PPPL PRINCETON PLASMA PHYSICS LABORATORY

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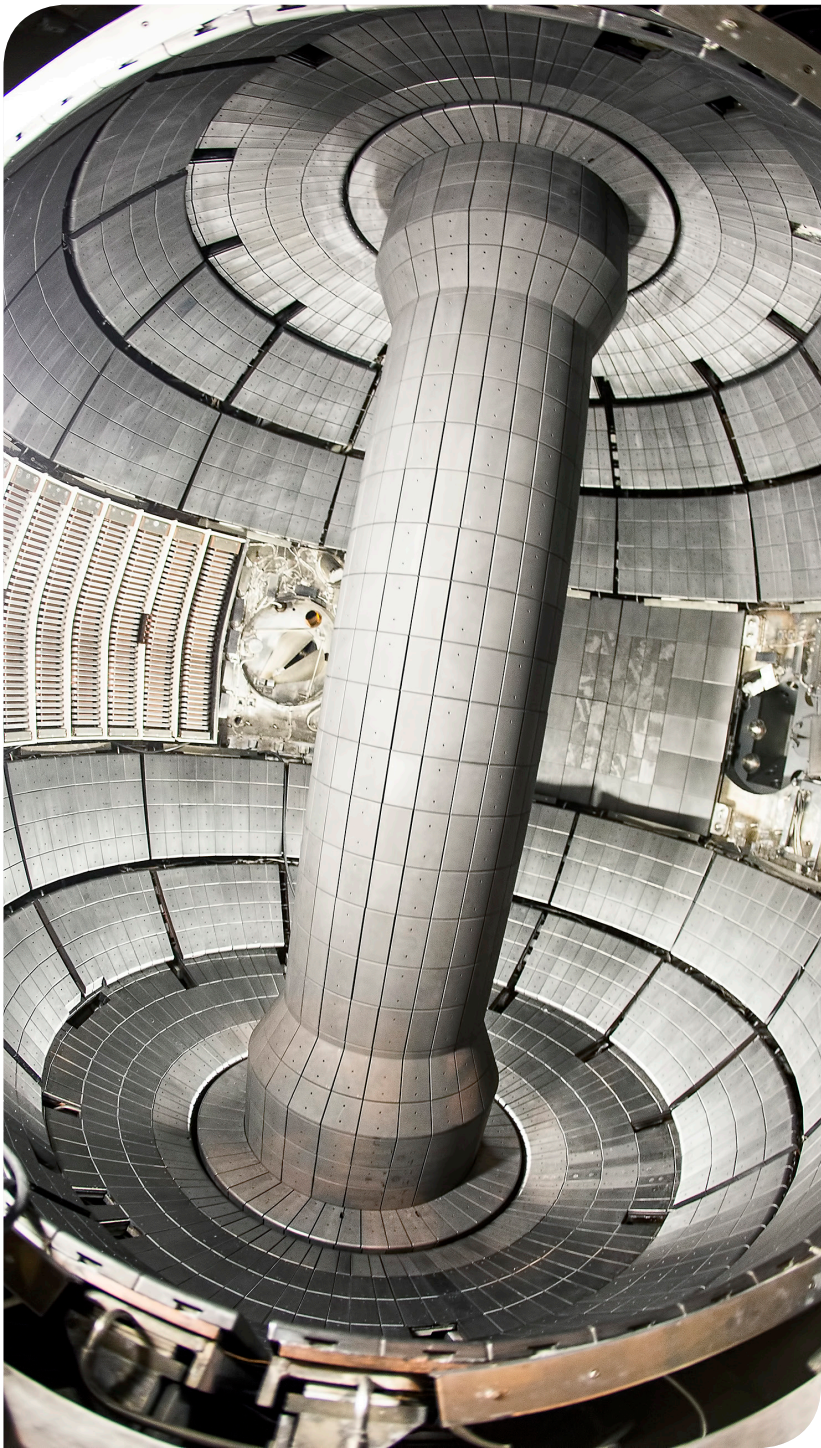
U.S. DEPARTMENT OF ENERGY

# Unveiling the Most Powerful Spherical Tokamak on Earth



Welcome to a new era in fusion research at the U.S. Department of Energy's Princeton Plasma Physics Laboratory. Today we unveil the National Spherical Torus Experiment-Upgrade (NSTX-U), the most powerful spherical tokamak in the world and the first major addition to the U.S. fusion program in the 21st century.

The NSTX-U represents a $94 million, nearly three-year upgrade of the original National Spherical Torus Experiment that ran from 1999 to 2011 in the Laboratory, which Princeton University manages for the U.S. Department of Energy. This overhaul doubles the heating power and magnetic field strength of the facility and increases the length of fusion experiments from one second to up to five seconds.

PPPL is the only DOE laboratory devoted to fusion science and research along the broad frontier of plasma

science and technology, and one of 10 national laboratories supported by the DOE's Office of Science. These institutions have a luminous history of scientific innovation and discovery in keeping with the goals of DOE.

Here is a brief overview of the NSTX-U spherical tokamak, its role in the worldwide quest for fusion energy and its mission over the next five-to-10 years.

**What's a tokamak?** A tokamak is the most successful device yet developed for confining superhot plasma within magnetic fields to produce fusion reactions. Plasma, an electrically charged gas that consists of electrons and atomic nuclei, or ions, makes up 99 percent of the visible universe and is often called the fourth state of matter. The sun and stars are made of plasma.

**What's a spherical tokamak?** Spherical tokamaks are compact facilities that are shaped like cored apples. This design compares with the bulkier, donut-like shape of conventional tokamaks that are now in wider use.

**What's so attractive about the spherical design?** The compact shape enables a spherical tokamak to confine highly pressurized plasma within lower magnetic fields than conventional tokamaks must use to create similar pressure. The original NSTX set records for the ratio of outward plasma pressure to inward magnetic field strength, a key ratio known as "Beta." Spherical tokamaks are thus cost-effective because fusion reactions require highly pressurized plasma and high magnetic fields are expensive to produce.

**What do PPPL researchers plan to investigate?** Scientists aim to see if the NSTX-U can continue to produce high-pressure plasmas with low-level fields under the hotter and more powerful conditions that the upgrade allows. If so, this capability could make the spherical design a strong candidate for a Fusion Nuclear Science Facility, a proposed next step in the U.S. fusion program that would test an integrated fusion-energy system in preparation for a demonstration fusion power plant.

**What else do researchers aim to discover?** Further experiments will test the upgrade's ability to tame the hot plasma particles that escape from confinement and can damage the tokamak's walls — an issue of critical importance to ITER, the international fusion experiment under construction in France. Also under investigation will be new ways to start and sustain the electric current that creates the plasma and completes the confining magnetic field.

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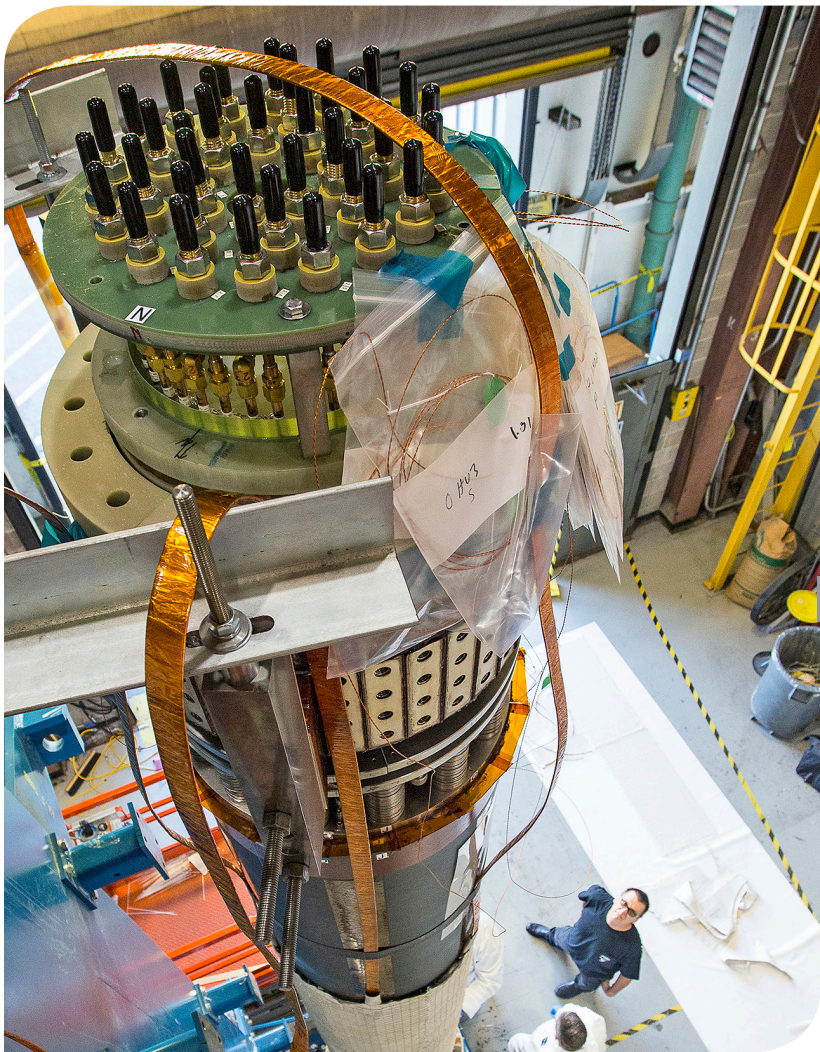
# Building the Most Powerful Spherical Tokamak

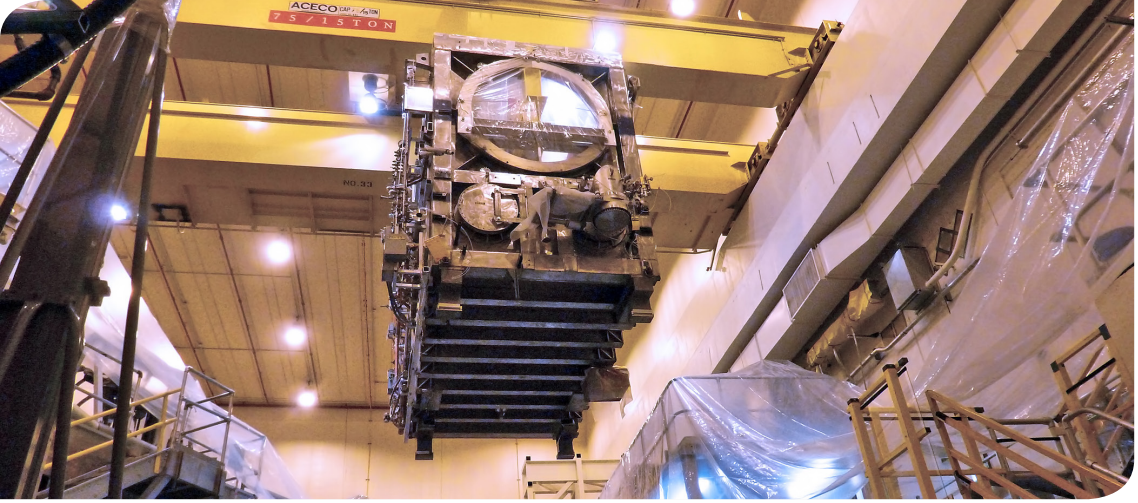
Two major new components power the National Spherical Torus Experiment-Upgrade: A widened center stack that doubles the magnetic field strength and plasma current and quintuples the length of fusion experiments, and a second neutral beam injector that doubles the tokamak's heating power. Taken together, the new parts boost the NSTX-U operating conditions closer to those that will be found in a commercial fusion power plant.

"This project was more complex than building the NSTX in the first place," says Mike Williams, head of engineering and infrastructure and associate director of the Laboratory. "We had to figure out how to reinforce the existing facility to withstand the increased electromagnetic forces produced by the upgrade."



## Here is a look at the major steps in the NSTX-U construction:

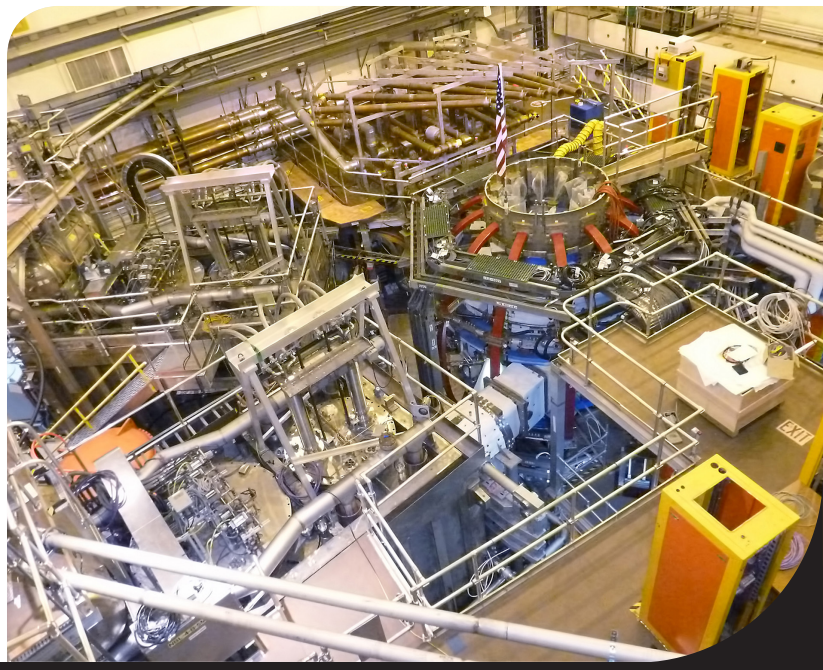
Creating the new center stack meant sanding, brazing, welding and applying insulation tape to each of the 36 copper conductors that make up the 21-foot-long magnet. Technicians then bound the conductors together through repeated applications of vacuum pressure impregnation — a potentially volatile process. They next fabricated a coil that winds around the bundle to induce current into the plasma.




The final step called for using an overhead crane to lift the magnet over a 22-foot shield wall, which the bundle cleared by inches, and carefully lower it into the center of the spherical tokamak. “This was really a watershed moment,” Williams said of the installation, which completed the center stack construction.

Installing the new neutral beam injector required even heavier lifting. Technicians first spent months taking apart, decontaminating and refurbishing the truck-sized, 70-ton device, which was originally used with the Lab’s now-dismantled Tokamak Fusion Test Reactor. They then towed the injector into the NSTX-U test cell, attached it to the overhead crane and hoisted it over the shield wall.

Workers next hooked up the device and its power supplies, cables, cooling-water pipes and other equipment in the already crowded test cell. Last came the task of cutting a window into the NSTX-U vacuum vessel and aligning the beam to within 80 thousands of an inch of a target inside the vessel. “The whole thing was fraught with challenges and difficulties,” said engineer Tim Stevenson, who headed the beam box project. “It was a monumental team effort that took a great deal of preparation. And when it was show-time, everyone showed up.”



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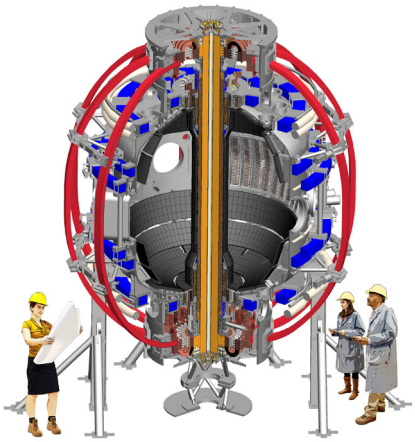
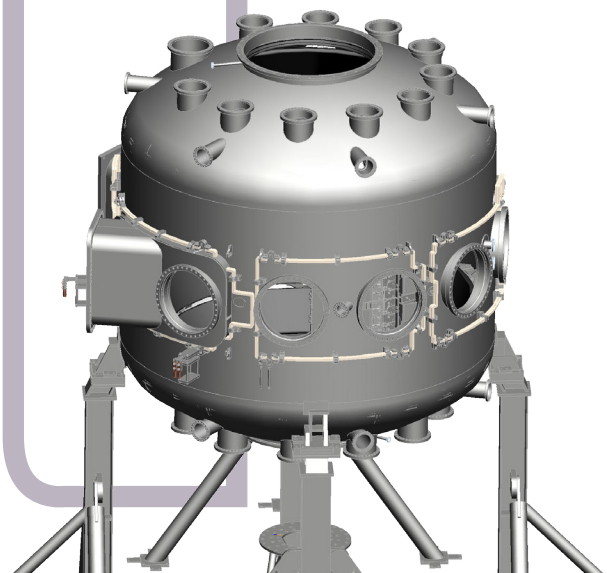
# Components of the NSTX-U



**Height and weight of whole machine:**
23.3 feet, 85 tons

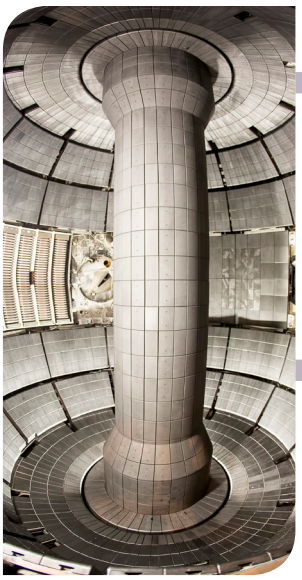
## Vacuum Vessel

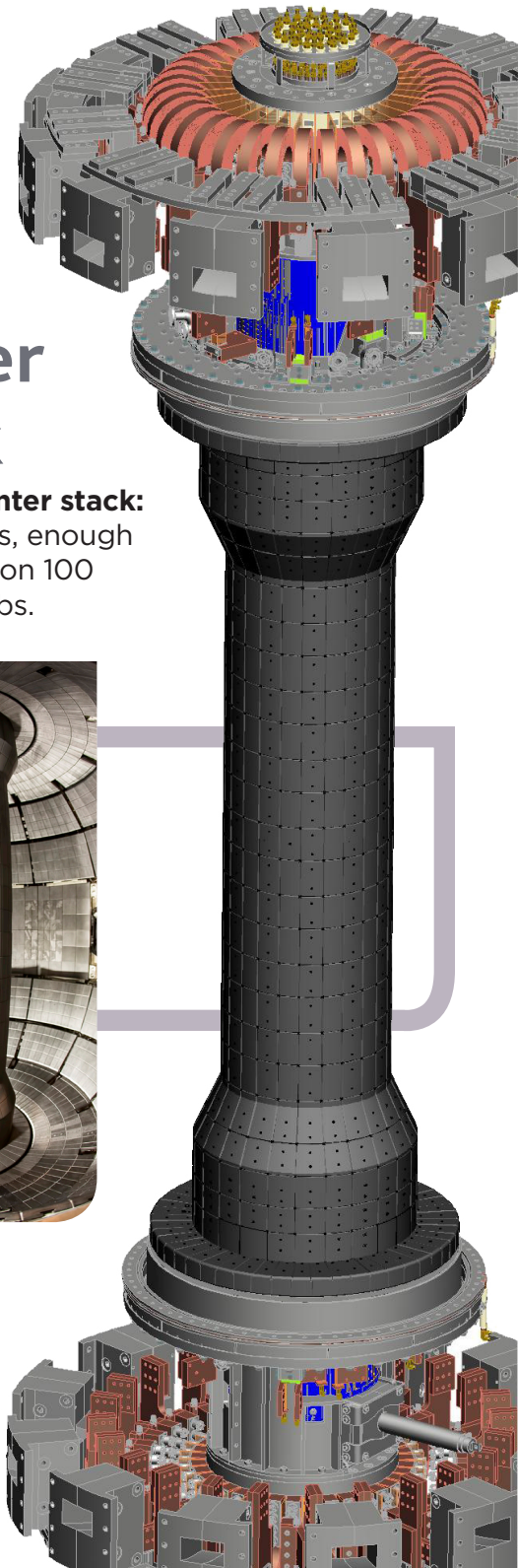
**Overall diameter and vacuum vessel diameter:**
16.6 feet, 11.2 feet



## Center Stack

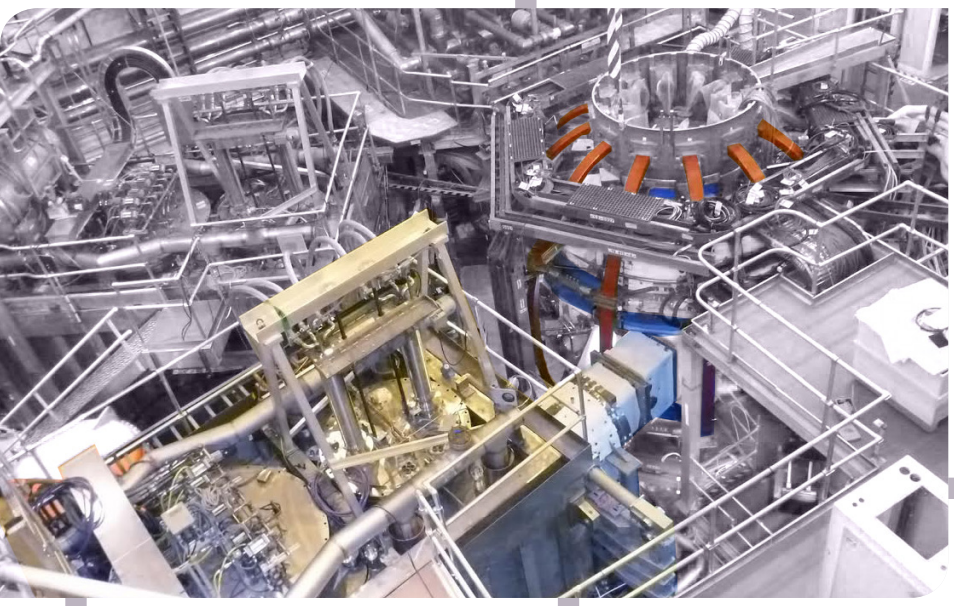
**Current in center stack:**
2 million amps, enough to light 2 million 100 watt light bulbs.

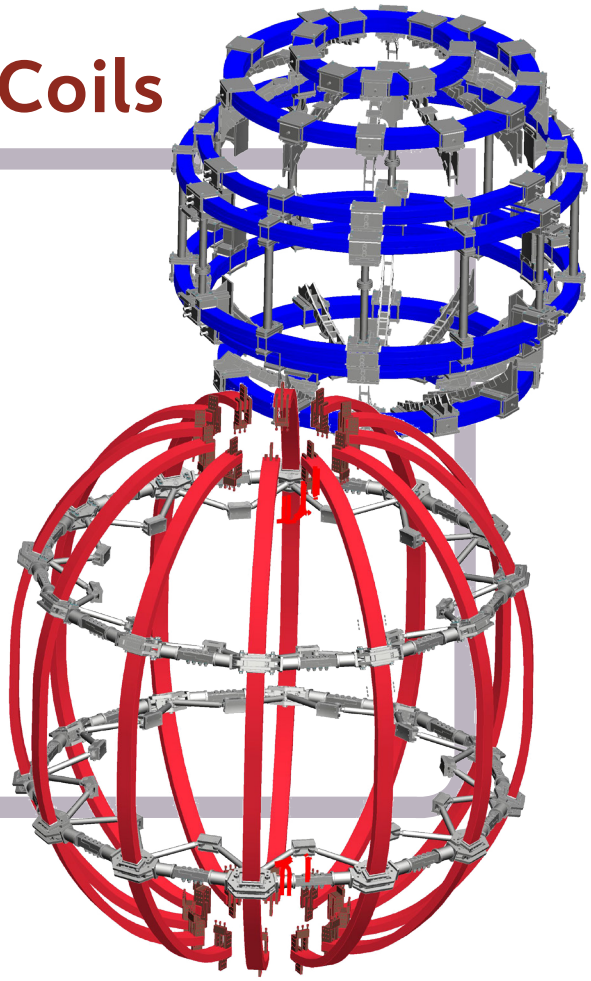




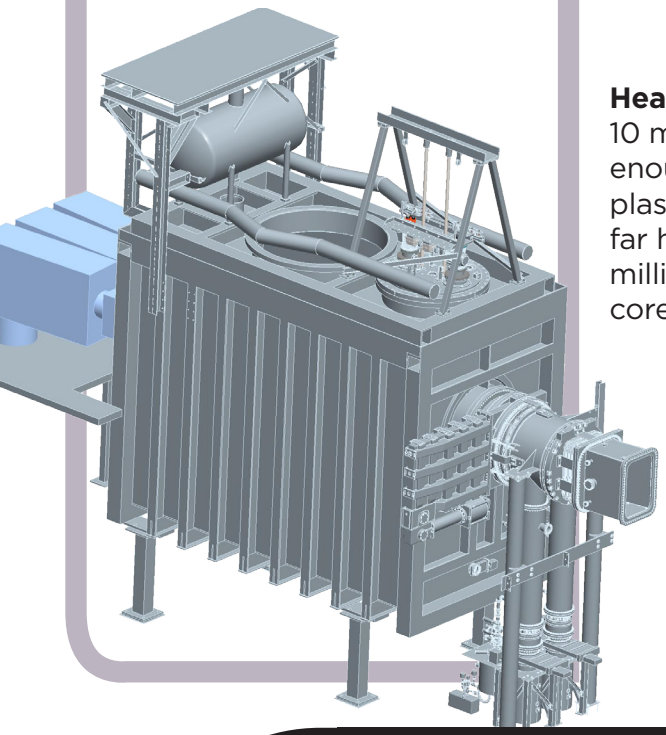
# Poloidal Coils and Toroidal Coils

**Magnetic field strength:**
1 tesla, or 20,000 times the strength of the Earth's magnetic field





## Neutral Beam



**Heating power:**
10 million amps, enough to produce plasma temperatures far hotter than the 15 million degree Celsius core of the sun.

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# Builders and Users

**CONSTRUCTING THE NATIONAL** Spherical Torus Experiment Upgrade took years of detailed planning and oversight. The team in charge brought decades of experience to the task, working together to make the $94 million upgrade a reality.

## The Builders

### Ron Strykowsky: Massive coordination of details for a massive project

Ron Strykowsky compares his role as overall manager of the NSTX-U project to that of an orchestra leader conducting a team of expert musicians. Strykowsky coordinated all the engineers and technicians who constructed the device, overseeing schedules and costs and ensuring that the project met all staffing needs. He estimates that by March of 2015, 209 employees at PPPL had logged 559,487 hours working on NSTX-U – the equivalent of one person working 24 hours a day seven days a week for 64 years. "I look at it more as a conductor who doesn't know how to play any instruments," the 32-year veteran of PPPL says. "You don't tell anyone how to play the violin. You ask: 'What do you need to play the violin better?'"

### Tim Stevenson: A key player finds joy in his multiple roles on the NSTX-U

Tim Stevenson gets a gleam in his eye when he talks about the upgrade. He headed the team that installed a second massive 75-ton beam box that will double the experiment's heating power. That was just one of his tasks: As head of project management at PPPL, Stevenson monitored all NSTX-U projects to ensure that they were carried out safely and according to plan. It's still "a joy" coming to work every day after 31 years at the Laboratory, Stevenson says. "I'm thrilled to be an engineer here," he adds. "We are making a star and making new knowledge. How cool is that?"

### Larry Dudek: Managing major components of the upgrade

Larry Dudek has been building things since joining PPPL in 1980. He most recently oversaw construction of major components of the NSTX-U, including the center stack that houses the magnets that form the heart of the upgrade. A key task was reinforcing the machine to withstand the increased electromagnetic forces within the upgraded facility. The low-key engineer compares this to installing a V-8 engine in a compact car. "You have to worry about the structure of the car, is it going to be able to handle the extra loads?" he says. Looking back, he is gratified by the quality of everyone's work. "It's a big achievement to have this machine upgraded and running," he says. "It's a big relief."

### Construction Manager Erik Perry: Bringing the project in safely and on time

Erik Perry is a hands-on supervisor. "If the people are here I've got to be here," he says. With 50-to-70 technicians working 10-hour shifts seven days a week to complete the upgrade, Perry was up at 5 a.m. to check emails each day. He oversaw the progress of construction twice every morning and twice in the afternoon, seven days a week, then rechecked emails at 10 p.m. when the late shift arrived. In his 38 years at PPPL, Perry has never missed a deadline. "The biggest thing is to try to make sure that everything is done safely and that everything gets done correctly and in the most efficient manner," he says. He has strong motivation. "I'm still here for the fusion," he says. "I want to see it made available to the world."

### Michael Williams: Overseeing the Big Picture

As associate director for Engineering and Infrastructure at PPPL, Michael Williams' oversees the big picture — a skill he has developed over his 39 years at the Laboratory. Williams is modest about his contributions to the NSTX upgrade. "I stepped in occasionally to keep the gears greased and working but in the end, they really did all the work," he says of the construction team. When pressed, he acknowledges that the project took intricate planning and a multitude of meetings. "There were daily meetings, weekly meetings, scheduled meetings, spontaneous meetings, hallway meetings," he says. "An effort of this magnitude requires a lot of coordination and you can't accomplish that coordination without a plethora of meetings." He now looks forward to seeing the fruit of everyone's labors. "There's an increase in excitement in the Lab as a whole," he says. "Operating NSTX is the lifeblood of the Laboratory."

## The Users

### Jon Menard: Setting the scientific direction

Jon Menard's task as program director for the NSTX-U calls for guiding research on the upgraded machine, which he helped design. With more than 300 U.S. and international researchers using the facility, organizing the research program is a challenging and exciting task. "It's very satisfying intellectually," says Menard, who joined PPPL in 1999 after earning his PhD from Princeton and has since won a 2004 Presidential Early Career Award for Scientists and Engineers and a 2006 Kaul Foundation Prize. "It's really setting the whole scientific direction of what we're doing with the machine and why," he says of his role.

### Masa Ono: Overseeing daily operations

Masa Ono helped design the NSTX and NSTX-U, for which he serves as project director. He oversees the daily operation of the experiment and faces new challenges each day. "We usually don't do the same thing twice," he says. "That's part of the fun because it's a new experience every day." Ono joined the PPPL staff in 1978 after receiving his PhD from Princeton University. His numerous honors include the 1999 Kaul Foundation Prize, an annual PPPL award, which he received for his work on the NSTX. "The NSTX-U will provide new capabilities so we can simulate how future devices operate," Ono says. "So it's a much more capable machine compared to NSTX."

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# Spinoffs

RESEARCH AT THE PRINCETON PLASMA Physics Laboratory has led to technologies and spinoffs with applications that extend far beyond the Lab's halls. Some examples:

## MINDS

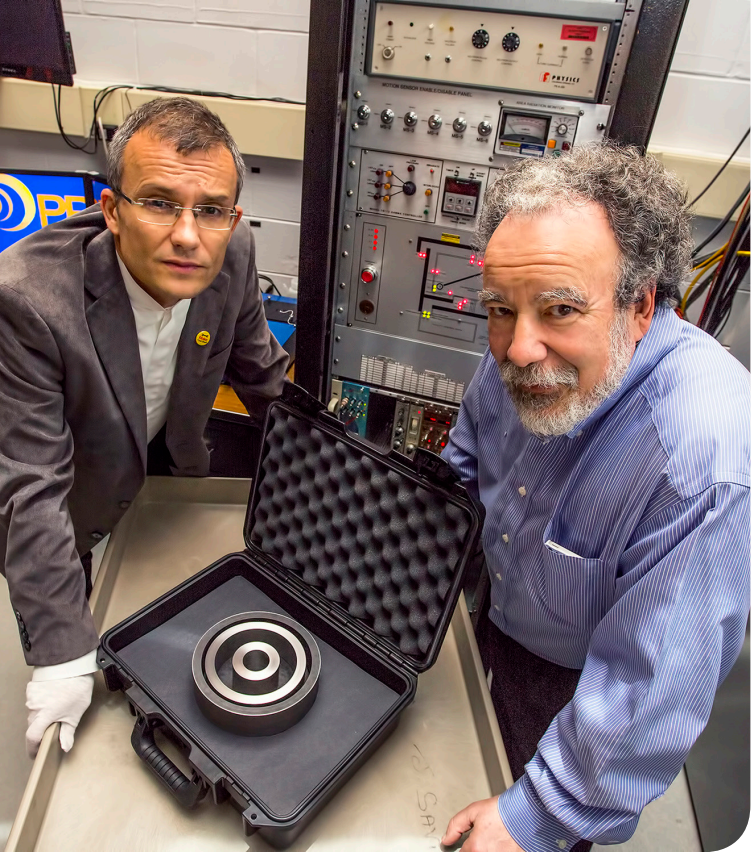
**Device created at PPPL helps protect America from radiological threats.**

A PPPL team has developed the Miniature Integrated Nuclear Detection System (MINDS), a device that can detect radiological weapons like so-called dirty bombs. MINDS can scan moving vehicles, cargo ships, luggage and other items for a variety of radiation, including x-rays, gamma rays, and neutrons, and can identify specific radionuclides. MINDS has been deployed at U.S. military bases as well as busy rail and bus commuter centers.

## Egg Pasteurization

**PPPL research has led to advances in health-related technology.**

Engineer Christopher Brunkhorst, working in partnership with the U.S. Department of Agriculture, developed a method of quickly pasteurizing eggs within their shells without damaging the delicate whites. A prototype machine the size of a shoebox sends radio-frequency waves through the egg while the egg rotates and cool water pours over the eggs to prevent the whites from getting too hot. The device can pasteurize eggs in their shells in around one-third the time of current methods. Commercialization of this patented apparatus could reduce the number of illnesses from egg-borne salmonella.



# Nuclear Weapon Verification

**Neutrons Used to Inspect Nuclear Weapons**
Physicists at PPPL and Princeton University are developing a novel method of verifying that nuclear weapons scheduled to be dismantled contain true warheads. This method, which would shoot beams of neutrons through a weapon to see how many pass through to detectors behind it, would not reveal any classified information that might lead to nuclear proliferation. Inspectors would compare the results to those obtained by beaming neutrons through a known warhead to see if the findings matched. Researchers are building a prototype at PPPL that will test the method by sending neutrons through a non-nuclear test object.

# Synthetic Muscle

**Man-made muscle promises better prostheses.**
The Lab's five-year partnership with Ras Lab LLC, a Boston-area company, has led to development of a special kind of polymer material suitable for synthetic muscle and other biotechnical uses, as well as for robotic applications. The material, created by Ras Lab founder Lenore Rasmussen, flexes and contracts when an electric current passes through it. In April, NASA delivered the polymer to the International Space Station to test the material's ability to withstand radiation in a space environment.

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# Fusion Machines of the World

**NSTX-U IS ONE OF AN ELITE GROUP** of magnetic fusion facilities scattered across the globe. These powerful and complex machines are advancing mankind's quest to harness fusion as a safe, clean and abundant source of energy for producing electricity. Here is a selection of major facilities.

## DIII-D

**Location:** San Diego, Calif.
**Start Date:** 1986
**Major Radius:** 1.66 meters
**Magnetic Field Strength:** 2.2 teslas

DIII-D is operated by General Atomics for the U.S. Department of Energy with a mission to provide the scientific basis for optimizing the tokamak approach to the production of fusion energy.

## National Spherical Torus Experiment (NSTX)

**Location:** Plainsboro, New Jersey
**Start Date:** 1999
**Major Radius:** 0.94 meter
**Magnetic Field Strength:** 1 tesla

The upgraded NSTX, known as NSTX-U, will operate as the most powerful spherical tokamak in the world.

## Alcator C-Mod

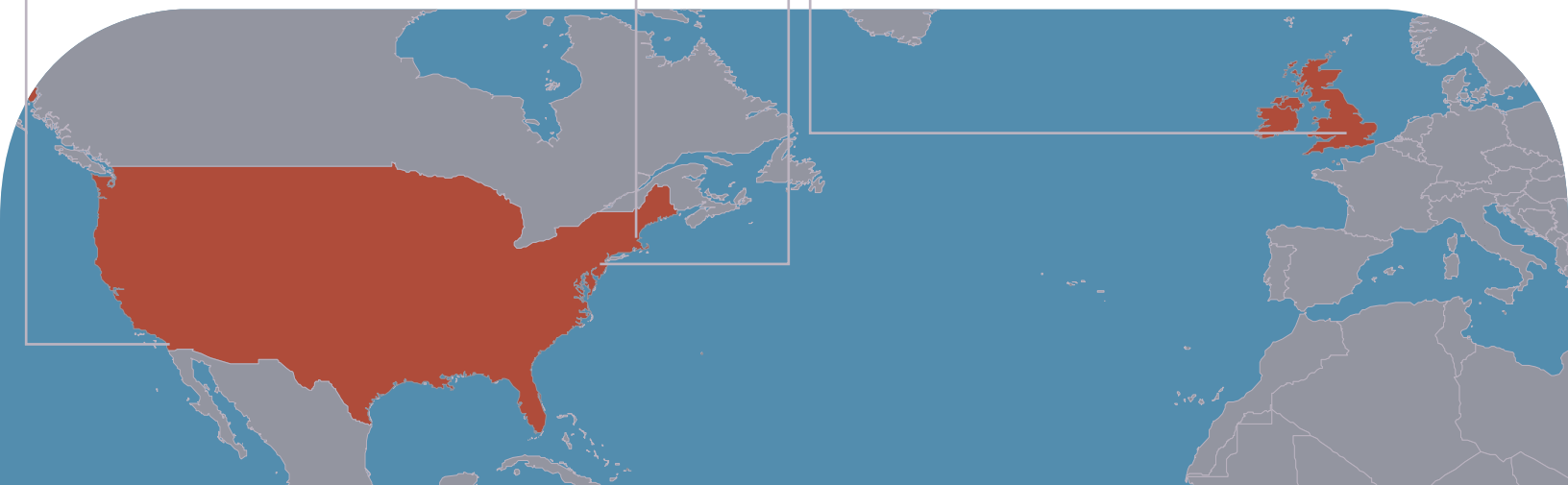
**Location:** Cambridge, MA
**Start Date:** 1991
**Major Radius:** 0.68 meter
**Magnetic Field Strength:** 5.6 teslas

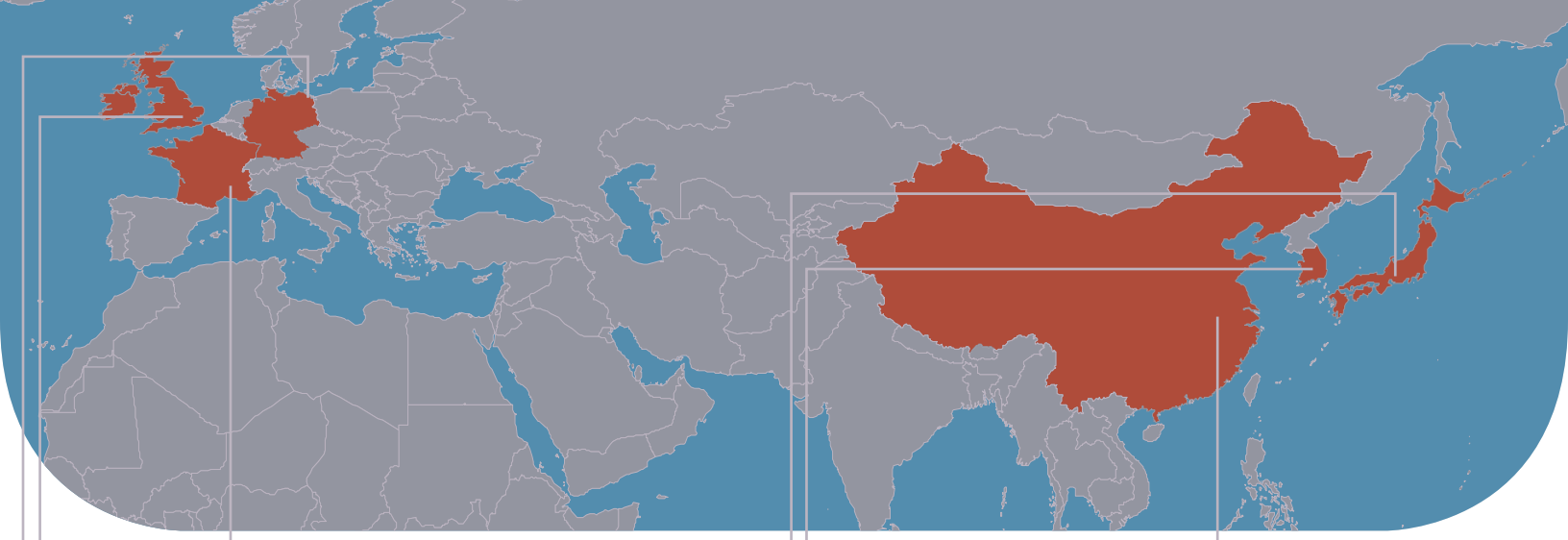
Alcator C-Mod is a high-magnetic-field tokamak operated by MIT for the U.S. Department of Energy.

## Joint European Torus (JET)

**Location:** Culham Centre for Fusion Energy in the United Kingdom
**Start Date:** 1984
**Major Radius:** 2.96 meters
**Magnetic Field Strength:** 3.45 teslas

JET is the largest tokamak now in operation.





## ITER

**Location:** Cadarache, France
**Start Date:** 2020s
**Major Radius:** 6.2 meters (The major radius measures the distance between the center of a fusion facility and the center of the plasma.)
**Magnetic Field Strength:** 5.3 teslas (For comparison, the strength of Earth's magnetic field is around .00005 tesla.)
ITER is an international experiment under construction by countries including the United States to demonstrate the feasibility of fusion power.

## Mega Amp Spherical Tokamak (MAST)

**Location:** Culham Centre for Fusion Energy in the United Kingdom
**Start Date:** 1999
**Major Radius:** 0.9 meter
**Magnetic Field Strength:** 0.6 tesla
MAST is currently being upgraded. Together with NSTX, MAST is one of the world's two leading spherical tokamaks.

## Wendelstein 7-X (W7-X)

**Location:** Germany
**Start Date:** 2015
**Major Radius:** 5.5 meters
**Magnetic Field Strength:** 3 teslas
W7-X is the largest and most advanced stellarator in the world.

## Experimental Advanced Superconducting Tokamak (EAST)

**Location:** China
**Start Date:** 2006
**Major Radius:** 0.45 meter
**Magnetic Field Strength:** 3.5 teslas
EAST, China's main fusion experiment, produces long-pulse, or steady-state, plasmas.

## Korean Superconducting Tokamak Advanced Research (KSTAR)

**Location:** South Korea
**Start Date:** 2008
**Major Radius:** 1.8 meters
**Magnetic Field Strength:** 3.5 teslas
KSTAR is the cornerstone of South Korea's fusion program.

## Large Helical Device (LHD)

**Location:** Japan
**Start Date:** 1998
**Major Radius:** 3.5 meters
**Magnetic Field Strength:** 3 teslas
LHD is a major stellarator with more than 15 years of research accomplishments.

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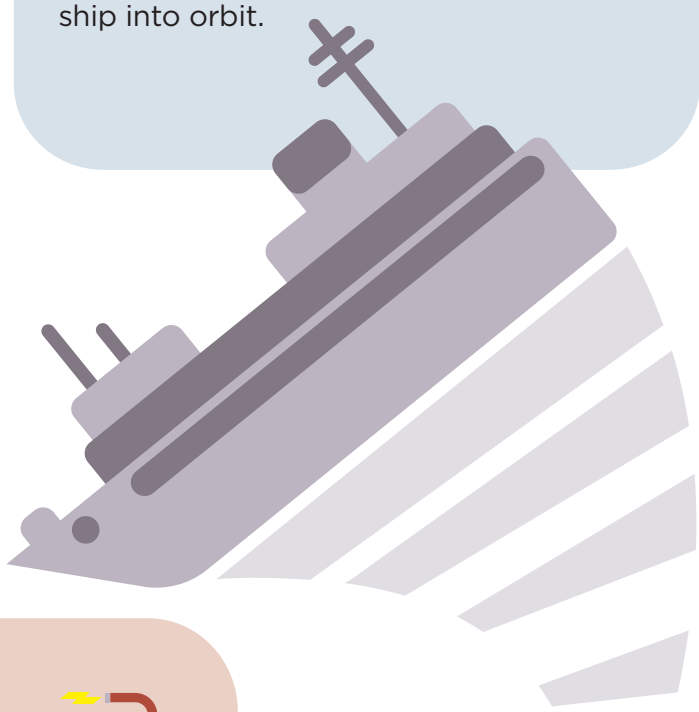
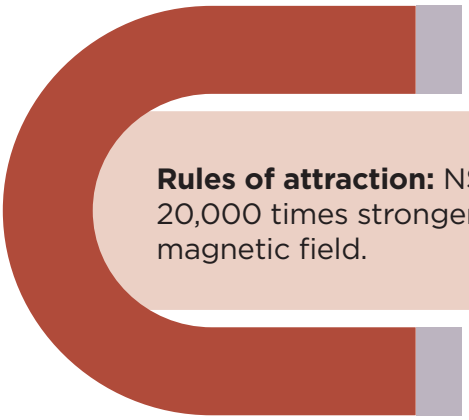
# NSTX-U Fun Facts

**Up and away:** The two 700-ton flywheels that power the NSTX-U could put a naval ship into orbit.

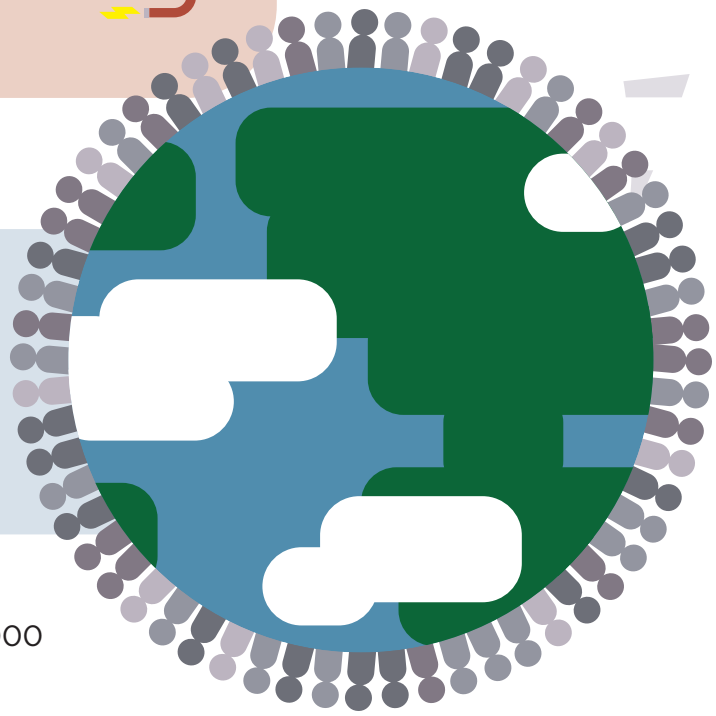


**Heart of the upgrade:** The NSTX-U center stack consists of 36 22-foot-long, 350-pound copper conductors.

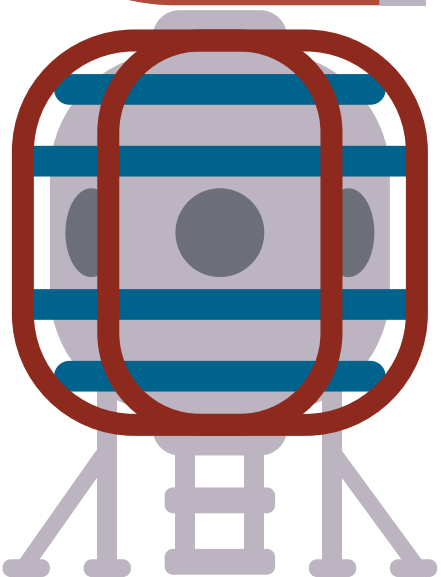
**Plenty of juice:** The 2 million amp current that will flow through the plasma could light 2 million 100-watt bulbs.



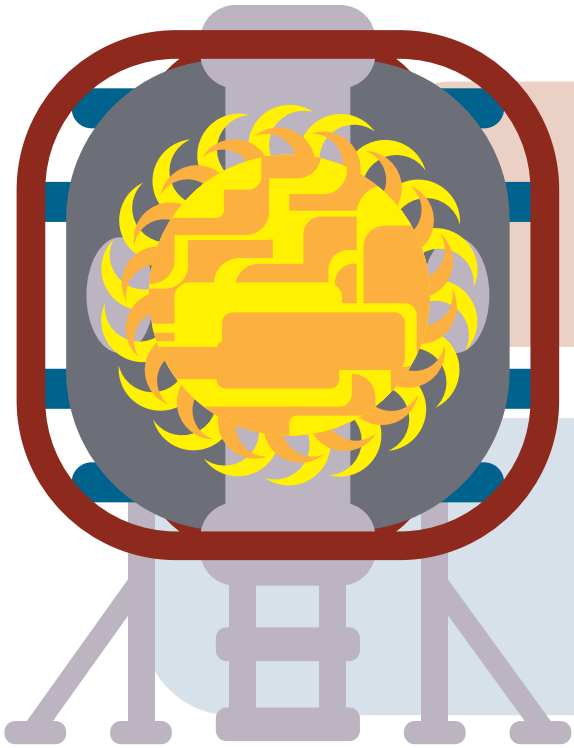
**Rules of attraction:** NSTX-U magnets are 20,000 times stronger than the Earth's magnetic field.



**All together now:** 60 research centers around the world will collaborate on NSTX-U.



**Time flies:** Technicians spent more than 360,000 worker hours building the NSTX-U.



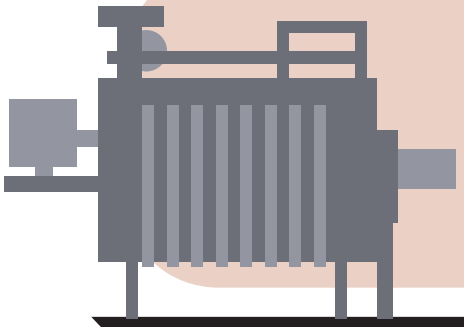
**Sunscreen won't help:** Temperature inside the NSTX-U will exceed the 15 million degree Celsius core of the sun.

**Space age material:** Graphite tiles inside the NSTX-U are similar to those used on the outside of space shuttles.

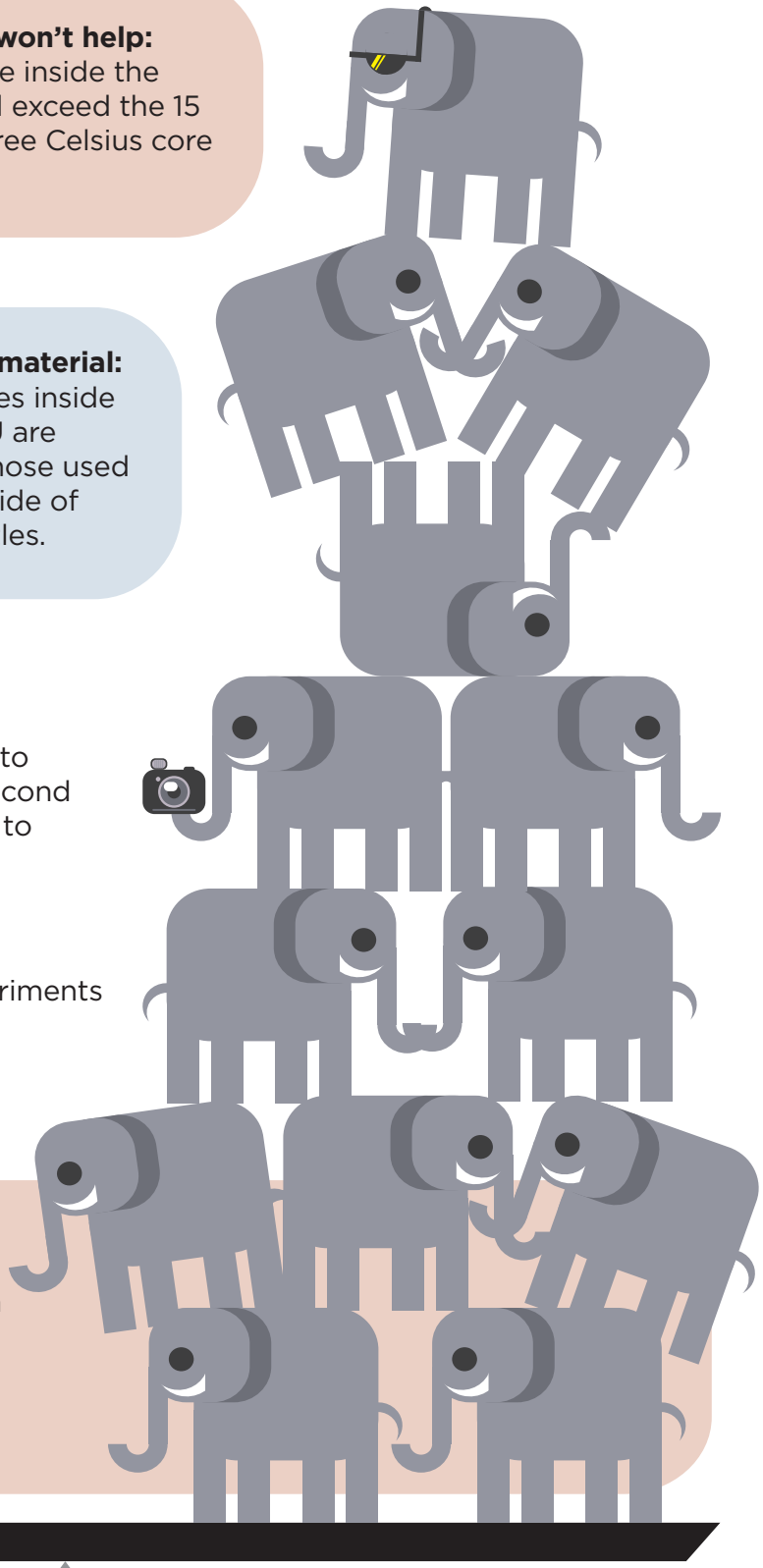
**Fast shots:** High-speed cameras that photograph NSTX-U plasmas can record 10,000 images per second.

**Faster shots:** The same cameras can record up to 400,000 images per second when researchers want to see plasma turbulence.

**Many experiments:** Researchers will run NSTX-U experiments every 10 to 15 minutes, or more than 30 times a day.



**Elephantine task:** PPPL installed a second neutral beam box that weighs 75 tons, or nearly 13 average-size male African elephants.



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