, lessen some of the challenges posed by fission products, particularly those of waste disposal.

Three main technical challenges must be resolved for fusion to be realized as a viable energy source.

First, practical fusion demands the production and control of a sustained fusion power source. For competitive commercial fusion energy, the plasma must be mostly self-heated rather than heated by external sources. In typical fusion designs, external heating is necessary to initiate fusion, but a self-heated burning plasma is achievable when enough fusion reactions are maintained over time with enough energy and enough confinement. ITER is specifically designed to achieve a self-heated, 500-MW plasma for 300 seconds with deuterium-tritium fuel, though this has yet to be fully realized. The readiness to deliver a sustained power source that can be rapidly scaled and commercialized to deliver reliable, economically viable, electricity-producing power still requires substantial development.

A second significant technical challenge is the development of materials appropriate for fusion reactor components. At this point, qualified materials that can withstand sustained fusion conditions over the lifetime of a power plant are not yet available. Developing materials, technology, and design solutions that ensure sufficient lifetimes of fusion reactor components applies to multiple fusion concepts. Moreover, materials will

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likely set the timescale and economics for viable fusion power plants. Fusion material needs are even more extreme than in current fission reactors. In a fusion reactor, components immediately surrounding the burning plasma will receive heat and particle flux from the plasma, as well as neutron heating and degradation from deuterium-tritium fusion reactions. Some materials can absorb fusion fuel, and materials breakdown could pollute or even extinguish the plasma. Materials properties and evolution under operation also impact heat extraction for electricity conversion. These materials must also protect ex-vessel components and superconducting magnets from neutron fluence. Furthermore, materials performance has implications for safety and licensing. Activities are currently underway to plan and develop testing environments for fusion materials that will accurately simulate fusion power plant conditions and aid in the assessment of novel materials.

A third major science and technology challenge is related to the fusion fuel cycle: the need to develop new technologies to capture fusion power efficiently. Even more fundamentally, tritium fuel will need to be produced from components inside a fusion reactor if the fuel cycle is to be closed and sustainable. It is assumed that deuterium-tritium fusion reactions will fuel the first generation of fusion pilot plants and power plants, because the reaction is "easier" to achieve. Though it is a limited resource, tritium can be produced when neutrons react with lithium. However, the production of tritium depends on specific fission reactors until fusion reactors can breed their own tritium. At present, there is enough tritium available for research and development activities, but the short half-life of tritium, combined with anticipated supply chain issues, adds pressure to that supply. For future pilot and power plants, new sources of tritium will be necessary. The United States is in an early stage of establishing the research and engineering activities necessary to meet the technology needs for breeding tritium and handling fusion power in the most efficient manner.

Outside of these technical challenges, fusion must also prepare for the demands of delivering baseload electricity in a safe, reliable, predictable manner that intersects productively with utility portfolios. As outlined in *Bringing Fusion to the U.S. Grid*, it is essential that preparations for a fusion pilot plant engage current utilities and energy stakeholders and incorporate lessons learned from the current nuclear industry.

NEW PARTNERSHIPS AND INVESTMENTS IN FUSION

The Biden administration recently announced a decadal vision for accelerating fusion energy and established a DOE fusion coordinator to work with the research and industrial sectors. This approach follows the recommendations of *Bringing Fusion to the U.S. Grid*: The "DOE should move forward now to foster the creation of national teams, including public-private partnerships, that will develop conceptual pilot plant designs and technology roadmaps that will lead to an engineering design of a pilot plant that will bring fusion to commercial viability." After a March 2022 White House summit, the DOE organized a multiday workshop in June about fusion energy development via public-private partnerships and a new milestone-based funding program. The topics explored ranged from technical challenges to practical considerations for effective cross-sector partnerships.

More than 25 private fusion companies have been established in the United States, and it is estimated that more than $4 billion has been invested in the U.S. fusion industry over the past decade. In September 2021, CFS demonstrated the performance of a large HTS magnet at 20 tesla. In 2022, Tokamak Energy achieved >100 million degree Celsius core ion temperatures in their spherical tokamak, ST40. This investment shows a business appreciation for energy innovation and edge energy opportunities to address global needs for carbon-free electricity. Industry groups such as the Fusion Industry Association continue to grow and advocate for the expansion of government funding for private fusion activities. Some companies are closely associated with government-funded research entities. Many private companies are exploring new confinement concepts for containing fusion reactions; some are proposing using novel fuels for fusion. Others are focused on near-term applications for fusion outside of electricity production.

Meanwhile, the DOE continues to support other avenues for private fusion engagement with public sector expertise. The ARPA-E program supports development of high-potential, high-impact technologies through short-term projects, some of which include high-power gyrotron, radio-frequency heating, neutronics modeling, and HTS magnet technology development for fusion applications. Project teams can include both publicly and privately funded institutions. The DOE Innovation Network for Fusion Energy (INFUSE) program provides the fusion industry with opportunities to access the technical support available at DOE laboratories and universities that is necessary to move new or advanced fusion technologies forward. Since 2019, INFUSE has supported 47 collaborations with industry partners, including projects with CFS, Energy Driven Technologies, General Fusion, HelicitySpace, Magneto Inertial Fusion Technologies, Renaissance Americas, TAE Technologies, and Tokamak Energy.

WHAT'S NEXT?

As the private, public, and government sectors work toward the common goal of a U.S. fusion pilot plant, an essential step to practical fusion electricity, experts agree that much remains to be done on the science and engineering side to realize the technologies that will bring this goal to fruition.

To clear the path to commercialization, rapid expansion is necessary across multiple disciplines and entities to resolve low technology readiness level issues. Open communication, collaboration, and coordination between public and private stakeholders to disseminate knowledge, technology, and experience will accelerate progress. Tactical research and development is needed to maximize the probability of credible power plant designs reaching commercial viability. Across sectors, the community must draw on all resources, including critical lessons learned and data from ITER, the nuclear industry, private industry, and other domestic and international facilities and industries. Above all, U.S. fusion goals require rapid expansion of a diverse workforce with expertise in fields from physics to nuclear science to materials science, as well as all types of engineering and computer science, and even economics and public policy. Though we may not be able to predict when fusion will join fission as a crucial component of the U.S. carbon-free energy portfolio, our expert opinion from the field is that this coming decade will be a pivotal one for the future of fusion.

Cami Collins (collinscs@ornl.gov) is an R&D scientist and the advanced tokamak group leader in the Fusion Energy Division at ORNL. She has served on multiple community planning program committees, in APS-DPP, and in fusion outreach, with a special focus on recruitment and retention of women in fusion energy careers.

To keep up with current fusion news, resources, and job opportunities, visit usfusionenergy.org.

(Image: Ana Kova for U.S. Fusion Outreach)