The Promise of Fusion

Limitless Clean Energy

Excitement Abounds in the U.S. Fusion Program

- A recent National Academies of Sciences report concluded "Now is the right time for the United States…to take steps towards the development of fusion electricity for the nation's future energy needs."

- The U.S. fusion community has joined together to develop a unified strategic plan that will provide world leadership in key areas of fusion development on the path to a fusion pilot plant in the next few decades.

- U.S. fusion facilities, bolstered by new upgrades, are carrying out pioneering research into the science of high-temperature plasmas and meeting the challenges of preparing for a next generation of devices that will demonstrate copious fusion power and prepare for a fusion pilot plant.

- Increases in congressional funding in FY18-19 have enhanced U.S. activities dramatically, attracting increased interest from highly qualified graduate students, post docs, and early career researchers.

- ITER construction towards initial operation is now over two-thirds complete, with scheduled first plasma operations only five years away.

- Private investment in fusion is ramping up, striving to develop technologies that may accelerate the timeline to the demonstration of fusion electricity.

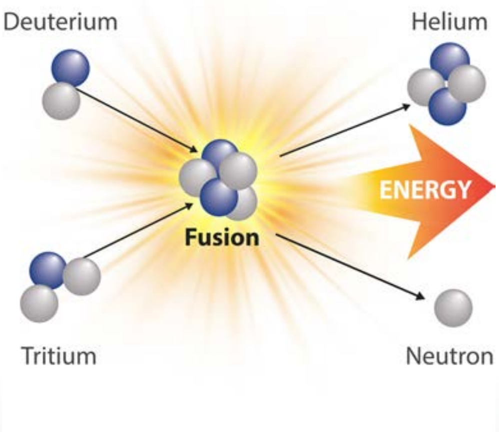
Fusion energy promises to be a key part of the world's energy landscape in the latter half of this century. Increased investment is needed to ensure that the U.S. remains at the forefront of this important technology.

Table of Contents

What is Fusion
and how can we make it?

Fusion is the energy source that powers the sun and other stars in our universe.

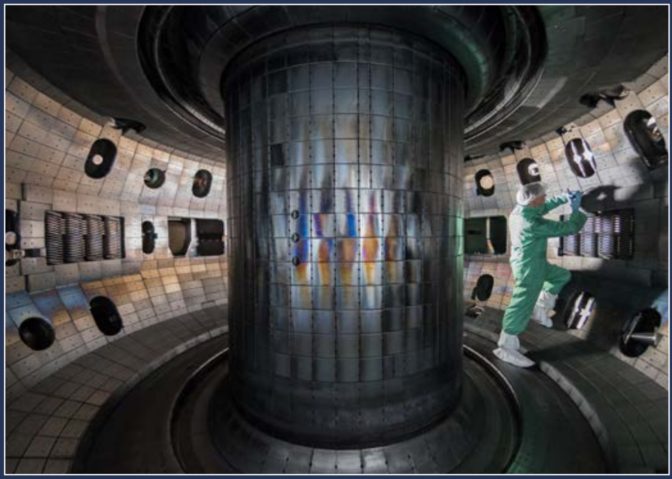
Fusion is the ultimate source of life and energy on earth.



When two light nuclei fuse to create a single heavier one, large amounts of energy are released. Fusion is far more efficient than other methods of energy production, producing millions of times more energy per gram of fuel than burning oil.

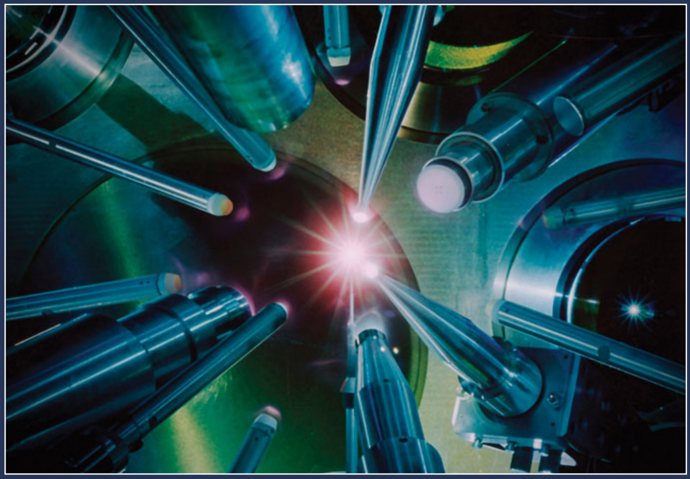
Very intense conditions are necessary to create fusion. In stars, gravity compresses hydrogen to enormous pressures until protons fuse together. Temperatures reach 25 million degrees, and the densities are immense.

We can't create such intense gravitational pressures on earth, so scientists have developed other methods to confine the fuel and create a fusion reaction.



Magnetic Confinement Fusion

Strong magnetic fields hold hydrogen in a "plasma" state, where it has been heated until it becomes a mix of charged particles and free electrons. This plasma is further heated to fusion conditions using microwaves or particle beams. Pressures are much lower than inside a star, but the temperatures are several times higher – often hundreds of millions of degrees.



Inertial Confinement Fusion

Extremely powerful lasers or electrical discharges are used to implode a tiny fuel pellet or capsule. This forms a plasma that briefly reaches densities and temperatures high enough to induce fusion.

Fusion offers the potential for nearly

Limitless Clean Energy

Fusion is clean and carbon-free: It produces no emissions and the only byproduct is helium.

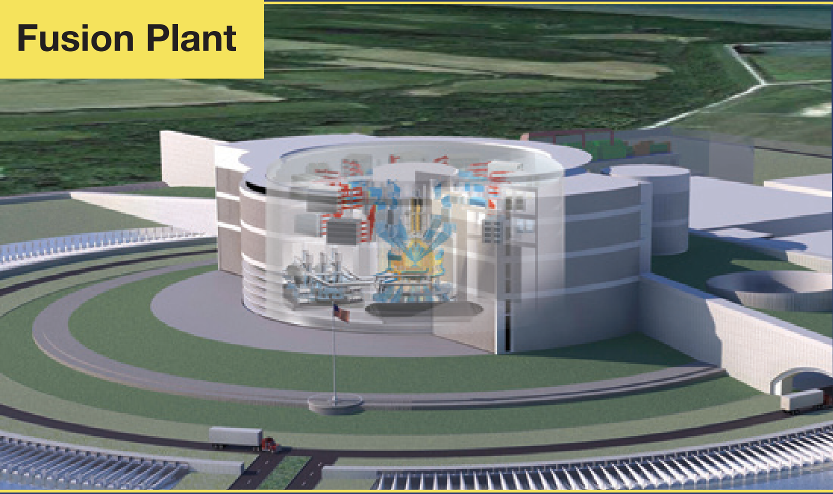
Fuel for fusion power is cheap and abundant: Its primary fuels are deuterium and lithium, which are abundant and readily available on Earth.

Fusion-powered electricity will be available 24/7: Fusion plants will run around the clock, providing clean, always-on electricity that can work with solar and wind generation.

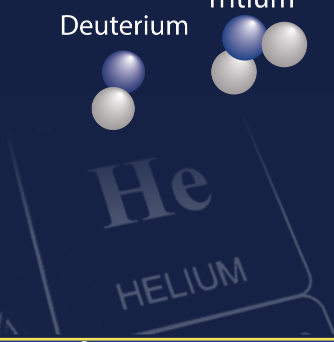
Fusion is safe: The fusion reaction stops quickly and safely when external power is removed.

To produce 1,000 megawatts of electricity for one day
(enough for one million homes)

Fusion Plant



A fusion plant will consume only 1 pound of deuterium and 1.5 pounds of tritium



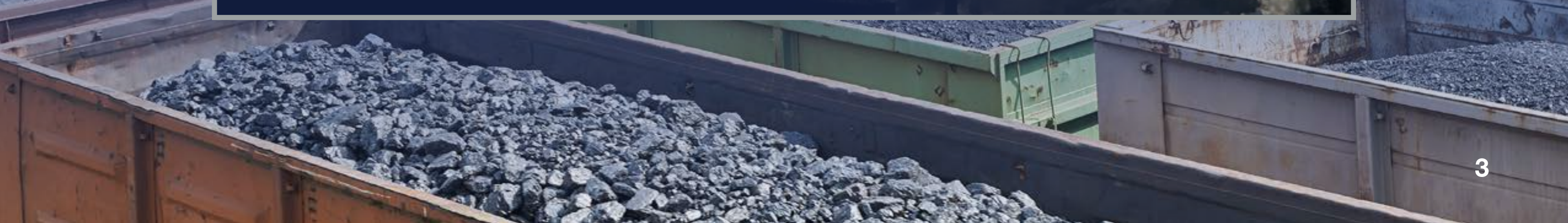
and it produces only 2 pounds of helium.

Versus

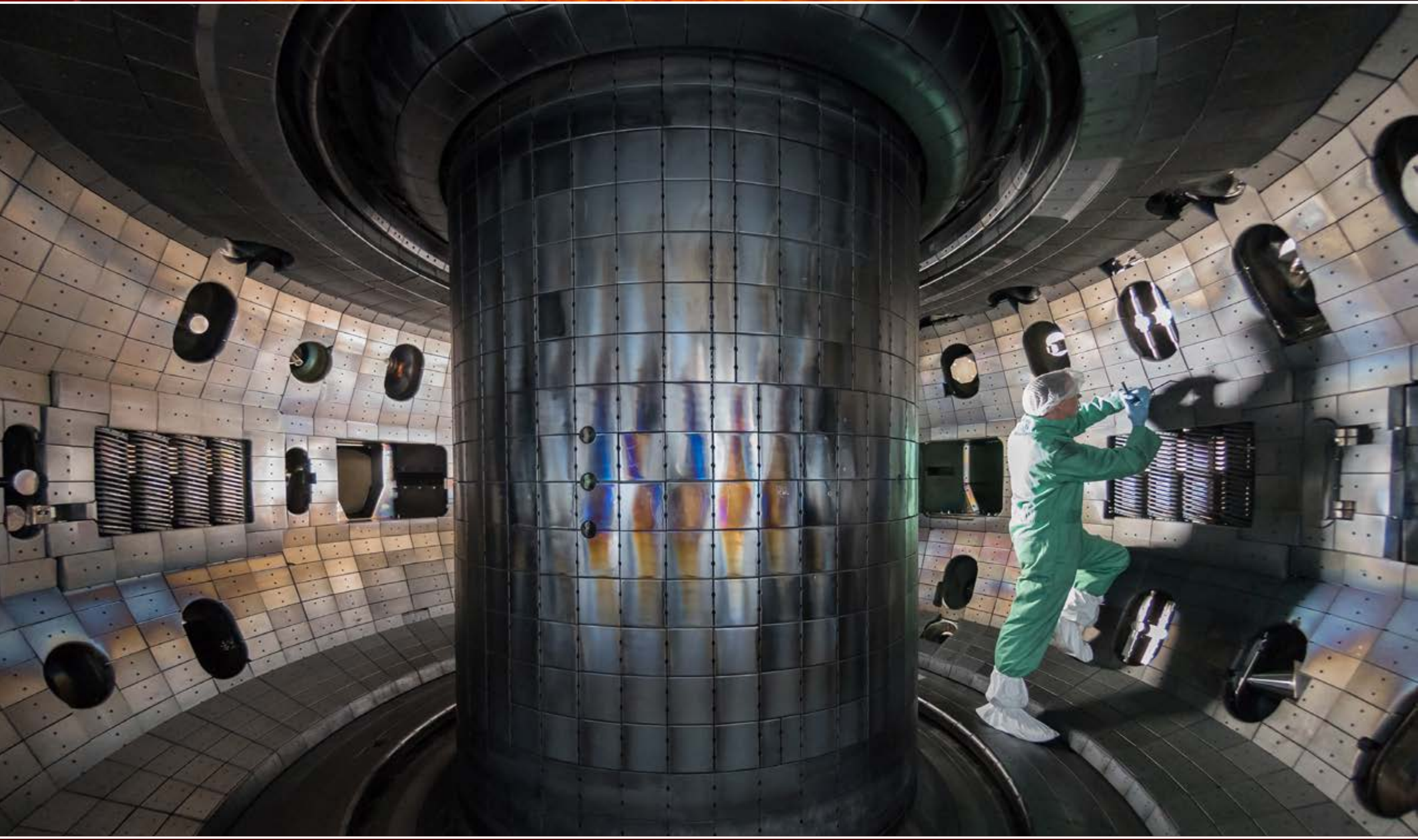
A coal plant consumes 18 million pounds of coal, and leaves behind

- **60 million pounds of CO_2**
- **1.2 million pounds of SO_2**
- **160,000 pounds of NO_2**
- **4 million pounds of ash and solid waste**

Coal Plant



DIII-D National Fusion Facility



Harnessing the Power of the Sun

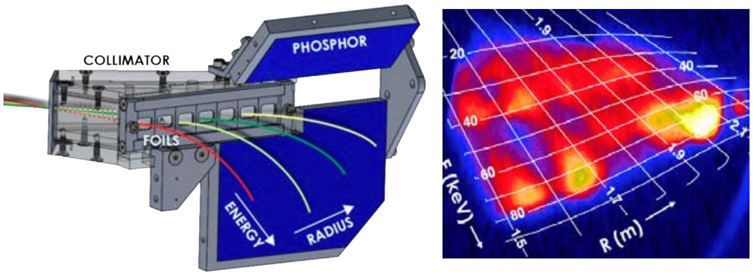
DIII-D is the largest magnetic fusion facility in the U.S., with several unique operational capabilities and a comprehensive set of measurement systems.

Research at DIII-D is aimed at building the pathway to practical fusion energy through cutting-edge plasma science, state-of-the-art engineering, and high-performance computing and simulations. Many of the parameters of future fusion power plants were first established at DIII-D, making it a critical component of the U.S. fusion community's plan to create a next-generation fusion pilot plant.

In recent years, scientists at DIII-D have solved a number of key physics problems for practical fusion power, among them techniques to limit and mitigate conditions that could damage the reactor, as well as techniques for maintaining a fusion plasma for extended periods. The DIII-D team has also developed operating scenarios for application to ITER–the multinational fusion experiment being built in France to demonstrate the practicality of fusion as an energy source–while pioneering important measurement techniques that will be necessary for future fusion reactors

The science being pursued at DIII-D has been highlighted in hundreds of peer-reviewed articles and presentations at scientific conferences.

Award-Winning Science Advancing New Energy and Technology Research and Development



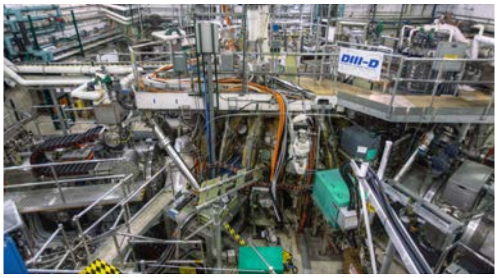
A novel Imaging Neutral Particle Analyzer measures neutralized fast ions escaping from the DIII-D tokamak plasma

- Seven-time winner of the "John Dawson Award for Excellence in Plasma Physics Research" from the American Physical Society
- 47 Fellows of the American Physical Society
- Pioneered innovative approaches that have provided solutions to several key fusion challenges

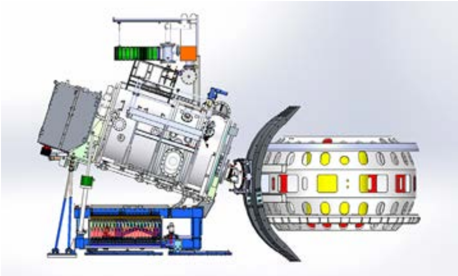
Major Hub for the U.S. and International Scientific Communities

- More than 650 collaborating researchers from over 100 institutions worldwide
- Partnerships with seven U.S. national laboratories
- 40 universities among collaborators with more than 80 doctoral theses produced
- Over 150 current graduate students and post-doctoral users

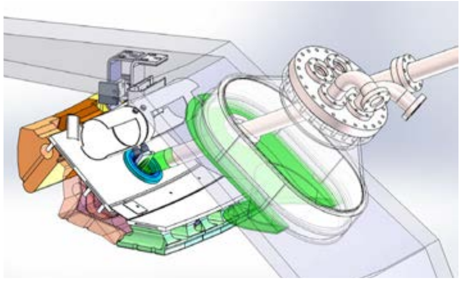
DIII-D National Fusion Facility, San Diego, California



Upgrades to Stay on the Cutting Edge of Fusion Plasma Research



Off-Axis Neutral Beam



Top-Launch Electron-Cyclotron Current Drive

- New high-frequency "Helicon" antenna
- High-Field-Side Lower Hybrid Current Drive
- Divertor improvements and diagnostics

DIII-D completed a year-long major upgrade in May 2019 that has significantly increased its capabilities for exploring high-pressure plasmas and conditions relevant to future fusion reactors. This research is expected to inform the design of future fusion power plants. Further upgrades are planned that will both increase heating power and drive higher levels of current in the plasma to help stabilize and maintain it for longer periods.

ITER is Rapidly Progressing with U.S. Support

ITER is the largest scientific experiment ever built on earth and will provide scientists with a first glimpse at how plasmas self-organize when fusion reactions provide most of the heating. ITER's goal is to generate ten times the energy required to heat the plasma and sustain that reaction for more than 400 seconds - both critical in demonstrating the feasibility of fusion. In 2019, this unprecedented project of 35 nations surpassed the two-thirds mark of construction toward readiness for first operation.

U.S. Technology Community is Contributing Many Critical High-Tech Components

- Central Solenoid
- Diagnostics
- Toroidal Field Coil Conductor
- Disruption Mitigation System
- Steady-State Electrical Network
- Pellet Injection (Fueling) System
- Electron Cyclotron Heating Transmission Lines
- Ion Cyclotron Heating Transmission Lines
- Tokamak Exhaust Processing System
- Tokamak Cooling Water System
- Vacuum Auxiliary and Roughing Pumps System

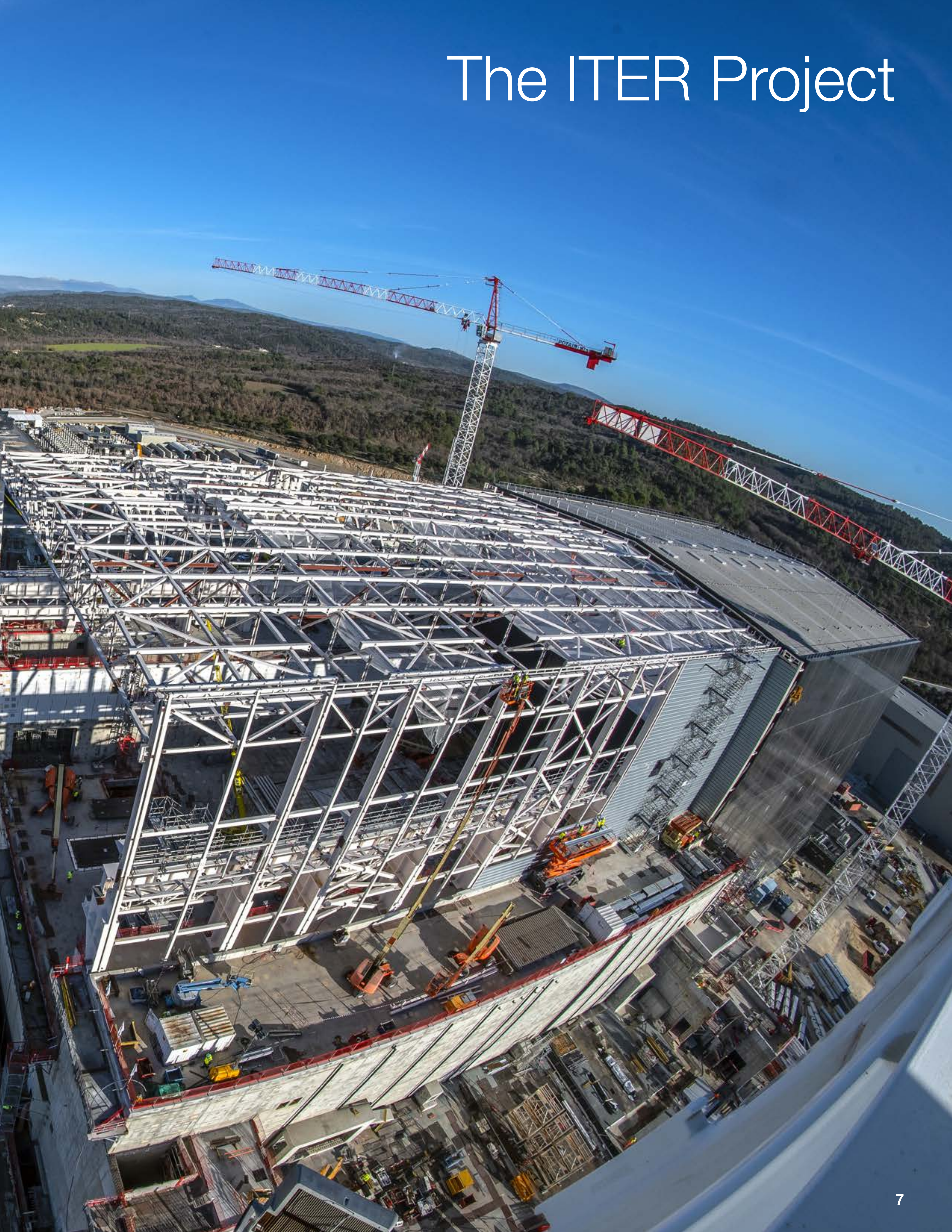
U.S. Participation in ITER is Vital

- Full participation endorsed by National Academies of Sciences' Burning Plasma Committee
- U.S. receives 100% of data and results for 9% of the construction cost
- More than 80% of U.S. funding for ITER is spent in the U.S., helping to develop critical high-tech skills in our domestic workforce
- Supports more than 1,000 high-tech domestic jobs
- Keeps U.S. fusion community at the forefront of global innovation

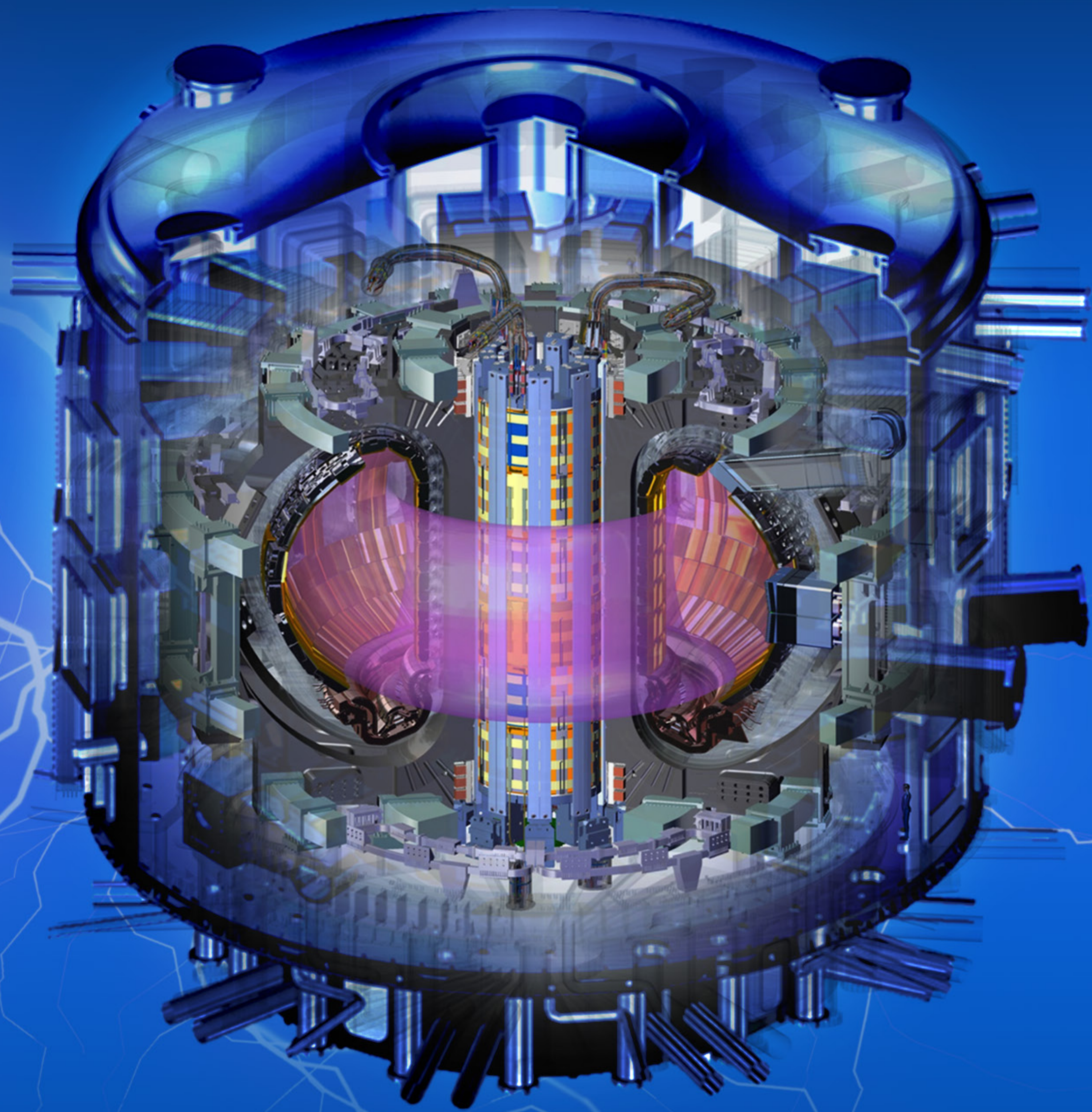
"The United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant."

—National Academies of Sciences 2018 report

The ITER Project



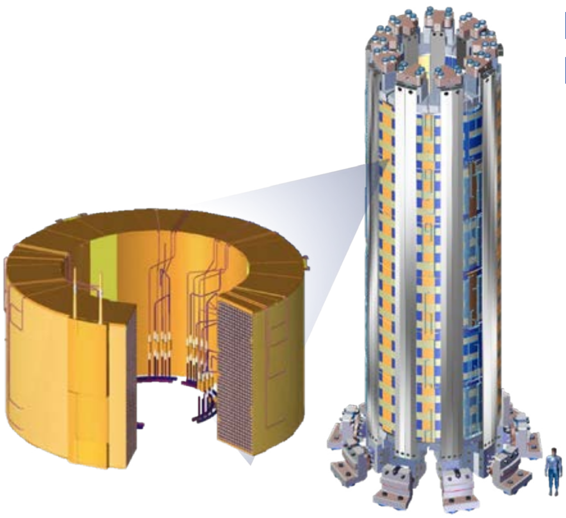
ITER Central Solenoid



The Heart of ITER

General Atomics is fabricating the world's largest pulsed superconducting magnet – ITER's Central Solenoid. When completed, the five-story, 1,000-ton magnet will rest at the heart of the ITER fusion facility in France and play a critical role in helping achieve ITER's goal of demonstrating the viability of fusion as a practical energy source. The Central Solenoid consists of around 22 miles of superconducting cables assembled to within a few tenths of an inch accuracy. This magnet will drive 15 million amperes of electrical current in ITER's plasma, powering ITER in its quest to prove that nuclear fusion – the process that powers the stars – can produce virtually limitless, safe, clean and renewable energy.

Science and Technology



ITER Central Solenoid consists of six modules and a structure with an overall height of 59 feet

ITER Central Solenoid Precision Fabrication Processes

- **Winding:** For each of the six modules, 3.6 miles of 2-inch square superconductor is wound to high accuracy to form a coil 14 feet in diameter and seven feet tall.
- **Heating:** The coiled module is processed in a convection furnace to create the superconducting alloy.
- **Insulating:** The 250,000-pound coil is lifted and the turns are separated to apply 180 miles of insulating tape.
- **Encapsulating:** The coil is placed in a mold for injection of 1,000 gallons of epoxy.
- **Testing:** Magnet coils are cooled to -450° F (4 K) and tested to simulate ITER operations.

Turn insulation of module nearing completion

Other GA-Supplied ITER Technologies

- Low-energy-loss, high-power microwave transmission line components.
- Software for real-time plasma control.
- Methods to prevent uncontrolled collapse of ITER plasmas.
- **Low-Field-Side-Reflectometer:** measures plasma density profiles.
- **Wide Angle Visible & Infrared Viewing System:** monitors plasma hot spots.
- **Toroidal Interferometer Polarimeter:** measures plasma density.

Four ITER CS production modules in various stages of fabrication, from left, prepping the module for vacuum pressure impregnation, following heat treatment, post-turn insulation and fabrication complete, prepared for testing.

Broader Benefits of
Harnessing Star Power

Spinoff Technologies from Fusion Energy Research

Many basic science discoveries, while important by themselves and foundational in their fields, also yield spinoff applications or enabling technologies not envisioned by the scientists doing the original work. This is what makes investment in science like fusion energy research so powerful – the impact extends well beyond the laboratory.

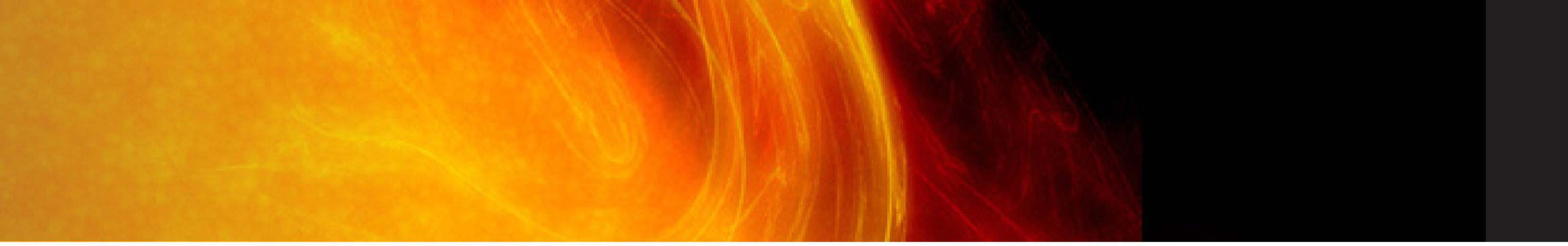
In the quest for fusion energy, numerous new scientific frontiers and technologies have been, and are being, created. Many of these innovations and insights are proving to be invaluable in applications far afield from fusion energy research.

Spinoff technologies from fusion investments have had a transformative effect on society, with the public benefiting greatly in areas such as electronics, lighting, communication, manufacturing, and transportation. Owing to its interdisciplinary nature, many different fields of study have benefited from fusion research.

Electromagnetic Aircraft Launch System

The *USS Gerald R. Ford* was the first aircraft carrier to use an electromagnetic catapult, enabled by fusion science. Developed by General Atomics using knowledge gained in fusion research, the Electromagnetic Aircraft Launch System, or EMALS, is now replacing the Navy's steam catapults on new *Ford*-class carriers. The use of electromagnetics lowers operating costs and improves catapult performance. The enabling innovation came from fusion research that allowed for a precise control of the sequencing magnets. For EMALS, that precision enables adjustable launch capacity and expands the range of aircraft that carriers can now launch.

EMALS

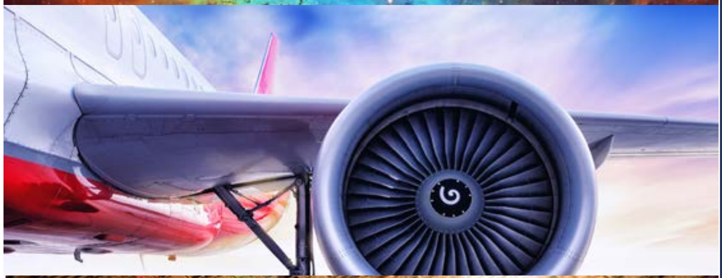


Driving Innovation in Computing

Understanding and controlling the complexities of fusion plasmas is one of the key areas of inquiry for DOE's supercomputing program at facilities like the Summit supercomputer at Oak Ridge National Lab.

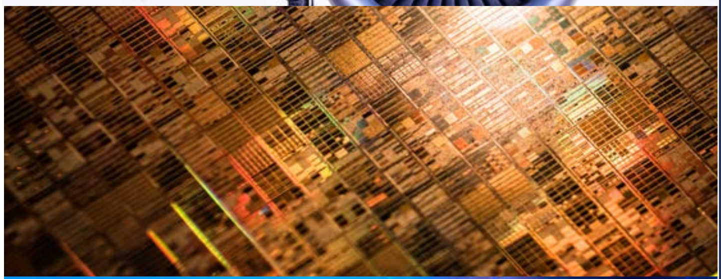
Understanding Our Universe

Using the knowledge and tools needed to control fusion plasmas, fusion computing codes have been used at CERN to improve the Super Proton Synchrotron, which provides beams for the Large Hadron Collider, an engine for discovery about the fundamental structure of matter and elementary particles.



Safer, More-Efficient Jet Engines

To handle the extreme heat inside a jet engine, turbine blades are typically spray coated with ceramic particles injected in a plasma jet. Research fueled by fusion studies has been vital in optimizing the process.



Silicon Wafers

Plasmas are used to etch and deposit materials on thin silicon wafers. Advances in plasma technology have improved the performance of the process, helping to double the number of transistors on a chip every two years or so.

Spacecraft Propulsion

In plasma rockets, the energy and fuel are separate, allowing one to add more energy and achieve greater velocities – 10 to100 times that of chemical rockets. These plasma engines are being used to keep spacecraft in an assigned orbit.

Making GPS More Reliable

The faint signal transmitted by GPS satellites can easily be scattered by disturbances in a plasma layer called the ionosphere. Research into the stability of plasmas has advanced our understanding of instabilities in the ionosphere and the potential disruption of satellite signals and communication.

For more information: https://science.energy.gov/fes/benefits/spinoff-technologies

The Promise of Fusion for the Next Generation

General Atomics (GA) and the staff at the DIII-D National Fusion Facility recognize an obligation to spread the word about the potential of fusion and sustain the current momentum for future generations. Staff at DIII-D volunteer in multiple programs that raise awareness of fusion energy to a broad and diverse audience.

Public Outreach

Since 1993, GA's Education and Outreach Team has provided tens of thousands of students, teachers, and members of the public with the opportunity to interact with scientists and engineers to better understand the science of fusion and the engineering challenges of developing fusion power plants. GA also helps organize and support the Plasma Sciences Expo and Science Teacher Day for the American Physical Society's Division of Plasma Physics. These events have exposed over 35,000 middle and high school students and teachers to plasma science in 27 cities across the U.S. over the past 30 years.

Alex Nagy, a member of the GA Education and Outreach Team, gives an explosive demonstration as part of the States of Matter series outreach event.

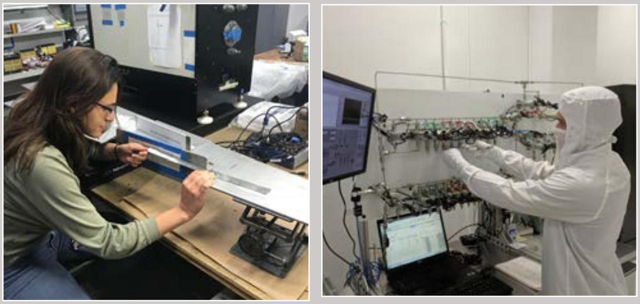
Attracting Diverse Minds

As part of its ongoing strategic planning process, the U.S. fusion community has recognized an urgent need to create a healthy climate of diversity, equity, and inclusion to address the challenges of fusion energy. DIII-D staff supports this effort by participating in numerous annual outreach efforts targeted at motivating women and other underrepresented groups to pursue careers in fusion. These programs include Better Education for Women in Science and Engineering, Expand Your Horizons, and the APS Conference for Undergraduate Women in Physics, the Anita Borg Leadership and Engagement program and a women of color mentorship program.

DIII-D volunteers, from left, Stephanie Diem, Kathreen Thome, Luz Meneghini, Livia Casali, and Cami Collins demonstrate the principles of plasma at an Expanding Your Horizons outreach event.

Moving Students from the Classroom to the Laboratory

Since 1992, DIII-D has hosted more than 200 interns through Science Undergraduate Laboratory Internship (SULI) and Community College Internship (CCI), as well as preceding programs. Each year, 10-15 SULI/CCI students spend the summer at GA, where they are assigned a staff mentor and given the chance to complete a project and write a research paper on their work. Through these programs, university students get to experience real-world, hands-on fusion research. Dozens of alumni from the program have gone on to careers in fusion research, including many who return to DIII-D.



SULI students work on scientific projects during their summer spent at General Atomics

Further Information

Important additional information about fusion and GA's work in the field is available in an online supplement to this booklet.

Visit www.ga.com/promise-of-fusion or or scan the QR code.

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