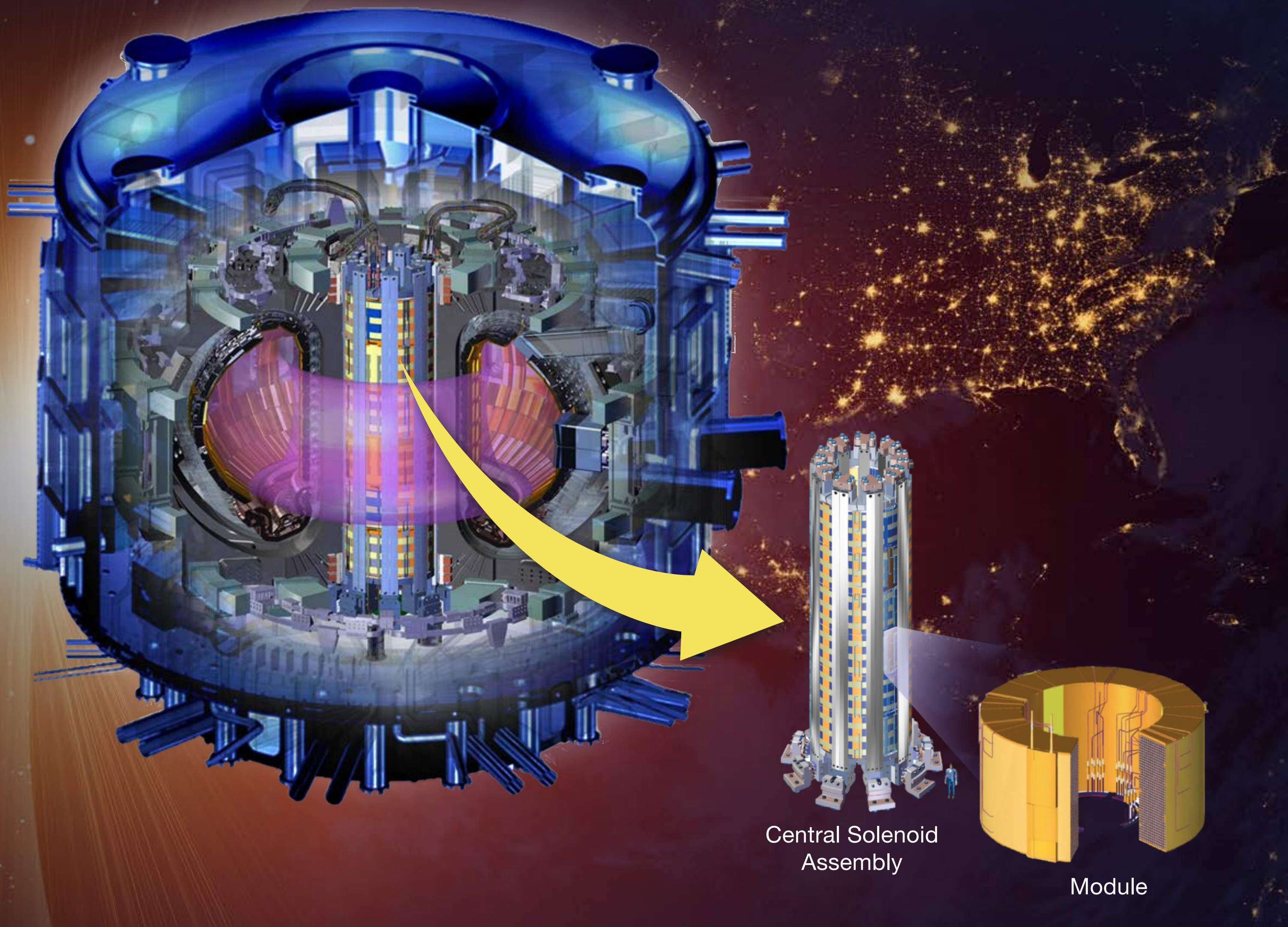
ITER Central Solenoid

The heart of the International Fusion Device



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The Rising Star of Fusion

It is a pivotal moment in the march toward clean and nearly limitless fusion energy.

Researchers worldwide are continually advancing the science and engineering we need to achieve cost-effective energy from fusion. After decades of work, many of the physical processes of fusion are well understood. That knowledge provides the basis for the construction of the ITER project – the largest science experiment ever built on earth.

Within five years, ITER will begin operations as it moves toward its goal of demonstrating the practicality of fusion as an energy source. The U.S. fusion community has joined together to develop a unified strategic plan that will guide efforts through a successful research program on ITER and on to a next-generation fusion pilot plant that will mark the dawning of the fusion era.

The revolutionary potential of fusion as an energy source is attracting growing attention, as demonstrated by more than a billion dollars of private investment flowing into U.S. companies, showing industry's readiness to partner with publicly funded researchers to complete the drive to practical fusion energy.

The timing for this moment is critical. Global population growth and increased demand could overwhelm existing electrical generation capacity at the very moment the world faces the urgent need to transition toward cleaner sources of energy.

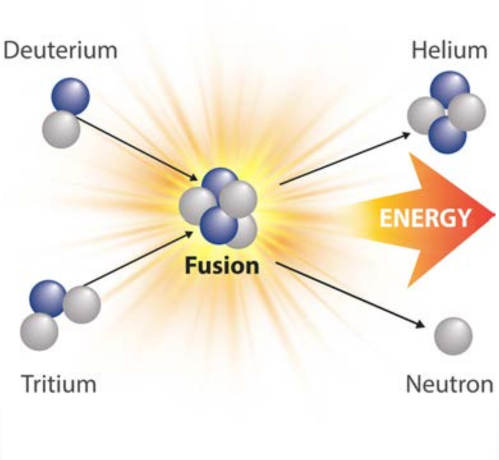
Fusion can meet that need. It is a clean and carbon-free source with a primary fuel source of deuterium and lithium, which are abundant and readily available on earth. It is safe and can provide always-on electricity that complements other sources of renewable generation.

We invite you to join us in the following pages as we explore the Promise of Fusion.

What is Fusion
and how can we make it?

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

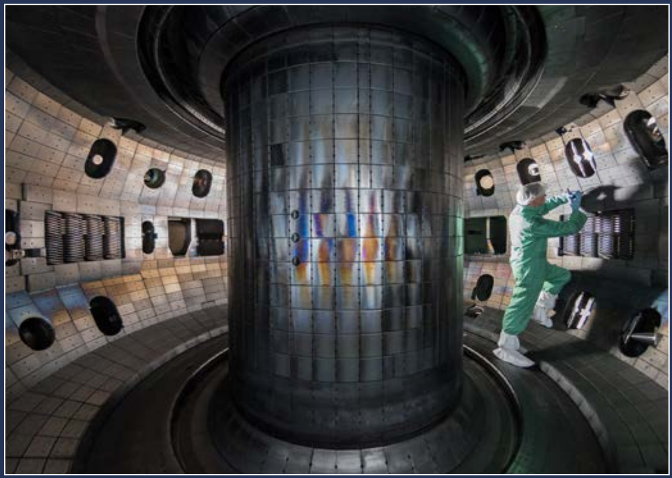
Fusion is the ultimate source of life and energy on earth.



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.

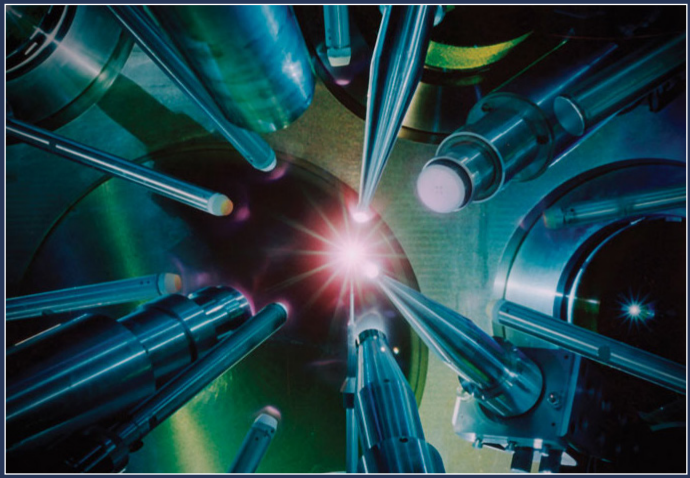
Very intense conditions are necessary to create fusion. In stars, gravity compresses hydrogen to enormous pressures until protons fuse together. Temperatures reach 25 million degrees, and the densities are immense.

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.

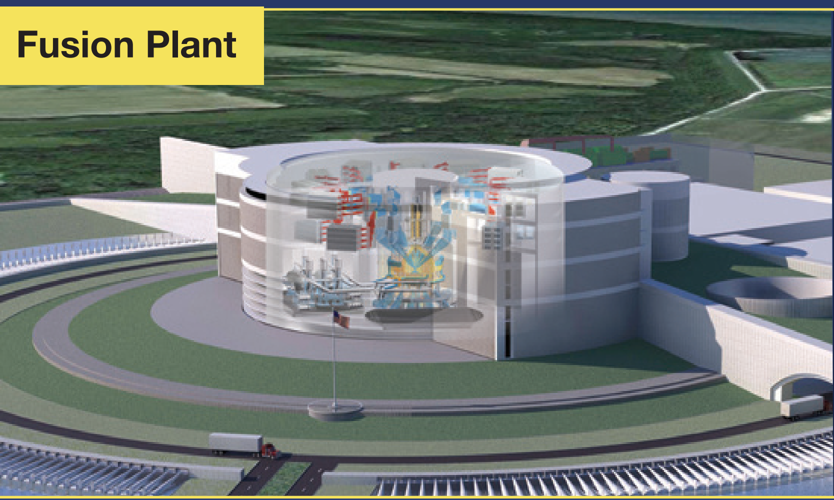
Fuel for fusion power is cheap and abundant: Its primary fuel is isotopes of hydrogen, which are abundant on Earth or available to be created in the fusion reactor.

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.

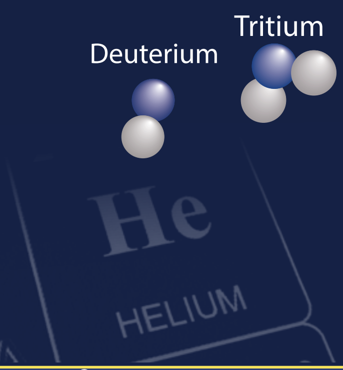
Fusion is safe: The fusion reaction stops quickly and safely when external power is removed.

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

ITER is Rapidly Progressing with U.S. Support

ITER is the largest scientific experiment ever built on earth and will provide scientists with a demonstration of 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 2021, this unprecedented project of 35 nations surpassed the 75 percent mark of construction toward readiness for first operation.

U.S. Technological Contributions to ITER

- 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

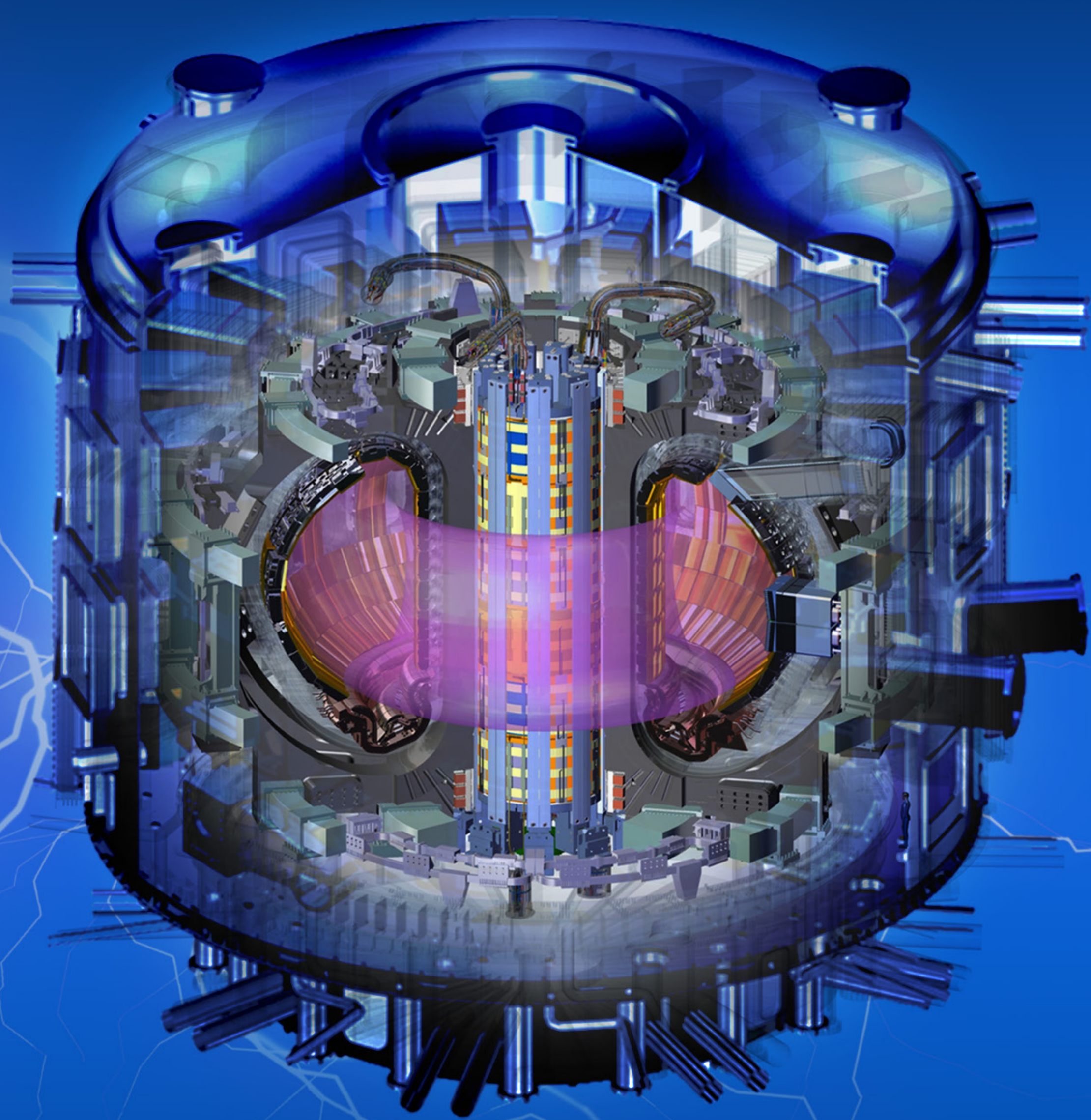
- Full participation endorsed by National Academies of Sciences' Burning Plasma Committee
- U.S. receives 100% of data and results for 9% of the construction cost
- More than 80% of U.S. funding for ITER is spent in the U.S., helping to develop critical high-tech skills in our domestic workforce
- Supports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

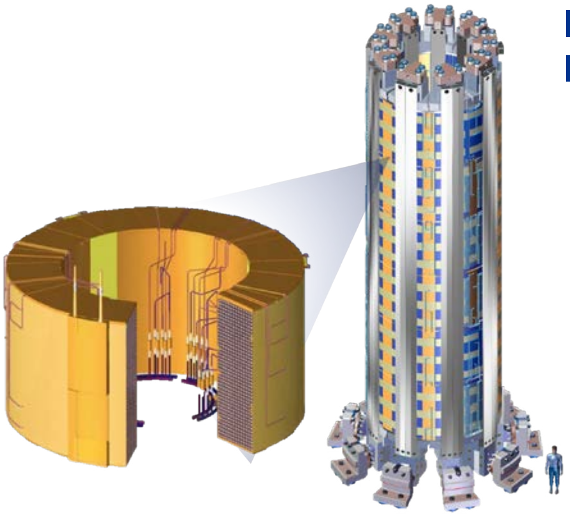
ITER Central Solenoid



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 -450º F (4 K) and tested to simulate ITER operations.

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.

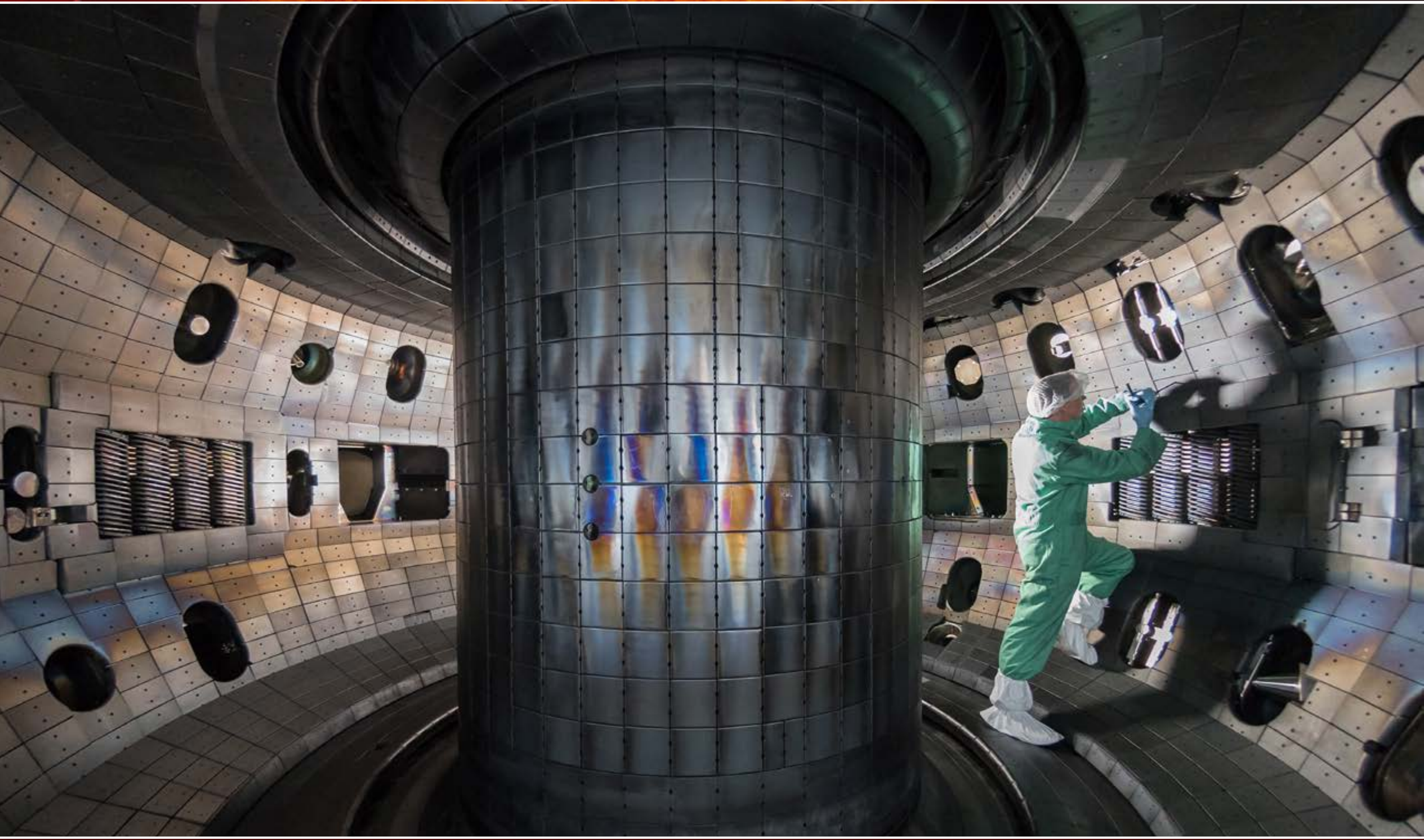
Turn insulation of module nearing completion

Plasma Diagnostics

- **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.

DIII-D National Fusion Facility



Harnessing the Power of the Sun

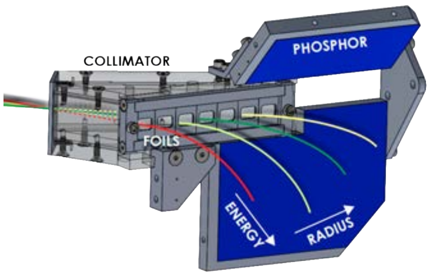
DIII-D is the largest magnetic fusion facility in the U.S., with several operational capabilities and a comprehensive set of measurement systems.

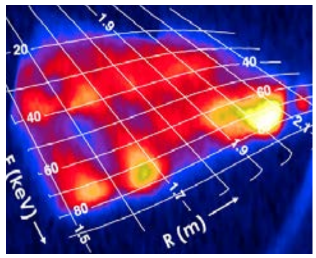
Research at DIII-D is aimed at building the pathway to practical fusion energy through cutting-edge plasma science, state-of-the-art engineering, and high-performance computing and simulations. Many of the parameters of future fusion power plants were first established at DIII-D, making it a critical 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 challenges 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





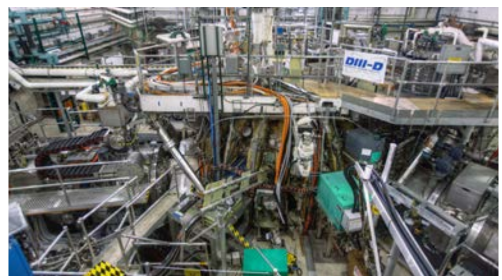
A novel Imaging Neutral Particle Analyzer measures neutralized fast ions escaping from the DIII-D tokamak plasma

- 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

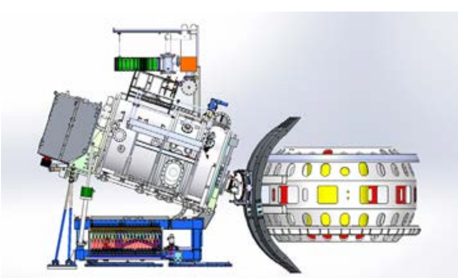
Major Hub for the U.S. and International Scientific Communities

- 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

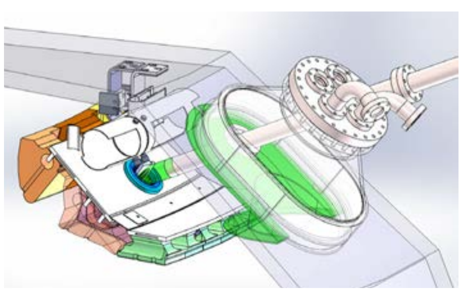
DIII-D National Fusion Facility, San Diego, California



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 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.

Advanced Materials Engineering

General Atomics is a Global Leader in Advanced Materials Engineering

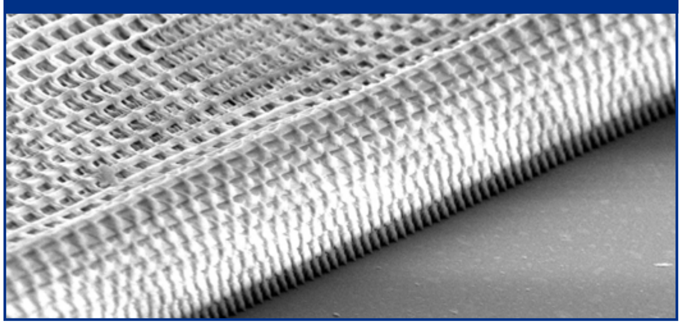
Precision Target Fabrication

General Atomics performs a wide range of novel and unique materials research and development to advance fabrication techniques and engineer materials at the micron level.

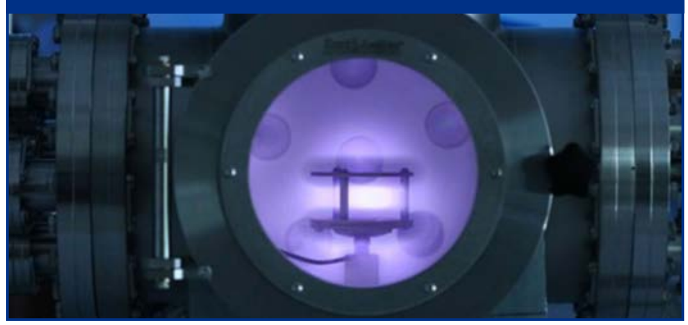
GA's has decades of experience supplying targets, target systems, and target support services for the U.S. DOE and other clients. This experience gives us unparalleled expertise in design and manufacturing capabilities and unrivaled precision in our finished products.

GA has developed a cutting-edge suite of capabilities used to manufacture innovative targets and components. These capabilities are available to outside collaborators looking for a partner to take on some of the most difficult fabrication, metrology, and technology development challenges.

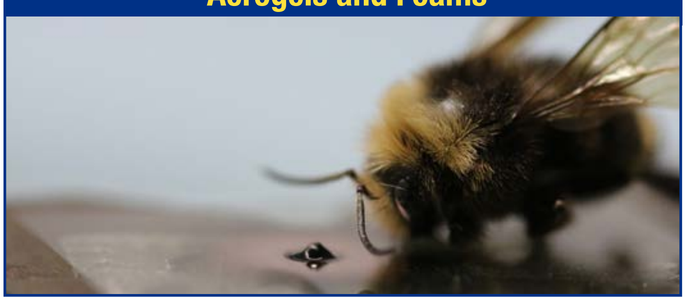
Additive Manufacturing



Coatings



Aerogels and Foams



Laser Micromachining

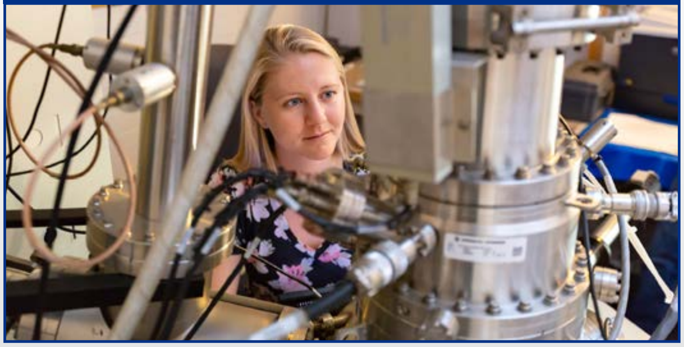
- Proven ability to manufacture unique components with precise, sub-micron tolerances.
- Combining fundamental research in the development of new materials and processes with state-of-the-art, secure facilities to customize solutions and meet customer needs.
- Innovative characterization and metrology capabilities.
- Techniques beyond optical means to measure every aspect of product fabrication.
- Products perform as designed from the moment they are delivered.

Cutting-Edge Approach to Fabrication and Metrology

Precision Manufacturing and Fabrication

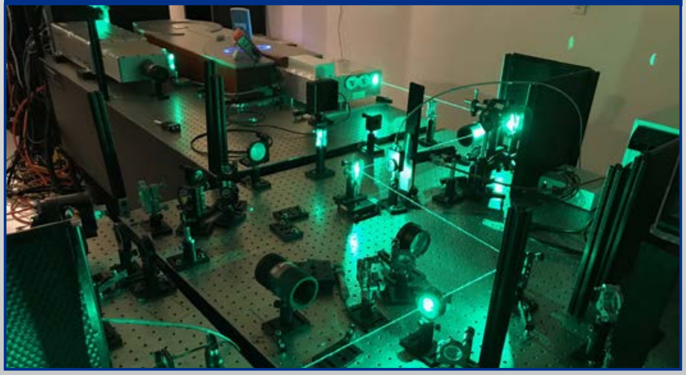
Creating extremely precise components with sub-micron tolerances

Precision Metrology and Characterization



Extensive in-house metrology using the latest technology

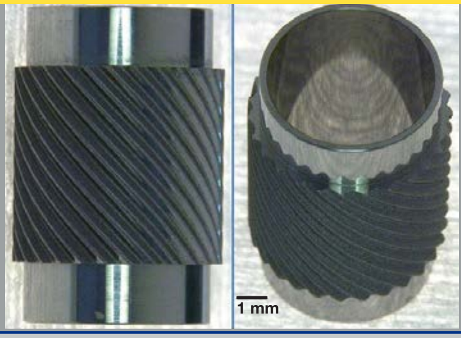
Laser Drilling and Machining



Custom laser cutting, drilling, and machining operations using a variety of wavelengths

Unique Material Capabilities

Beryllium Body with 200 µm PV Helical Ripple



Coating, plating, and machining capabilities to exacting tolerances in unique materials

Aerogels and Foams

Sub-millimeter mound of copper aerogel applied with a GA-developed nanoparticle deposition system

Classified Site and Personnel

Secure fabrication facilities, personnel, and communication channels

Broader Benefits of Harnessing Power of the Stars

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.

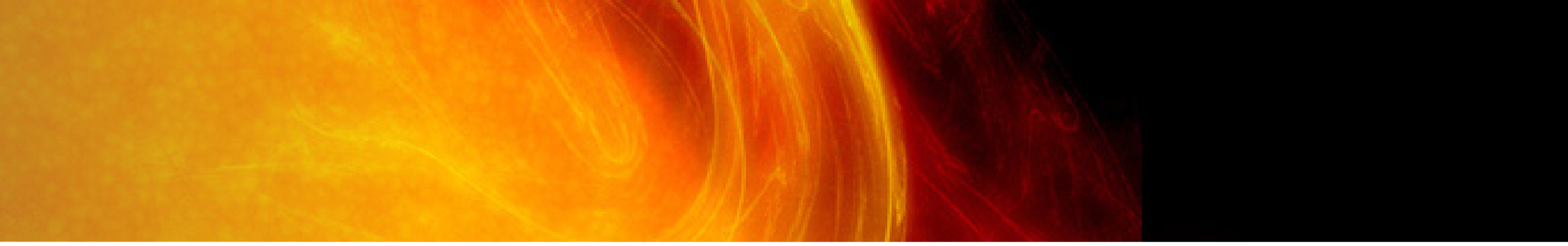
In the quest for fusion energy, numerous new scientific frontiers and technologies have been, and are being tcreated. Many of these innovations and insights are proving to be invaluable in applications far afield from fusion energy research.

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 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

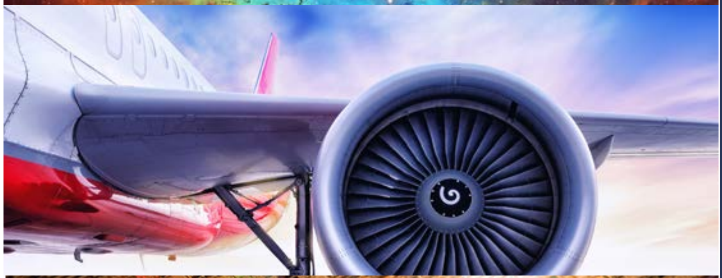


Driving Innovation in Computing

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.

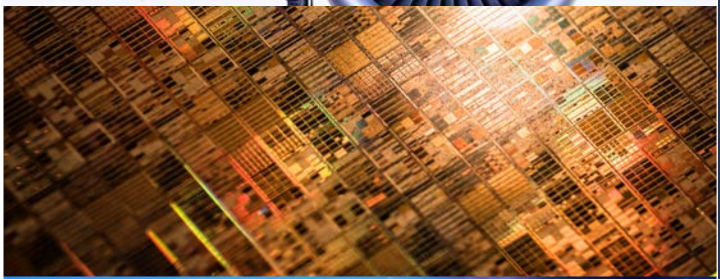
Understanding Our Universe

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

Visit https://www.ga.com/energy-group

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