From the Lab to the Grid:

An Action Plan for U.S. Advantage in Fusion Energy[1]

Introduction

Fusion energy could put the power of the Sun on Earth. As a clean, limitless energy source,[418] fusion could power the electric infrastructure of the future and help to achieve decarbonization goals.[419] Fusion's economic potential extends far beyond what is conceivable today.[420] Geopolitically, it could rewire foreign energy dependencies and unlock new defense and space capabilities.[421] Secure access to fusion will be a national security imperative, and fusion leadership would be a boon to the nation.

The Decade of Fusion is Here

A fusion future can soon be realized.[422] Thanks to private sector efforts, a commercially-practical fusion reaction that creates more energy than it consumes[423] could be achieved as soon as 2024.[424] A race for scale and commercialization will follow. If the United States organizes, it can win this race. The next decade will determine which countries become importers versus exporters of fusion. The Biden Administration's *Bold Decadal Vision for Commercial Fusion* is a key step in the right direction.[425] Now the nation must execute and build upon that vision to reap the economic, social, and geopolitical benefits that fusion can offer.

Guiding Policy:

The government must treat fusion as a strategic commercial endeavor rather than purely a science mission. Bringing fusion from the lab to the grid will require a series of smart business decisions: planning beyond the initial technological breakthrough; focusing ecosystem actors' on their competitive advantages; accelerating results through incentives; and cultivating fusion talent.

Action Plan Overview

With the might of the private sector, the United States can win the race for commercial fusion.[426] A coordinated effort by the U.S. Government to fund, implement, and empower commercial fusion will unleash a new industry – centered in America – that addresses key climate and geopolitical challenges. Such an action plan should contain the following core elements:

- *Get Fusion On the Grid by 2030*
- *Empower DOE with a Commercial Fusion Mission*
- *Leverage Actors' Core Strengths*

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[1] See Future Platforms Interim Panel Report, Special Competitive Studies Project (November 2022).

- *Add Government Fuel Where it Will Accelerate Commercialization*
- *Determine a Basic Regulatory Framework Within the Next Year*
- *Balance Information Sharing and Intellectual Property Protection*
- *Bolster the Fusion Supply Chain*
- *Foster a Broad Base of Fusion Talent*

Diagnosis:
The private sector has accelerated decades of research in national and collaborative international labs, collectively investing more than $5 billion in fusion's development.[427] The United States is the hotbed of this commercial fusion activity, housing more than half of the world's 35 known fusion companies.[428] Commercial actors have progressively shortened the timeline for demonstrating a net-positive fusion reaction to 2025, and have announced plans for fully-operational pilot facilities producing electricity by the early 2030s.[429]

Regardless of who achieves the first breakthrough, fusion will ultimately be a race for commercial scale. This demands additional innovation and scale in materials, compute, and manufacturing as well as concurrent efforts to update regulations. Advancements in AI have already enabled[430] – and will continue to enable – faster and more efficient fusion research and development.[431] Furthermore, national advantages in materials engineering[432] and manufacturing[433] may need to be cultivated to meet requirements of demonstration and operational facilities. Private fusion firms are sufficiently capitalized and likely will be able to achieve specific technological milestones, but government support will be key to catalyze and scale a commercial ecosystem.

Recognizing the need for national leadership, the U.S. Government recently launched a laudable *Bold Decadal Vision for Commercial Fusion Energy*.[434] Already the vision has increased coordination within government, and efforts such as the Department of Energy's (DOE) milestone-based development program are expanding public-private partnerships.[435] Nonetheless, shifting fusion from a purely scientific to a commercial mission will require a deep cultural shift within the government.

Other nations have also recognized fusion's importance, and some are better organized for the race ahead. The United Kingdom, for example, has made fusion a central tenet of its Ten Point Plan for a Green Industrial Revolution,[436] selected the location for a national pilot plant,[437] and attracted foreign fusion companies through a favorable regulatory environment.[438] More troublingly, China has plans for a fusion pilot plant and is replicating U.S. companies' technological approaches.[439] Even if not the first to achieve a breakthrough, China's ecosystem would likely be able to rapidly catch up and scale fusion technology – as it did with solar photovoltaics a decade ago.[440]

Action Plan Elements:

Get Fusion On the Grid by 2030:

Private sector progress has already compressed government fusion timelines by over a decade. Companies expect to achieve net energy by 2024 or 2025, are building pilot plants today that they expect to be operational as soon as 2030, and believe they can put fusion on the grid by the early 2030s.[441] With the right incentives, the government can accelerate those timelines. Congress has appropriated $50 million for a DOE Milestone Program to support commercial pilot plant efforts,[442] but longer-term and higher-dollar funding will be required to instill commercial confidence and enable long-term government planning.[443]

- To incent competition among companies to achieve their pilot plant plans on an even shorter timeline, the Biden Administration should announce a "Fusion Energy Earthshot"[444] of having at least three fusion pilot plants on U.S. soil successfully deliver fusion energy to the grid by 2030.

- Congress should fully appropriate the $325 million authorized for the DOE Milestone Program.[445] DOE should use companies' milestone program applications to inform future fusion funding, starting with the FY24 budget request.

- A National Mission Manager (NMM) in government should be empowered and held to account for getting fusion to the grid. The NMM must have the necessary budgetary and legal authorities to effectively implement the national action plan.

- The NMM should actively encourage multiple technical pathways — including magnetic, inertial, and magneto-inertial — for fusion at this stage. Competition amongst companies on different tech paths could accelerate commercialization, reduce the cost to consumers, mitigate supply chain vulnerabilities, and ultimately enhance the United States' competitive position.[446]

- The government should validate technical progress and set new fusion milestones to signal to private markets, lawmakers, regulators, suppliers, and the public the growing reality of commercial fusion.

Empower DOE with a Commercial Fusion Mission:

Fusion can no longer be an incremental science mission within DOE.[447] A program office with budgetary authority and a commercial fusion mission will be necessary to move fusion from the theoretical to the practical. The time to create this office is now. Waiting until a breakthrough occurs to create such an office will yield valuable time to other countries who will seek scale and commercialize the technology first.

- Congress should create an Office of Fusion Energy at the Department of Energy to implement the *Bold Decadal Vision.* The office's mission should be to get fusion on the grid and ultimately serve as the policy apparatus for a thriving U.S. fusion ecosystem.[448] DOE's Lead Fusion Coordinator could serve as the National Mission Manager.[449]

Leverage Actors' Core Strengths:
Different actors in the fusion ecosystem bring different strengths to the table. The U.S. Government can increase the impact of the *Bold Decadal Vision* by doubling down on what is already working, while streamlining efforts that are unnecessarily duplicative. Aligning ecosystem efforts around actors' core strengths in the following ways would streamline progress and deliver more impactful results:

- Fusion companies should focus on achieving a fusion breakthrough and competing against one another to build the best fusion pilot plants and commercialization plans.

- DOE and the national labs should focus on developing the supporting infrastructure (such as test stands), basic R&D, and science that will enable industry.[450] Additionally, they should lead the charge in supporting the education and training of the next generation of fusion energy scientists, engineers, and professionals.

- Public-private partnerships (PPPs) should be targeted to the areas of greatest potential impact. Government's scientific know-how and resources can continue to help de-risk and incentivize the frontiers of fusion research but must also increasingly help build out a commercial fusion ecosystem.

Add Government Fuel Where It Will Accelerate Commercialization:
Government spending on fusion will be essential both for catalyzing a commercial fusion ecosystem and eventually for supporting the delivery of fusion energy as a public good. The science programs underway today will remain important for driving the field forward, but Congress should make fusion activities eligible for other climate and national security-related funding vehicles today, and should prepare to grow the funding pot for longer-term fusion needs tomorrow. In the meantime, the government may find private actors interested in voluntarily supporting longer-term ecosystem needs.

- *Continue Partnerships like INFUSE & ARPA-E:*[451] The annually-recurring DOE INFUSE program, which gives companies access to labs and up to 80 percent government cost share,[452] should be sustained as a recurring expenditure and should focus on high-risk projects and proof-of-concepts for associated technologies that support the fusion ecosystem. Fusion-focused ARPA-E programs – which have leveraged 5-15x government dollars in private investment[453] – should be appropriated on a recurring rather than one-time basis.

- *Include Fusion in Other Existing Programs:* Government should consider additional vehicles for funding and partnering with fusion companies, such as making fusion-related activities eligible for clean energy tax credits. If fusion meets key mid-decade milestones, these programs should be expanded to add additional funds to support a fusion-focused buildout.

- *Align Investment Now for Longer-Term Needs:* The government should start planning for and aligning funding to build the R&D facilities and infrastructure, like test stands, that will be necessary to scale commercial fusion. Government can rally voluntary private investment around these ecosystem gaps by convening investment alignment working groups. While the government should ideally lead in funding R&D facilities, private actors could get the ball rolling on long pole items like the Fusion Energy Sciences Advisory Committee (FESAC)-recommended Fusion Prototypic Neutron Source (FPNS) test facilities.[454]

Determine a Basic Regulatory Framework Within the Next Year:
Companies need to know the regulatory world within which they will be operating to map their fusion commercialization plans. The Nuclear Regulatory Commission (NRC) is considering three basic options for fusion regulation: a materials framework like particle accelerators, a utilization framework like fission, or a hybrid of the two.[455] Adopting fission regulations for fusion – a fundamentally safer energy source – would likely drive commercial actors out of the United States.[456] Prolonged regulatory uncertainty via a hybrid approach would risk the same, and could cede to rivals first mover advantage in setting global safety standards and shaping international standards bodies.

- The NRC should vote as early as possible to codify the use of a byproduct materials framework (Part 30) to regulate fusion, rather than a utilization framework (Part 53) or a hybrid approach (Part 30/Part 53).[457] The details of these regulations can be worked out over a longer timeline, but a basic framework that separates fusion from fission must be determined today.

Balance Information Sharing and Intellectual Property Protection:
As with much of the science community, fusion research has been highly collaborative. The rise of private fusion companies has begun to shift those traditional information sharing paradigms. National labs have decades of R&D experience, but gaps in the discourse between the labs and private companies can cause commercial actors to waste resources reinventing the wheel. Public-private partnerships can help bridge those gaps and foster needed trust, but all ecosystem

actors must recognize and guard against unlawful or unwanted knowledge transfer. Rivals are already attempting to duplicate U.S. fusion companies' successes,[458] and as fusion becomes a commercial reality, sabotage and IP theft will likely grow.[459]

- DOE should leverage ongoing and new PPPs to enhance information sharing between the national labs and commercial fusion companies, and should explore mechanisms for streamlining contracting and IP sharing processes so that PPPs can keep pace with industry.

- The government should provide companies at the leading edge of fusion technologies with access to adequate training and resources to mitigate information security vulnerabilities such as cybersecurity risks and intellectual property theft.

- ITER, a scientific collaboration amongst 35 countries, should remain an important driver of international fusion research and information sharing.[460] Looking ahead, ITER can also provide a forum for shaping the global norms of an international commercial fusion ecosystem and a model for how democracies can engage in global research and development while building in select research security measures.

Bolster the Fusion Supply Chain:
Fusion supply chains that used to exist in the United States have degraded due to long government timelines and have since moved abroad where they are vulnerable to geopolitical forces.[461] Already, some fusion startups have reported that they have trouble sourcing complex components from within the U.S. due to an absence of domestic firms capable of manufacturing them.[462]

- The NMM should lead a public-private roadmapping exercise to identify supply chain bottlenecks for the wider set of inputs required for commercialization and reshore or friendshore suppliers of key precision materials.[463] Leveraging the commercial demand for complex industrial components to scale a durable fusion supply chain can concurrently help drive a revitalization of U.S. manufacturing.

Foster a Broad Base of Fusion Talent:
The United States must convince the 21 commercial fusion companies[464] based in the U.S. to stay and attract the fusion entrepreneurs of the future. Public-private incentives and regulatory certainty will go a long way, but must deliver before the business equation pushes firms abroad.

- Framing work associated with fusion as part of a bold, national mission – such as powering the nation on limitless, clean energy – can drive educational investments and inspire future generations to pursue careers to help recreate the power of the sun on earth.[465]

- Experts can help policymakers at all levels, including state and local officials, understand the potential of fusion energy and disseminate the benefits regarding fusion's safety and its potential to their constituents.

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418 Boštjan Videmšek, Nuclear Fusion Could Give the World a Limitless Source of Clean Energy. We're closer Than Ever To It, CNN (2022). Fusion is expected to generate four times more energy than nuclear fission and four million times more than fossil fuels. See Making It Work, ITER (last accessed 2022). Fusion could also help advance other energy and climate-related technologies, such as advanced hydrogen production, water desalination, direct CO2 capture, electrofuel, and chemical production. *See* Latest News, ITER (last accessed 2022).

419 See Miklós Dietz, et al., Will Fusion Energy Help Decarbonize the Power System?, McKinsey & Company (2022).

420 Fusion energy has been valued as a $40T market if it replaces just 1% of global energy draw. See Nuclear Fusion Market Could Achieve a $40 Trillion Valuation, Bloomberg Intelligence (2021).

421 See Melanie Windridge, The New Space Race Is Fusion Energy, Forbes (2020); Written testimony of Scott Hsu before the Senate Committee on Energy and Natural Resources (2022).

422 Tom Wilson & Ian Bott, Nuclear Fusion: Why the Race to Harness the Power of the Sun Just Sped Up, Financial Times (2021).

423 Several technological approaches are being pursued to sustain a relevant plasma energy breakeven point in which the energy output of a fusion reaction exceeds its input ($Q > 1$) for a certain amount of time, demonstrating the commercial viability of the energy source. Approaches range from the mainstream (magnetic, inertial, and magneto-inertial confinement) to the unconventional (muon-catalyzed fusion). See The Global Fusion Industry in 2022, Fusion Industry Association (2022); 60 Years of Progress, ITER (last accessed 2022).

424 Haje Jan Kamps, Helion Secures $2.2B to Commercialize Fusion Energy, TechCrunch (2021); David Chandler, MIT-Designed Project Achieves Major Advance Toward Fusion Energy, MIT News (2021).

425 Readout of the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy, The White House (2022).

426 Written testimony of Bob Mumgaard before the Senate Committee on Energy & Natural Resources, The Federal Government's Role in Supporting the Commercialization of Fusion Energy (2022).

427 As of writing, the Fusion Industry Association reported $4.7 billion in private investment in fusion. See The Global Fusion Industry in 2022, Fusion Industry Association at 6 (2022). Since publication of the FIA report, fusion company TAE Technologies reported an additional $250 million in funding, bringing total private investment in fusion over $5 billion. See Timothy Gardner, U.S. Nuclear Fusion Company TAE Raises $250 Million in Latest Round, Reuters (2022).

428 New Survey of Fusion Energy Companies Throws Spotlight on Important Growing Industry, UK Atomic Energy Authority (2021); The Global Fusion Industry in 2022, Fusion Industry Association at 7 (2022).

429 Haje Jan Kamps, Helion Secures $2.2B to Commercialize Fusion Energy, TechCrunch (2021); David Chandler, MIT-Designed Project Achieves Major Advance Toward Fusion Energy, MIT News (2021).

430 See Department of Energy to Provide $21 Million for Artificial Intelligence and Machine Learning Research on Fusion Energy, U.S. Department of Energy (2020); Martin Greenwald, Machine Learning, Harnessed to Extreme Computing, Aids Fusion Energy Development, MIT News (2022); Barry Fitzgerald, Faster Fusion Reactor Calculations Thanks to Machine Learning, Phy.org (2021); Rebecca Sohn, Fusion Plasmas Meet Their Match in Reinforcement Learning, IEEE Spectrum (2021).

431 See UK Atomic Energy Authority, AI Has Star Power to Accelerate Fusion, UK Government (2022); Jonathan Spencer Jones, AI to Accelerate Fusion R&D, Power Engineering International (2022); Abigail Beall, Why Cracking Nuclear Fusion Will Depend on Artificial Intelligence, NewScientist (2020); Oliver Peckham, Eyeing Nvidia's Omniverse for Fusion Reactor Design, HPCwire (2022).

[432] See Oliver Freeman, Nuclear Fusion: Building a Star on Earth Is Hard, Which Is Why We Need Better Materials, The Conversation (2021); UK Fusion Materials Roadmap, UK Atomic Energy Authority (2021); Valentina Ruiz Leotaud, Lithium Could Help Control Extreme Heat in Future Fusion Facilities, Mining.com (2021).
[433] See Future Fusion Reactors Could Be Built on 3D-Printed Ceramics, Oak Ridge National Laboratory (2021).
[434] Readout of the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy, The White House (2022).
[435] Department of Energy Announces $50 Million for a Milestone-Based Fusion Development Program, U.S. Department of Energy (2022).
[436] A £222 million public-private partnership will build a pilot plant by 2040 and another £184 million public-private partnership will lay the foundations for commercial fusion innovation. See Ten Point Plan for a Green Industrial Revolution, UK Government at 26 (2020).
[437] The UK announced in October a power station in Nottinghamshire as the site for a prototype fusion plant it plans to build by 2040. A concept design for the plant is expected to be completed by 2024. See Site of UK's First Fusion Energy Plant Selected, UK Government (2022).
[438] For example, a top Canadian fusion company, General Fusion, decided to build its first reactor in the UK. See Jonathan Tirone, Bezos-Backed Fusion Startup Picks U.K. to Build First Plant, Bloomberg (2021).
[439] The PRC called for "comprehensive research facilities for critical systems of fusion reactors" in its 14th Five Year Plan. See CSET Original Translation: China's 14th Five-Year Plan, Center for Security and Emerging Technology at 14 (2021). PRC efforts underway to pursue fusion include a startup called Energy Singularity that has raised an estimated $59 million, and a government backed research effort called the Experimental Advanced Superconducting Tokamak. The ENN Fusion Technology R&D Center claims to be one of seven companies with over $200 million in funding. See Energy Singularity - Funding, Financials, Valuation & Investors, Crunchbase (last accessed 2022); The Global Fusion Industry in 2022, Fusion Industry Association (last accessed 2022). Another PRC-backed initiative is the Experimental Advanced Superconducting Tokamak (EAST) reactor program. See Ben Turner, China's $1 Trillion 'Artificial Sun' Fusion Reactor Just Got Five Times Hotter Than the Sun, Live Science (2022). On China's plans for a fusion pilot plant, See Federal Pivot to Supporting Commercial Fusion Energy Underway, American Institute of Physics (2022).
[440] See David Hart, The Impact of China's Production Surge on Innovation in the Global Solar Photovoltaics Industry, Information Technology & Innovation Foundation (2020).
[441] On commercial timelines, see Haje Jan Kamps, Helion Secures $2.2B to Commercialize Fusion Energy, TechCrunch (2021); David Chandler, MIT-Designed Project Achieves Major Advance Toward Fusion Energy, MIT News (2021). On current U.S. Government timeline, see John Mandrekas & Colleen Nehl, Informational Webinar: Milestone-Based Fusion Development Program, U.S. Department of Energy at Slide 4 (2022).
[442] The first phase of the milestone program is expected to make between three and five awards, up to a total $50 million, for "pre-conceptual designs and technology roadmaps." Milestone applications allow for-profit companies to partner with national labs, universities, and other organizations. See Milestone-Based Fusion Development Program Funding Opportunity Announcement, Department of Energy at 11 (2022).
[443] The milestone program was modeled on the NASA COTS program, which was successful because an upfront investment of $500 million over five years gave the private sector confidence and enabled NASA to plan over a longer-time horizon. See Written testimony of Bob Mumgaard before the Senate Committee on Energy & Natural Resources, The Federal Government's Role in Supporting the Commercialization of Fusion Energy (2022); Dennis Stone, NASA's Experience in Other Transaction Authority to Foster Development, NASA (2022).
[444] First announced in June 2021, DOE's "Energy Earthshot" program aims to "accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade." Previous Energy Earthshots have included the Hydrogen Shot, the Long Duration Storage Shot, the Carbon Negative Shot, the Enhanced Geothermal Shot, the Floating Offshore Wind Shot, and, most recently, the Industrial Heat Shot. See Energy Earthshots Initiative, U.S. Department of Energy (last accessed 2022).
[445] The Energy Act of 2020 authorized a combined $325M for FY 2021-2025 for DOE to create a "'milestone-based development program' that would award participants funding to support the R&D to enable construction of new full-scale fusion systems 'capable of demonstrating significant improvements' in performance within 10 years of the legislation's enactment." See Amy Roma, Energy Act of 2020—Variety of Provisions for Fission and Fusion, Hogan Lovells (2020).
[446] Those who attempted to scale solar energy reflected that delaying deciding a technical path would have been beneficial, see Garrett Nilsen, Scaling Solar: Lessons Learned, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy at slide 13 (2022).
[447] Fusion is currently a basic science mission within the Department of Energy's Office of Science. See Fusion Energy Sciences, U.S. Department of Energy (last accessed 2022).

[448] In a private engagement with SCSP, a fusion company noted that the Department of Energy's Office of Nuclear Energy could provide a model for an applied fusion office.
[449] The Bold Decadal Vision created this position, which currently reports to the Undersecretary for Science and Innovation. See Fact Sheet: Developing a Bold Vision for Commercial Fusion Energy, The White House (2022).
[450] See Andrew Holland, The Voice of a New Industry, Fusion Industry Association (2022).
[451] The Biden Administration requested $32 million for all fusion-related public-private partnerships in fiscal year 2023, encompassing both the milestone-based program as well as the smaller INFUSE program, which supports collaborations between private fusion ventures and DOE national labs. See DOE Office of Science Budget: FY22 Outcomes and FY23 Request, American Institute of Physics (2022).
[452] New DOE Program Connects Fusion Companies with National Labs, U.S. Department of Energy (2022); Ahmed Diallo, Innovation Network for Fusion Energy (INFUSE) Program Overview, Princeton Plasma Physics Laboratory at 5 (2021).
[453] $30 million government funding in ARPA-E ALPHA program leveraged $570 million in private funds, and $40 million government funding in BETHE leveraged $200 million in private funding. See Written testimony of Bob Mumgaard before the Senate Committee on Energy & Natural Resources, The Federal Government's Role in Supporting the Commercialization of Fusion Energy at 7 (2022).
[454] Creating a Fusion Prototypic Neutron Source facility will be an essential step towards commercializing fusion as it would generate important data for the development of the necessary high-performance structural and plasma-facing materials. See Brian Egle, et al., U.S. Fusion D-Li Neutron Irradiation Facility: Fusion Prototypic Neutron Source (FPNS) Technology Study, Oak Ridge National Laboratory (2019)
[455] James Broughel, New NRC Report Outlines Options For Regulating Nuclear Fusion, Forbes (2022).
[456] Fusion differs from traditional nuclear fission in that it relies on a continuous input of fuel as opposed to a chain reaction. See Fusion - Frequently asked questions, International Atomic Energy Agency (last accessed 2022); Amy C. Roma & Sachin S. Desai, The Regulation of Fusion – A Practical and Innovation-Friendly Approach, Hogan Lovells at 12-13 (2020).
[457] Preliminary White Paper – Licensing and Regulating Fusion Energy Systems, U.S. Nuclear Regulatory Commission (2022).
[458] See Chinese Fusion Energy Programs Are A Growing Competitor in the Global Race to Fusion Power, Fusion Industry Association (2021); Federal Pivot to Supporting Commercial Fusion Energy Underway, American Institute of Physics (2022) (citing congressional testimony by Princeton Plasma Physics Lab Director Steven Cowley).
[459] Fusion companies noted in private engagements with SCSP that IP protection is one area where fusion companies that do not or cannot prioritize security costs can learn best practices from the national labs.
[460] What is ITER?, iter.org (last accessed 2022).
[461] See Daniel Clery, Out of Gas, Science (2022); Catherine Clifford, This Government Lab in Idaho Is Researching Fusion, the 'Holy Grail' of Clean Energy, as Billions Pour Into the Space, CNBC (2022); Alan Neuhauser, Scoop: Russia Sanctions Threaten Commonwealth's Supply Chain, Axios (2022); David Matthews, ITER Faces Further Delays if Key Parts Stuck in Russia, Science Business (2022).
[462] SCSP Engagement with a commercial fusion company (May 2022).
[463] This could mirror the roadmapping exercise conducted by the UK's atomic energy agency in 2021. See UK Fusion Materials Roadmap, UK Atomic Energy Authority (2021).
[464] The Global Fusion Industry in 2022, Fusion Industry Association at 7 (2022).
[465] See e.g., Students at Institutions Across the U.S. Learn About Plasma and Fusion Research in New Program Managed by PPPL, Princeton Plasma Physics Laboratory (2021).