

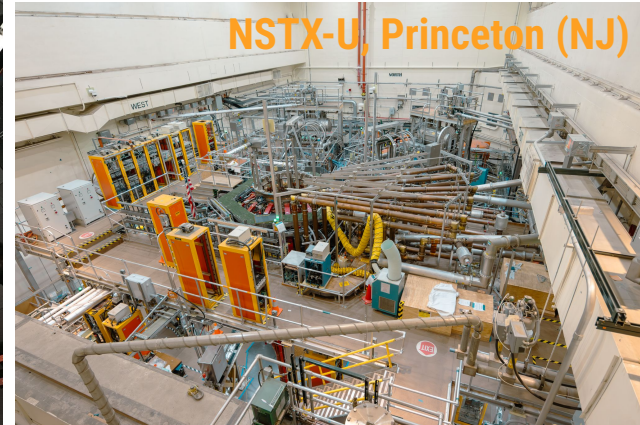
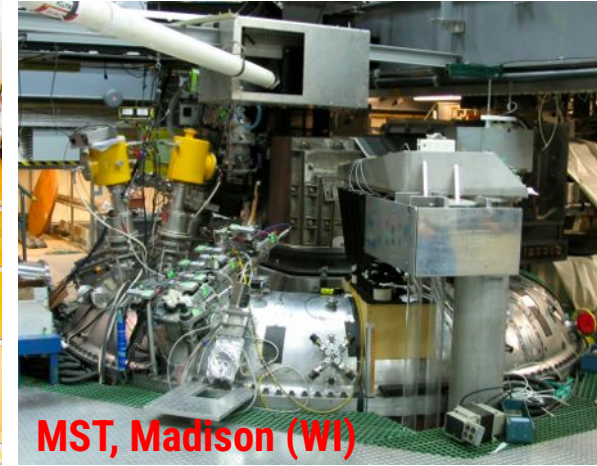
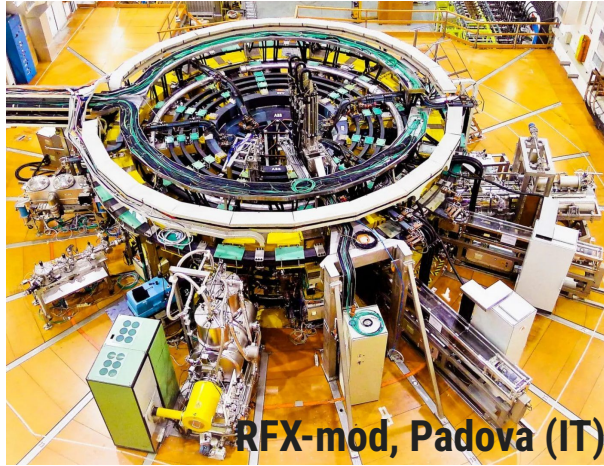


The National Spherical Torus Experiment Upgrade – Advancing the Physics of Fusion Energy

Dr. Stefano Munaretto, Research Physicist
Princeton Plasma Physics Laboratory
February 25, 2026, Rutgers University

Who am I?

- Born in Vicenza (Italy)
- PhD from University of Padova
- Postdoc at UW-Madison
- Scientist at General Atomics
- Research Physicist at PPPL



How do you contact me?



[ABOUT](#) [RESEARCH](#) [EDUCATION](#) [NEWS](#) [EVENTS](#) [ENGAGE WITH US](#) [CONTACT](#)

Stefano Munaretto

Research Physicist



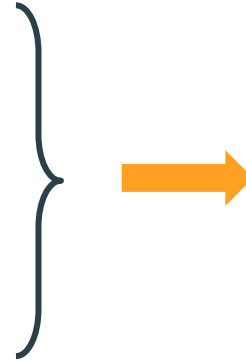
EMAIL
smunaret@pppl.gov

<https://www.pppl.gov/people/stefano-munaretto>

Stefano Munaretto is a Research Physicist of the Princeton Plasma Physics Laboratory and is in charge of the magnetic diagnostic system of NSTX-U. Stefano obtained a Master in Physics in 2008 with a thesis about "devices for the injection of pellets and measurement of the safety factor in magnetically confined plasmas" and a PhD in Fusion Science and Engineering in 2012 on "first wall conditioning and plasma edge studies in RFP and tokamak devices" both from the University of Padova, Italy. He has been research associate at the University of Wisconsin - Madison from 2012 to 2016 working on control of 3D magnetic fields and their application on the Madison Symmetric Torus device both in RFP and tokamak configuration. From 2017 to 2020 he was a scientist with General Atomics studying MHD with a particular focus on plasma response to applied 3D magnetic perturbations in DIII-D and maintaining the DIII-D magnetic diagnostic system. Since he joined PPPL in 2021, he is leading research efforts on 3D magnetic fields and magnetic diagnostic systems on several domestic and international devices.

Why fusion energy?

- By 2050, the planet could be **using twice as much electricity** compared to today.
- **Climate change** and **diminishing fuel reserves** mean that reliance on fossil fuels must be severely constrained



A new **large-scale, sustainable and carbon-free** form of energy is urgently needed

Some of the advantages that make fusion energy worth pursuing:

- **Abundant energy**
- **No CO₂**
- **No long-lived radioactive waste**
- **No risk of meltdown**

Outline

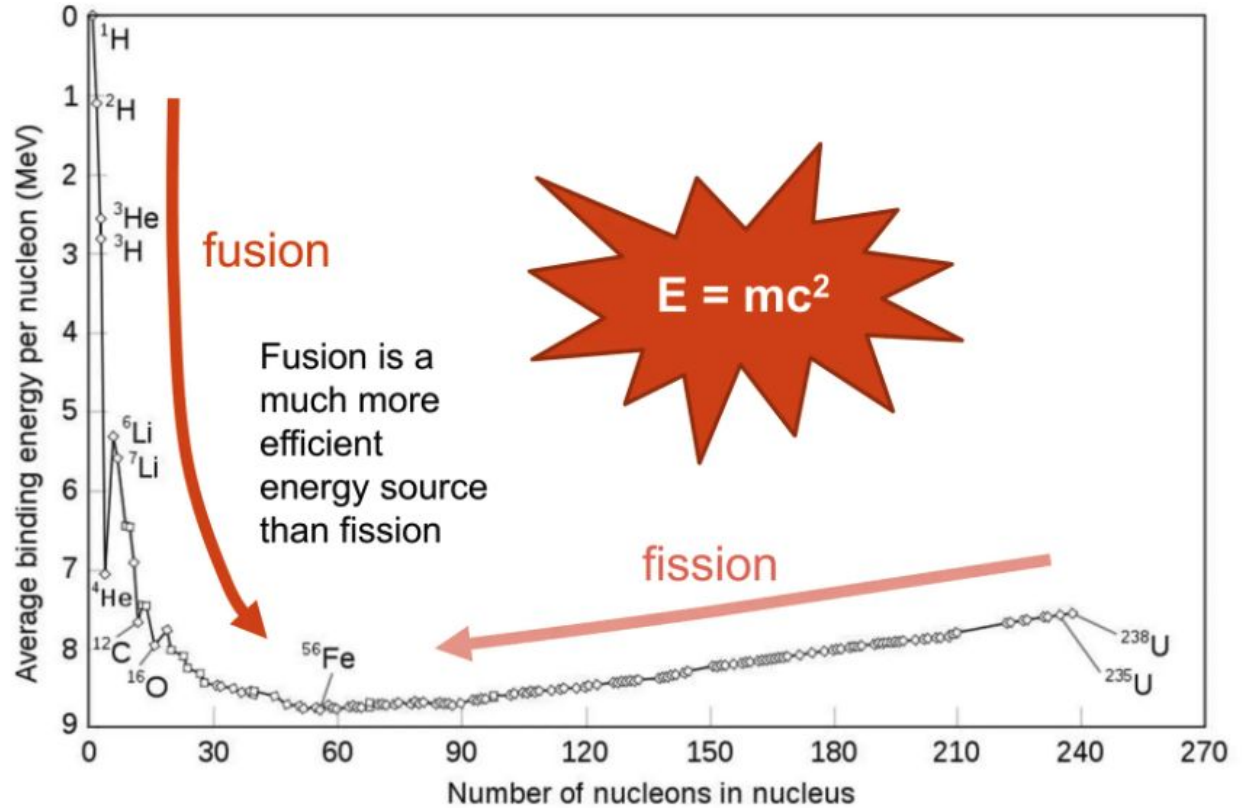
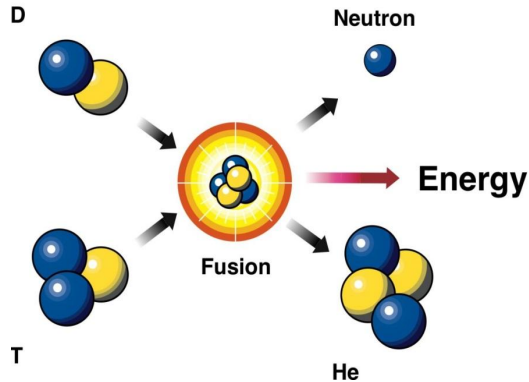
- Fusion overview
 - What is fusion? What is a plasma?
 - How do we make fusion on earth?
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 - The Princeton Plasma Physics Laboratory (PPPL)
 - The spherical tokamak concept
- Measuring the plasma
- How can I get involved?

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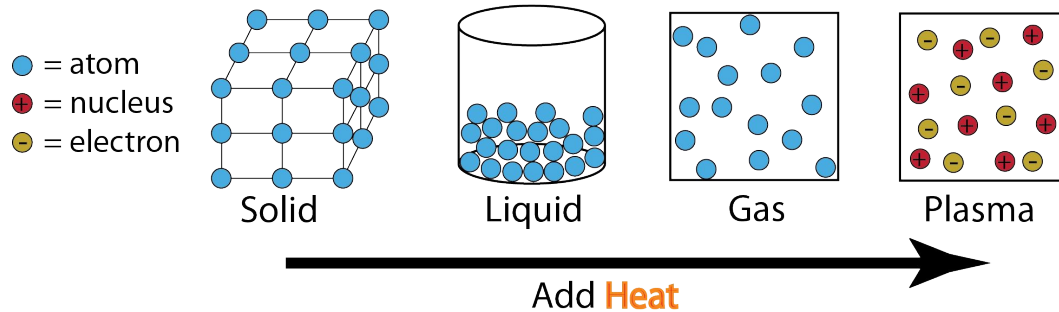
What is fusion?

Fusion is a nuclear reaction in which atomic nuclei of low atomic number fuse to form a heavier nucleus with the release of energy



What is a plasma? A “soup” of electrons and positive ions

States of Matter



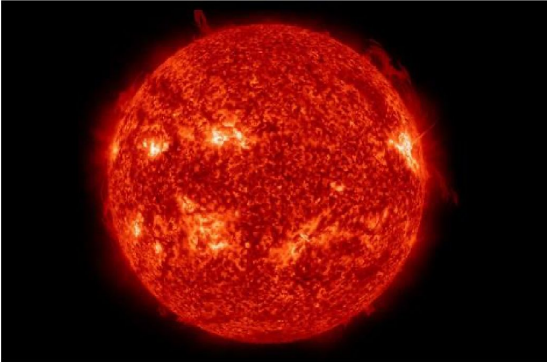
If we increase the temperature of a gas beyond a certain limit, the electrostatic forces which ordinarily bind electrons to atomic nuclei are overcome.

Instead of a hot gas composed of electrically neutral atoms, we have two co-mingled populations composed of electrons and positive ions.

The plasma needs to be confined in order to create fusion reactions

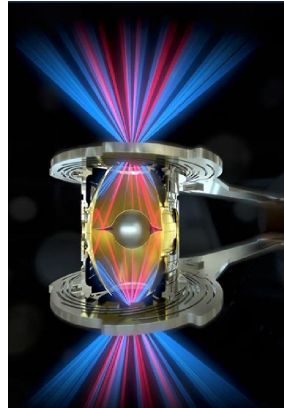
To make fusion happen, it is necessary to have a large number of nuclei (density, n) that move fast enough (temperature, T) and stay in the same space for a long enough time (confinement time, τ).

Gravitational Confinement



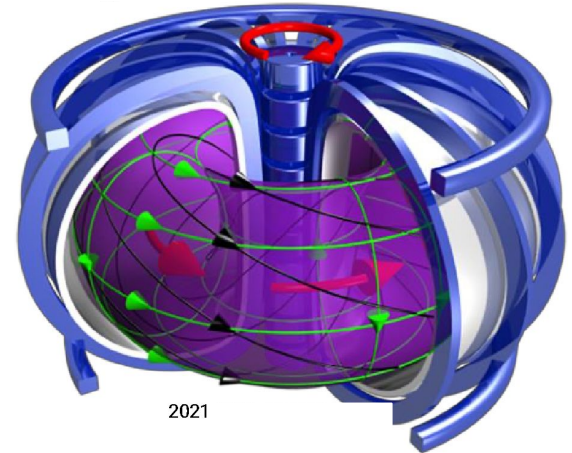
It takes a star worth of gravity to hold the hot gas together...even Jupiter @ 1000 x the volume of earth is not big enough to make fusion

Inertial Confinement



Compress the gas so that fusion occurs *before* it is blown apart

Magnetic Confinement

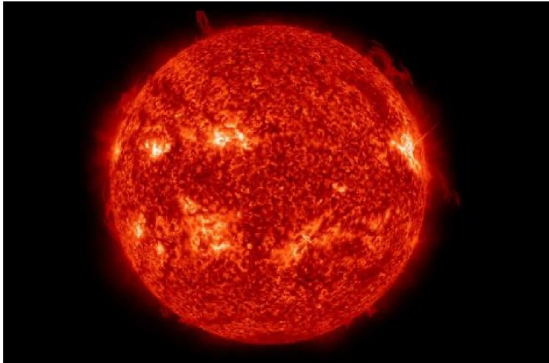


Make a magnetic field in a finite volume...it'll hold the plasma

The plasma needs to be confined in order to create fusion reactions

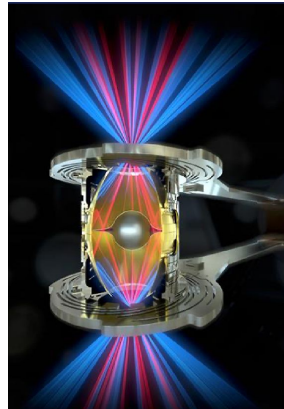
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Gravitational Confinement



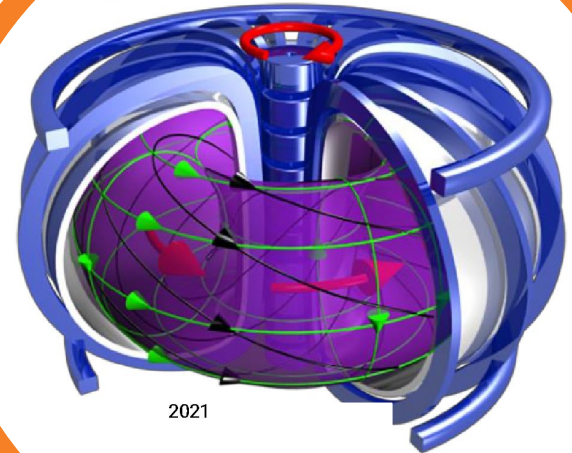
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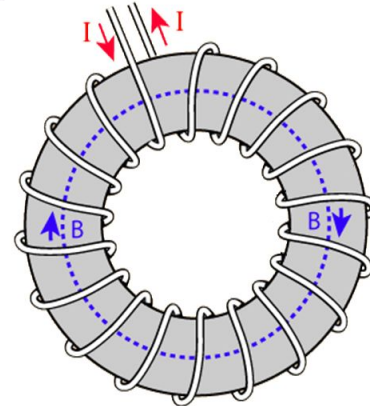
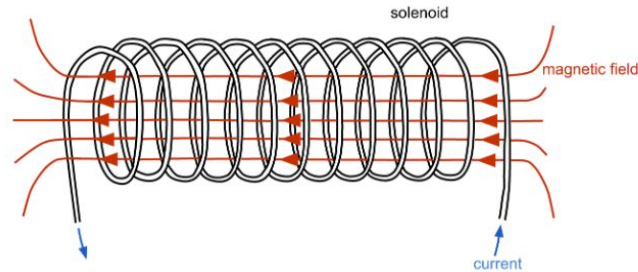
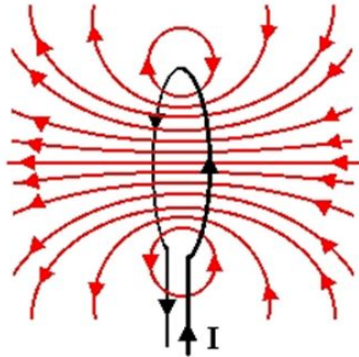
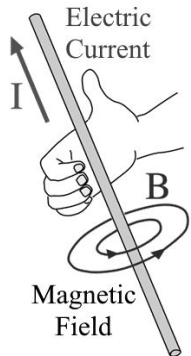
Magnetic Confinement



Make a magnetic field in a finite volume...it'll hold the plasma

Quick recap

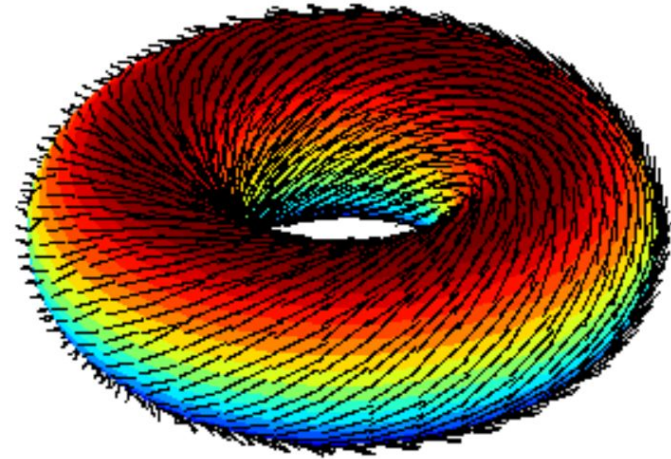
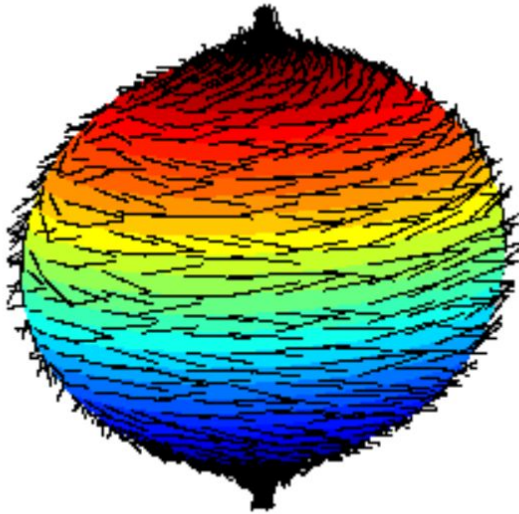
- We want to reproduce the sun on earth to produce clean and abundant energy
- To do that we heat up a gas of light elements to make plasma (a “soup” of electrons and positive ions)
- We use magnetic fields to keep the plasma in a container to allow them to collide



A hairy doughnut is quite easily combable

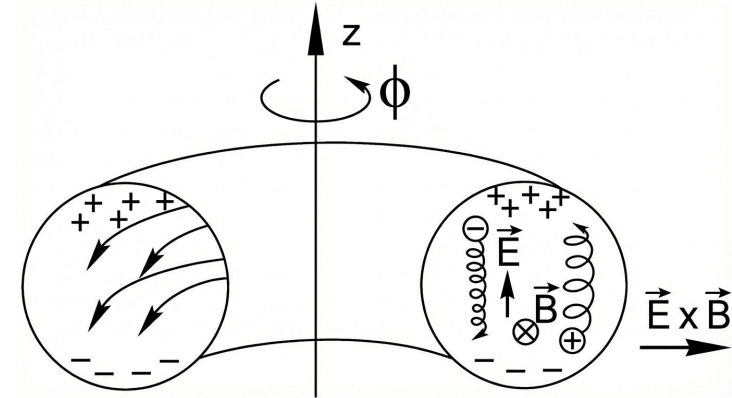
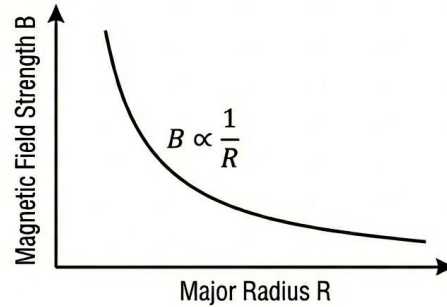
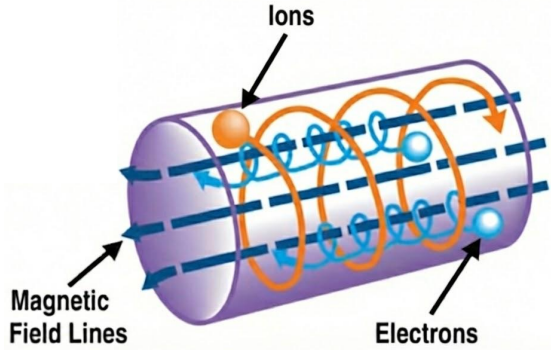
There is a theorem that states that “you can't comb the hair on a coconut”.

This means you cannot make a perfect sphere of magnetically confined plasma, because it will leak out someplace



A simple toroidal field gives poor confinement

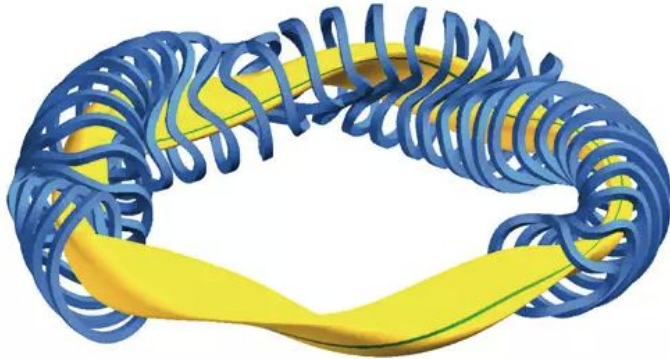
- Charged particles spiral around field lines
- Bending field into torus creates non-uniformities
- Electrons and ions drift apart vertically → charge separation
- Electric field created → particles expelled outward



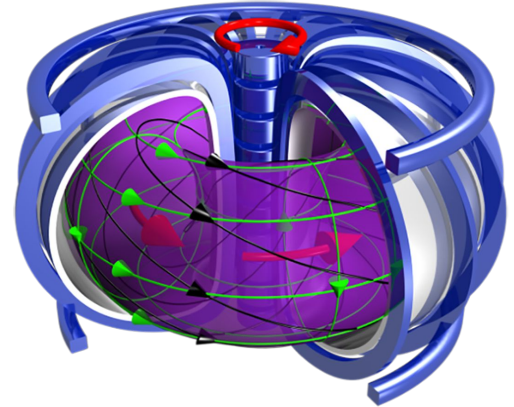
Solution: introduce a helical twist to field lines so drifts are compensated

Similarly to steep, banked turns that allow drivers maintain greater speeds into and through the turns, helical twist to field lines helps containing the plasma

Use non-planar magnetic field coils
-> **Stellarator**



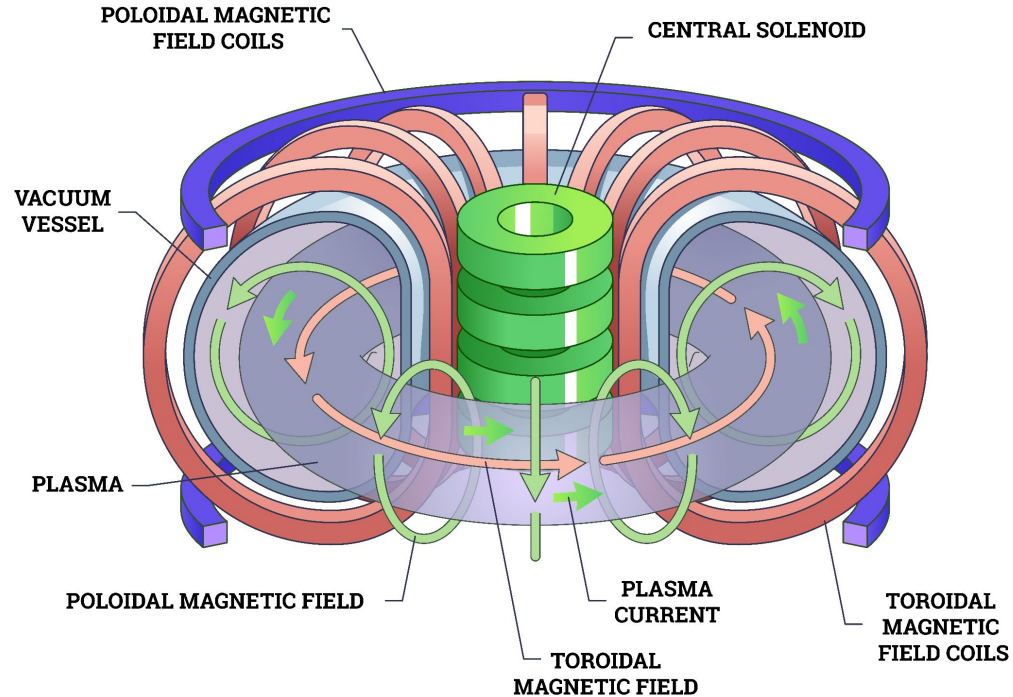
Toroidal current in plasma itself
-> **Tokamak**



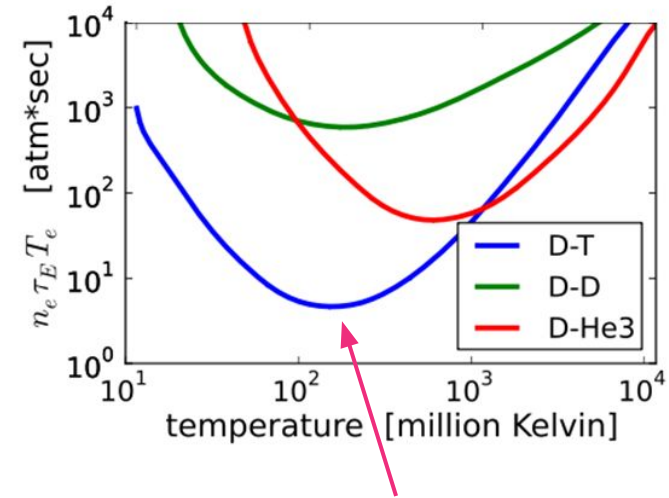
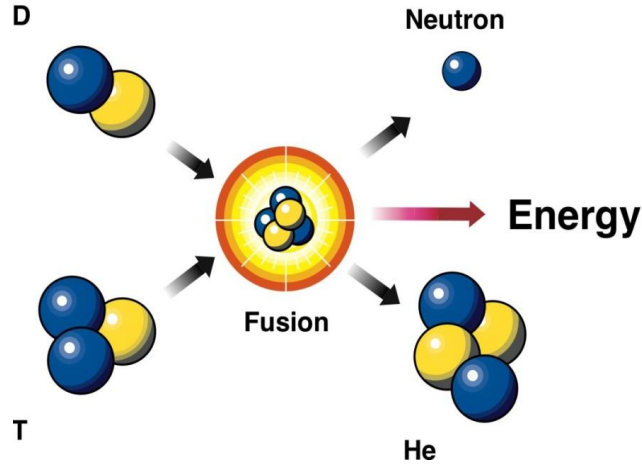
The plasma acts as the secondary of a transformer

To start the process,

1. Air and impurities are first evacuated from the vacuum chamber.
2. The magnet systems that will help to confine and control the plasma are charged up
3. The gaseous fuel is introduced
4. As a powerful electrical current is run through the central solenoid, the gas breaks down electrically, becomes ionized (electrons are stripped from the nuclei) and forms a plasma
5. As the plasma particles become energized and collide, they also begin to heat up (ohmic heating).

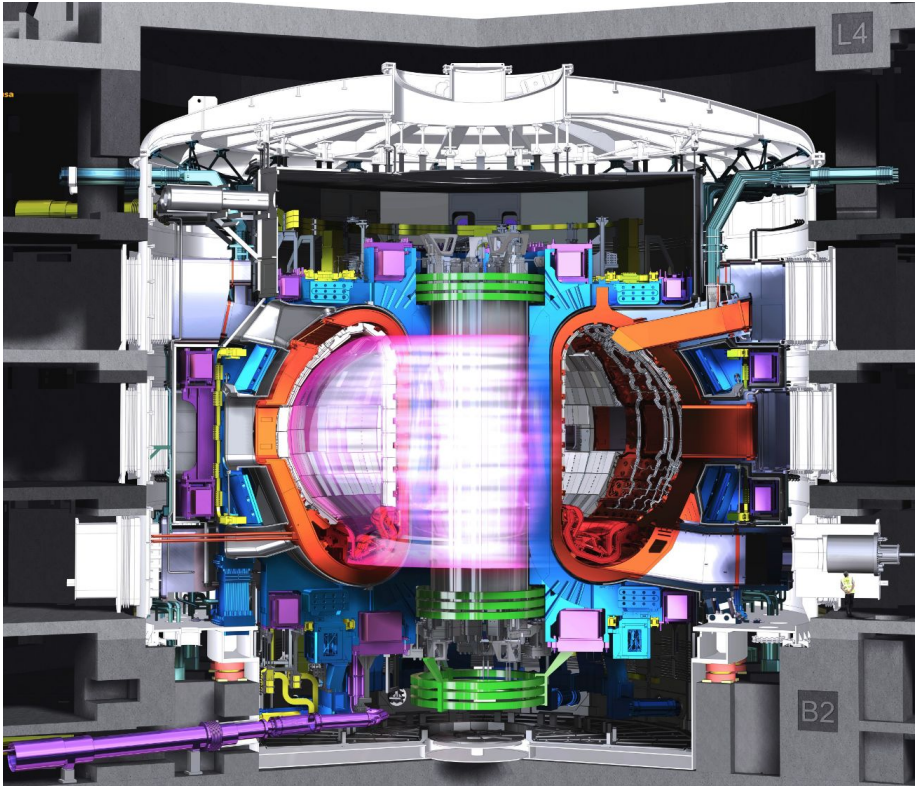


D-T is the fusion reaction that requires the lowest temperature (~360 million °F)



- Fusion is easiest at 200 million °K (magnetic fusion has already achieved it)
- Seawater contains deuterium in almost inexhaustible quantities.
- Tritium, a radioactive gas with a short half-life of 12.3 years, hardly occurs in nature. It can, however, be formed in a power plant from lithium.
- 1g of fuel generates ~ 90 MW-hours of energy, the equivalent of ~ 11 ton of coal.

ITER: a collaboration between 35 nations to demonstrate the possibility of achieving burning plasmas



ITER is the world's largest tokamak that is being built in southern France.

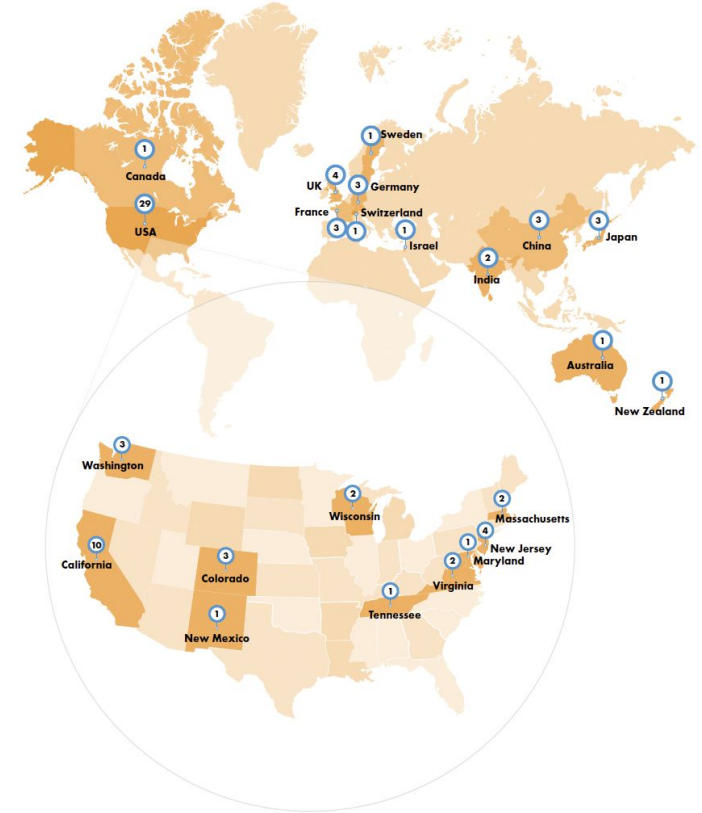
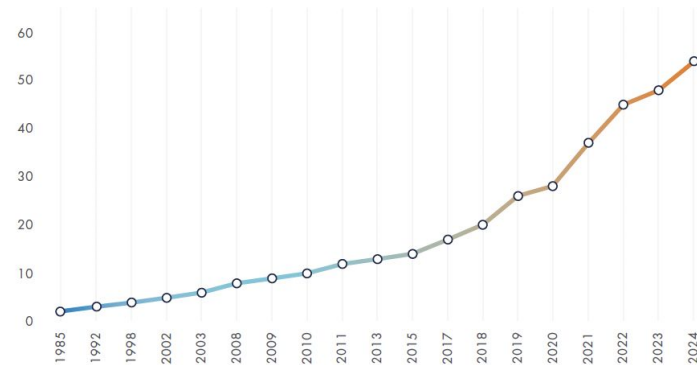
- Achieve a deuterium-tritium plasma in which the fusion conditions sustain themselves
- Generate 500 MW of fusion power from 50 MW of input power.
- Test tritium breeding

A growing number of private companies are interested in fusion

- The Fusion Industry Association is a non-profit organization composed of private companies working to make commercial fusion energy a reality. The images are from the 2025 Global Fusion Industry Report, available @ <https://www.fusionindustryassociation.org/>

Total number of private fusion companies by year

(Based on 2025 responses, excludes companies that have since folded or consolidated)



Outline

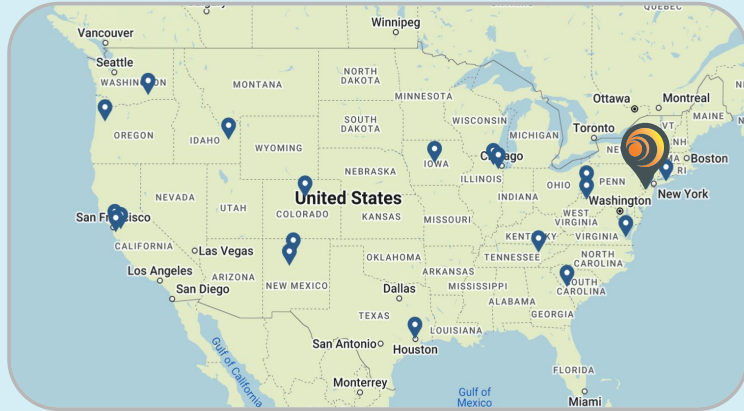
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The Princeton Plasma Physics Laboratory



U.S. DEPARTMENT OF
ENERGY

One of 17 Dept. of
Energy **National Labs**

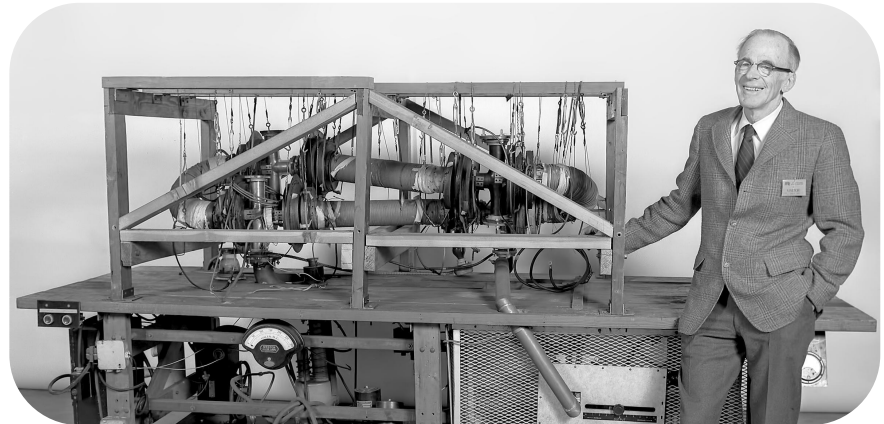


Managed by



**PRINCETON
UNIVERSITY**

- Magnetic fusion research at Princeton began as a classified government project in 1951 under renowned physicist Lyman Spitzer Jr., using the code name “Project Matterhorn.”
- PPPL Today: 700+ employees, \$150 Million+ government funding, 300+ annual publications



Top Projects

LOCATED AT PPPL:



NSTX-U

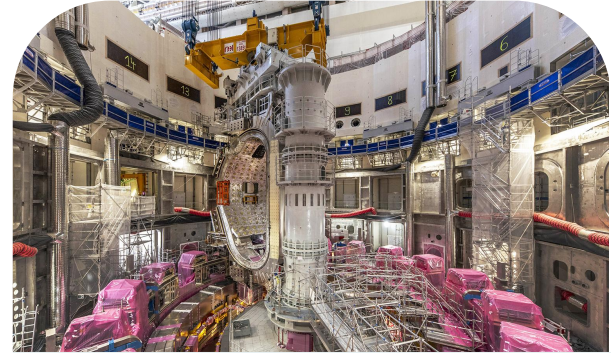
*National Spherical Torus
Experiment-Upgrade*



FLARE

*Facility for Laboratory
Reconnection Experiment*

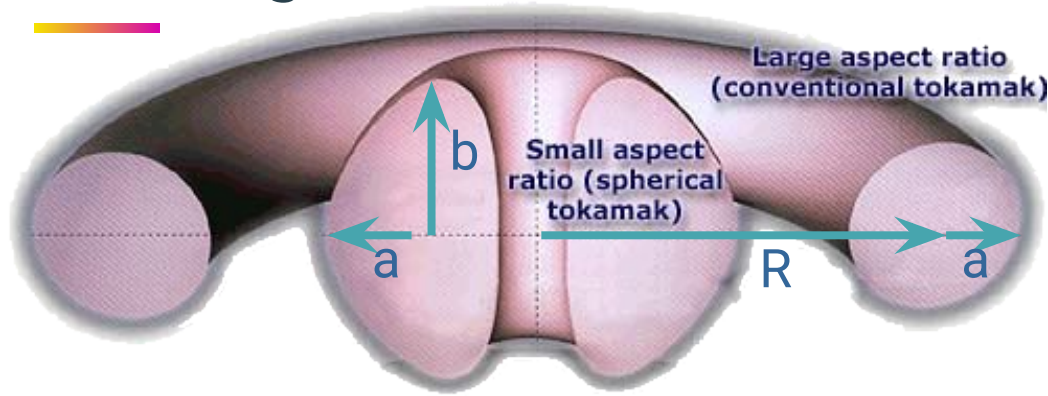
INTERNATIONAL PARTNER:



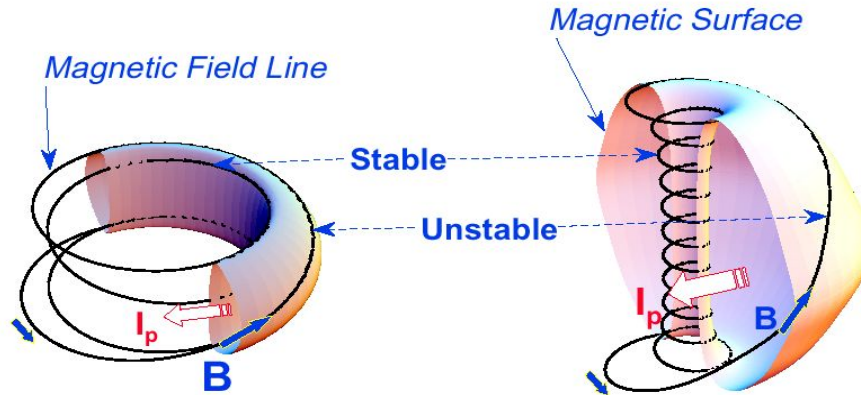
U.S. ITER

PPPL is designing and building diagnostic equipment and developing scientific data and software coding for the international facility.

NSTX-U is a spherical tokamak (ST), which has certain advantages



- STs are lower aspect ratio, have natural higher elongation
 - Smaller size can mean lower cost
- Challenges :
 - Managing the high heat flux

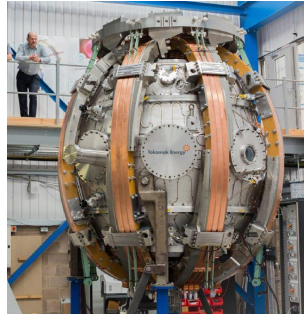


There is substantial interest in a ST as a Fusion Pilot Plant

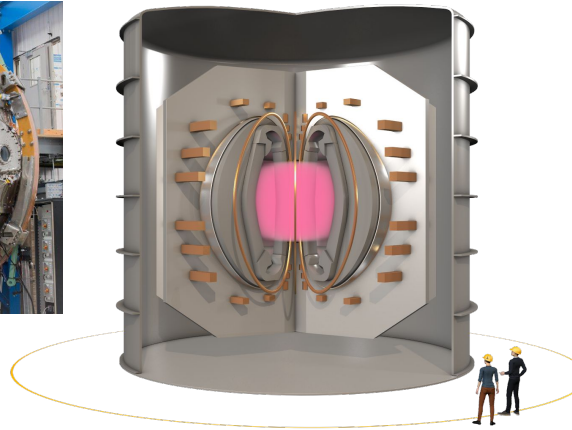
UK: Spherical Tokamak for Energy Production (STEP)



ST40

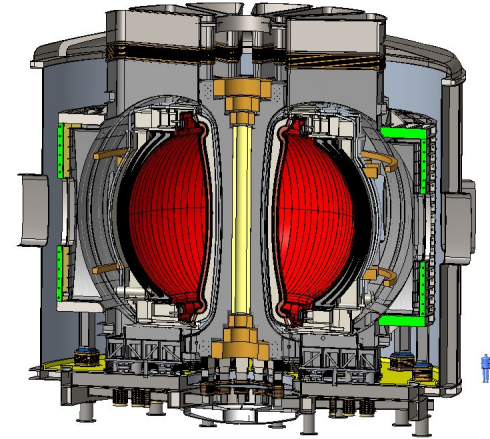


Future Pilot Plant

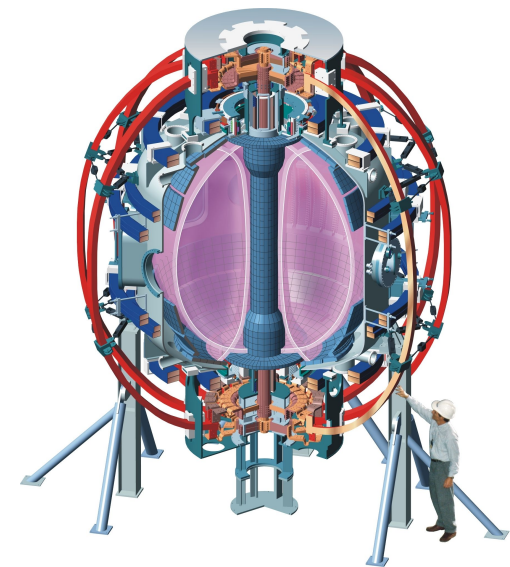
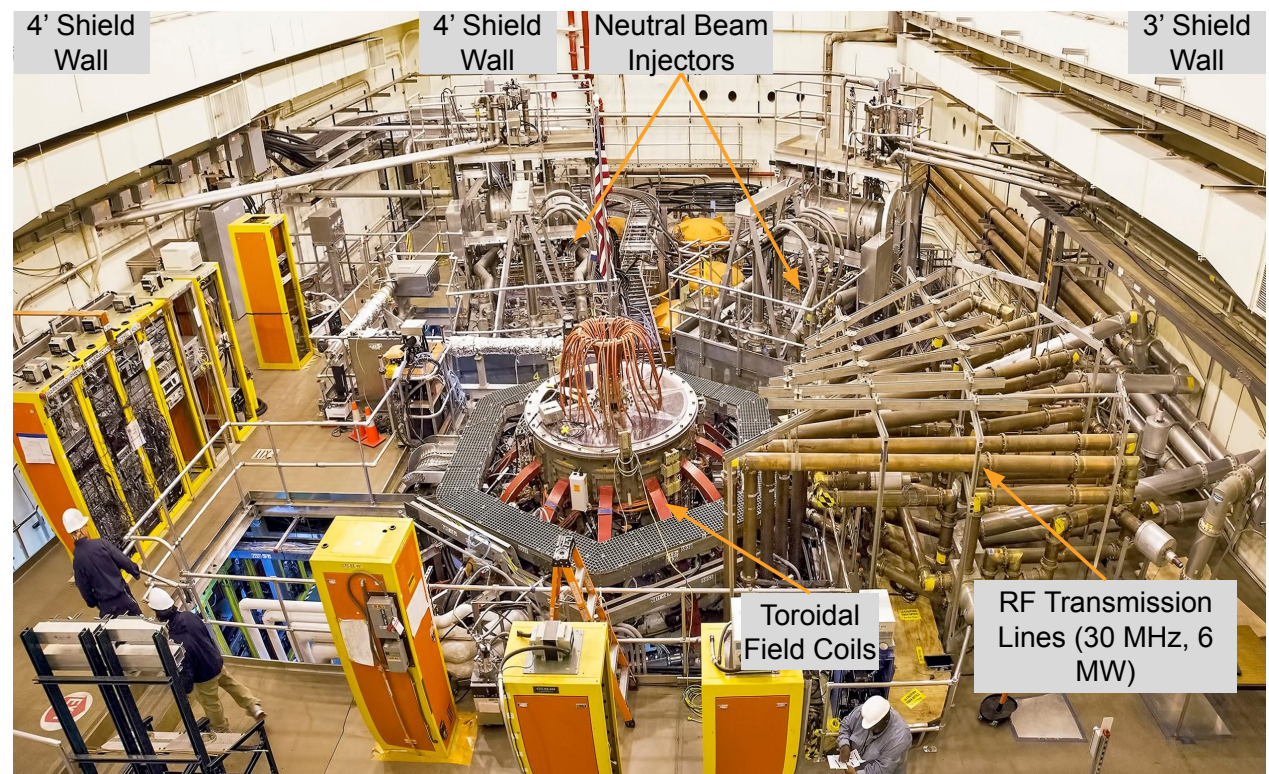


Tokamak Energy (UK/US private company): high-temperature super-conducting devices

US: ST Advanced Reactor (STAR)
(design study at PPPL)

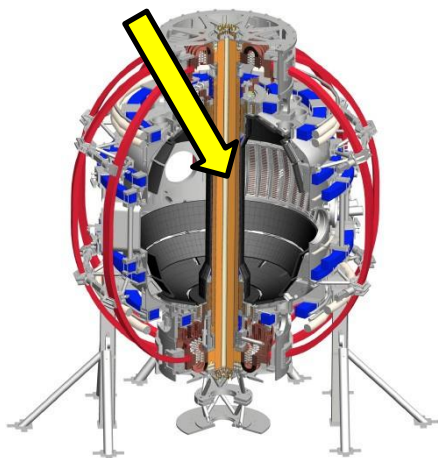


NSTX-U will be the highest power spherical tokamak in the world



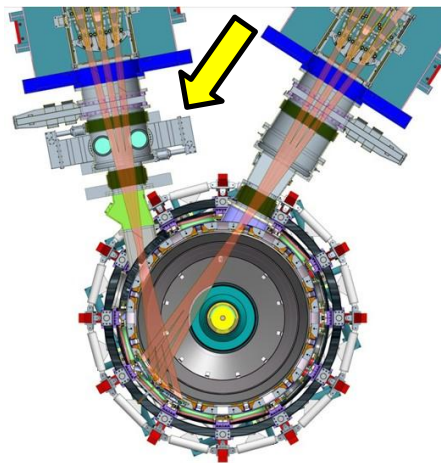
NSTX-U is currently getting an upgrade which will boost performance

New Central Magnet



- 2× toroidal field ($0.5 \rightarrow 1$ T)
- 2× plasma current ($1 \rightarrow 2$ MA)
- 5× longer pulse ($1 \rightarrow 5$ s)

Tangential 2nd Neutral Beam



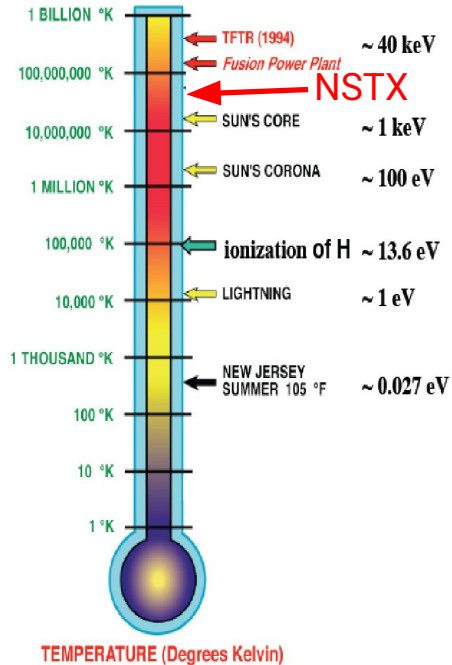
- 2× heating power ($5 \rightarrow 10$ MW)
- 2× current drive efficiency (tangential NBI)

- NSTX-U will access unique physics regimes that allow to study new physics
- 4× heat flux to surfaces
 - Study how to handle heat
- Full non-inductive current drive
 - Essential for future steady-state

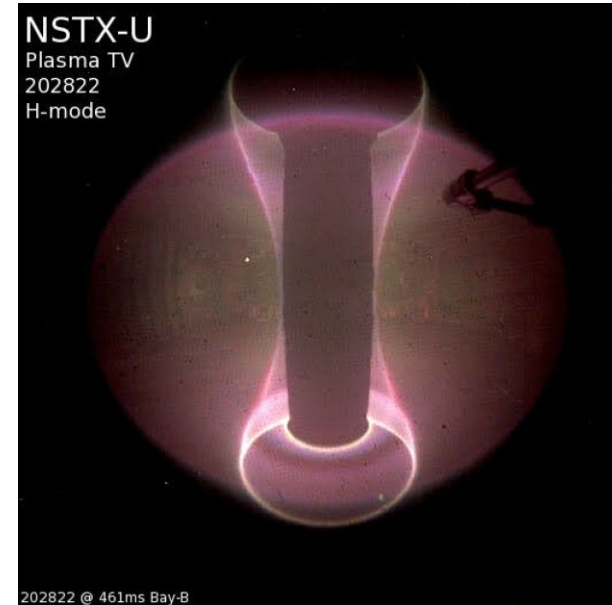


Like its predecessor, NSTX-U will be a research device

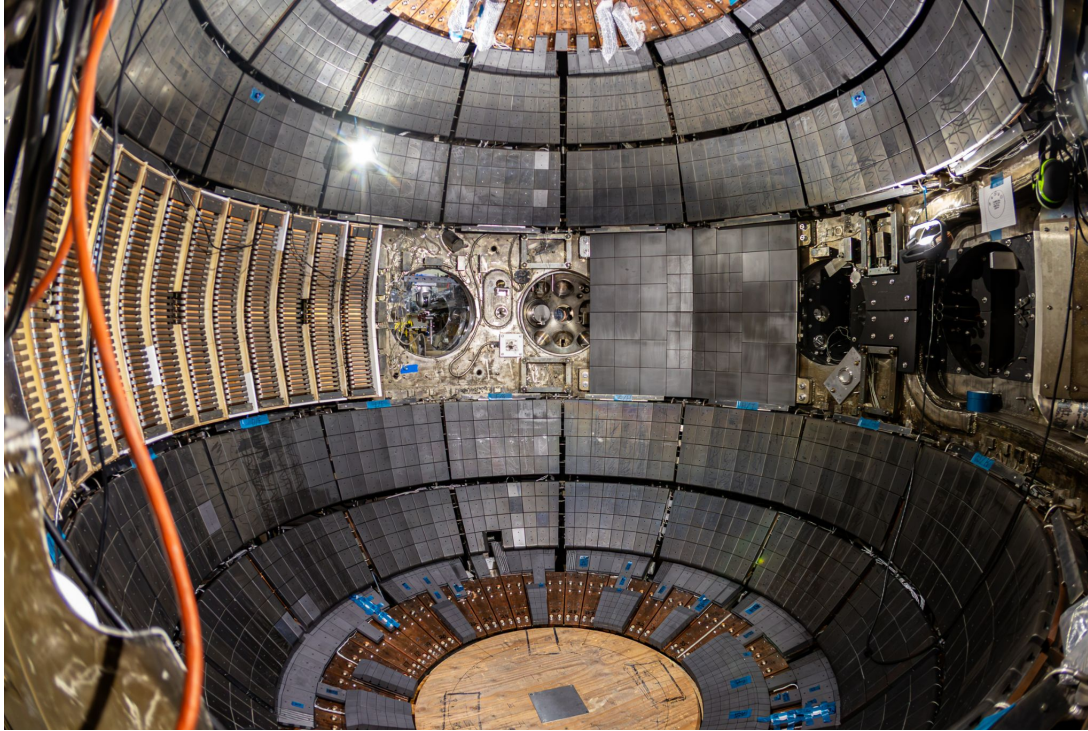
PLASMA THERMOMETER



- NSTX achieved temperatures of ~20 million °K
 - In plasma pulses lasting up to ~1.5 s
 - With very, very wispy density ~ one millionth of the density of air
- The plasmas in NSTX stored energy of up to half a megajoule
 - Sounds like a lot, but it's only like burning 17 grams of coal
 - The energy is confined for up to ~0.1s before it is lost
- The plasmas were heated by 5 megawatts of power
 - Like 200,000 light bulbs

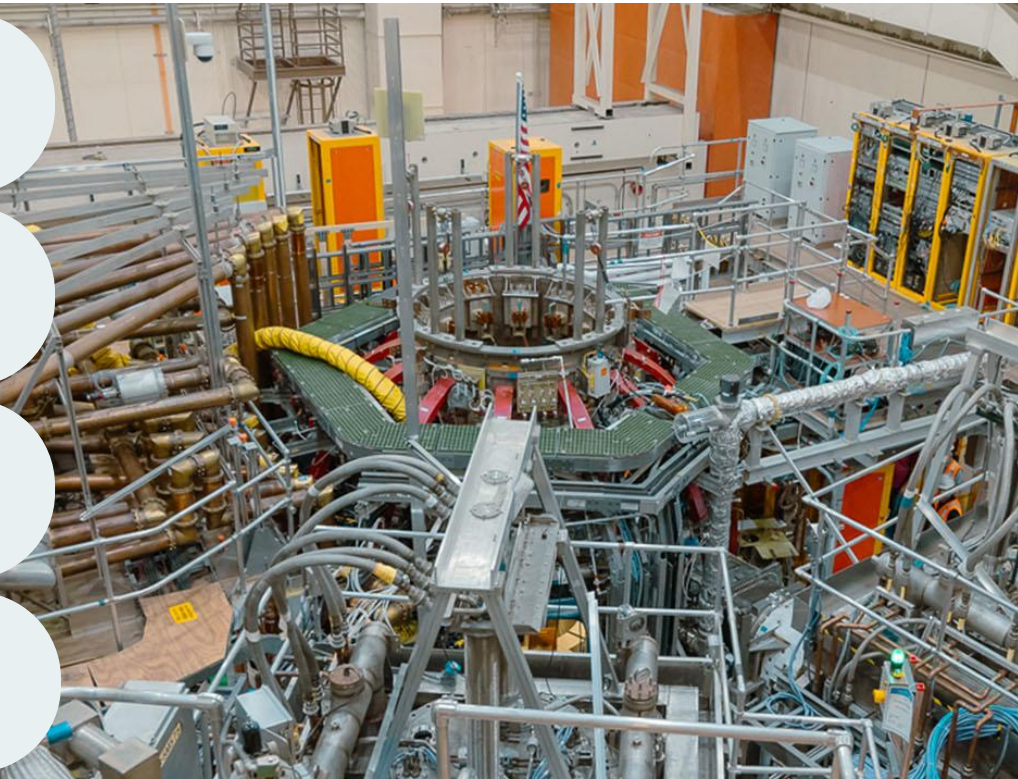


First plasma expected in 2026



NSTX-U (National Spherical Torus Experiment-Upgrade)

- The Lab's primary **fusion experiment**
- A compact design that makes it an ideal candidate for a **fusion pilot plant** followed by a **commercial reactor**.
- Produces high-pressure plasmas with less energy at lower costs
- A worldwide **user facility** that will test the viability of this design to produce cost-effective fusion energy



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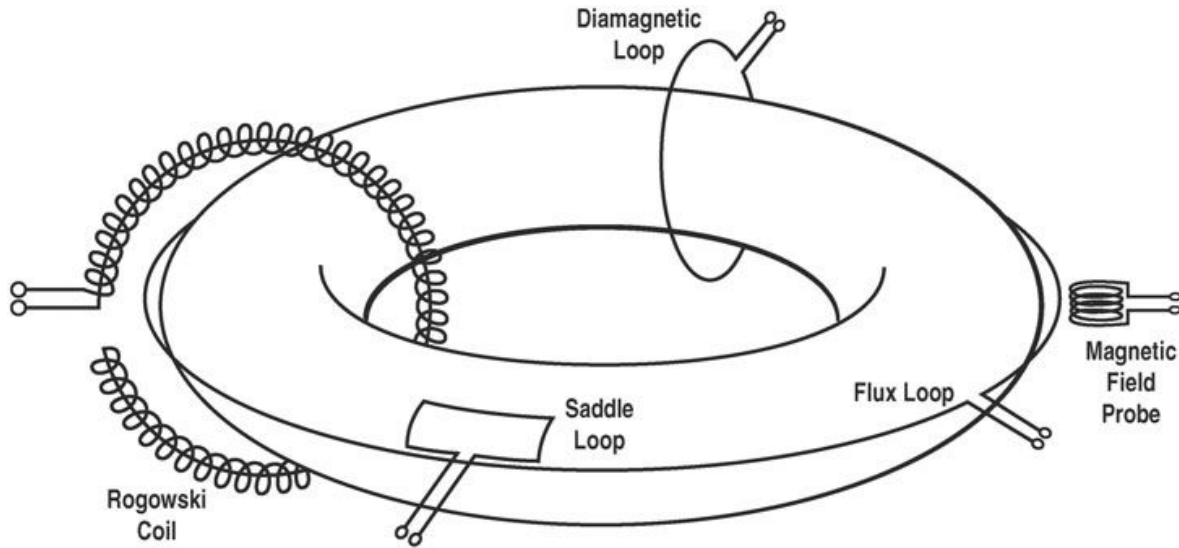
How do we measure and control the plasma?



- Measurement of the plasma and first wall parameters are essential to:
 - to provide input for real time machine protection systems
 - to provide input for real time plasma control systems;
 - to provide data for physics studies and for the evaluation of plasma performance.
- NSTX-U will have >50 diagnostics systems
- 4 important quantities, measured in most experimental devices, are:
 - plasma shape and position (magnetic diagnostic system)
 - plasma density (interferometer)
 - plasma temperature (Thomson scattering)
 - first wall temperature (IR camera)
- Reminder: NSTX-U is a research device. Power Plant will have different requirements

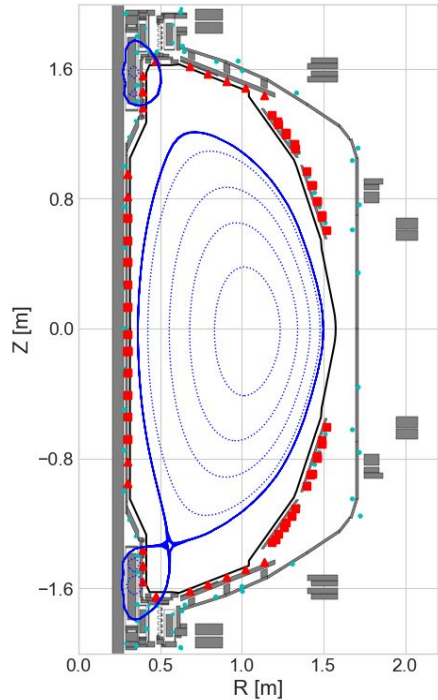
The magnetic diagnostic system (my expertise)

Magnetic sensors are mainly inductive sensors that measure the change in the magnetic flux (**Faraday's law**).

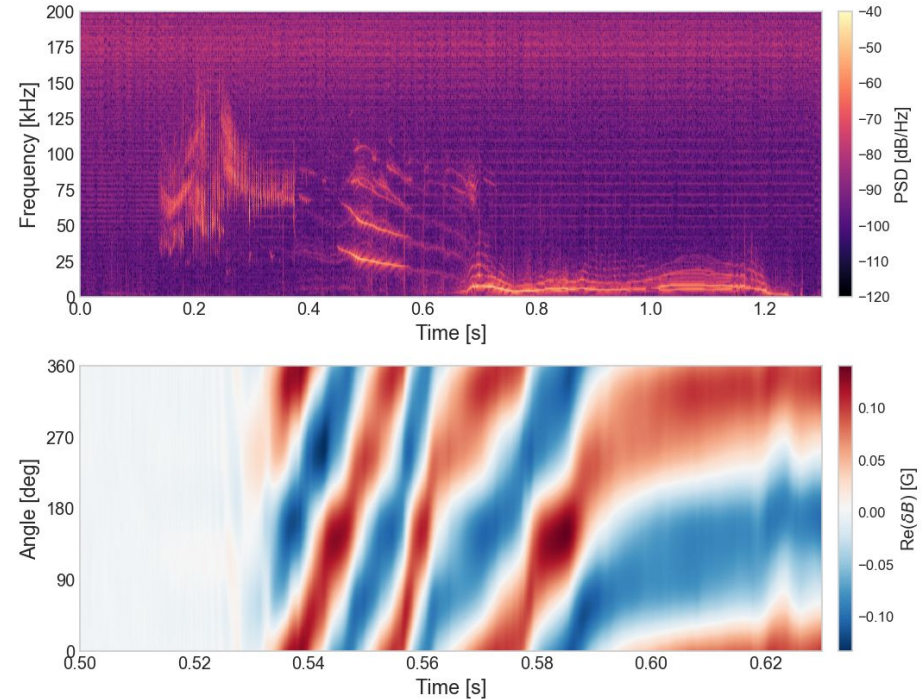


Used for the measurement of 2D and 3D fields

Poloidal array of sensors used to constrain 2D equilibrium reconstructions



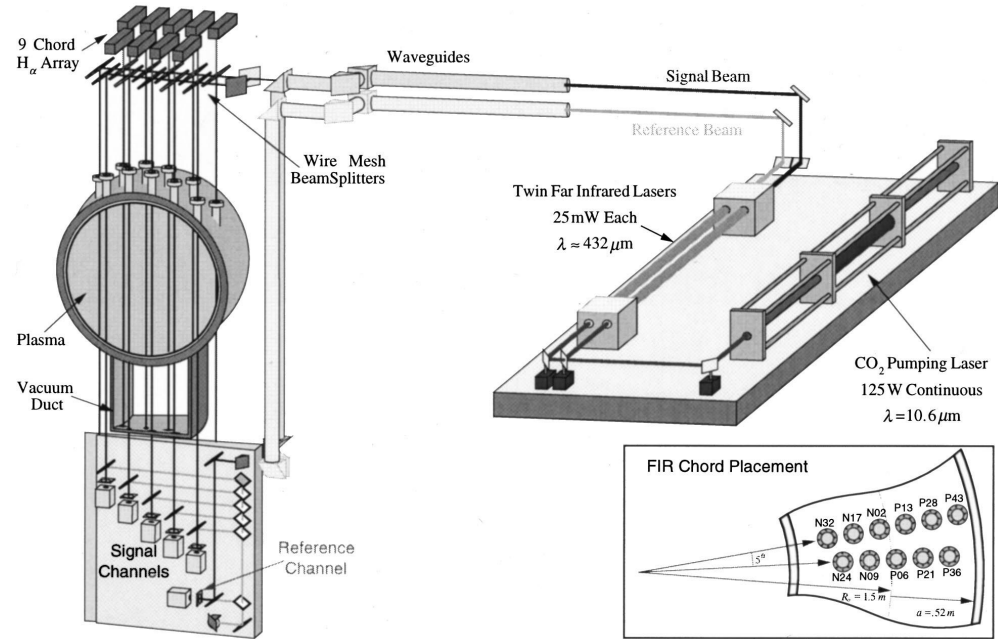
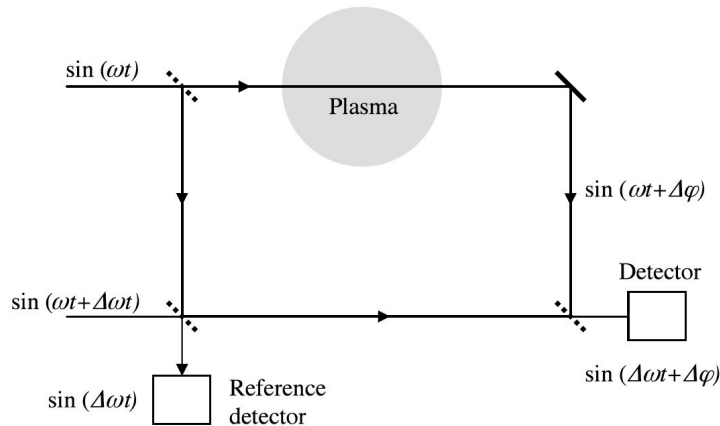
Toroidal array of sensors can identify 3D fields



The interferometer

The interferometer is based on the principle that an electromagnetic wave will propagate through plasma and air at different rates.

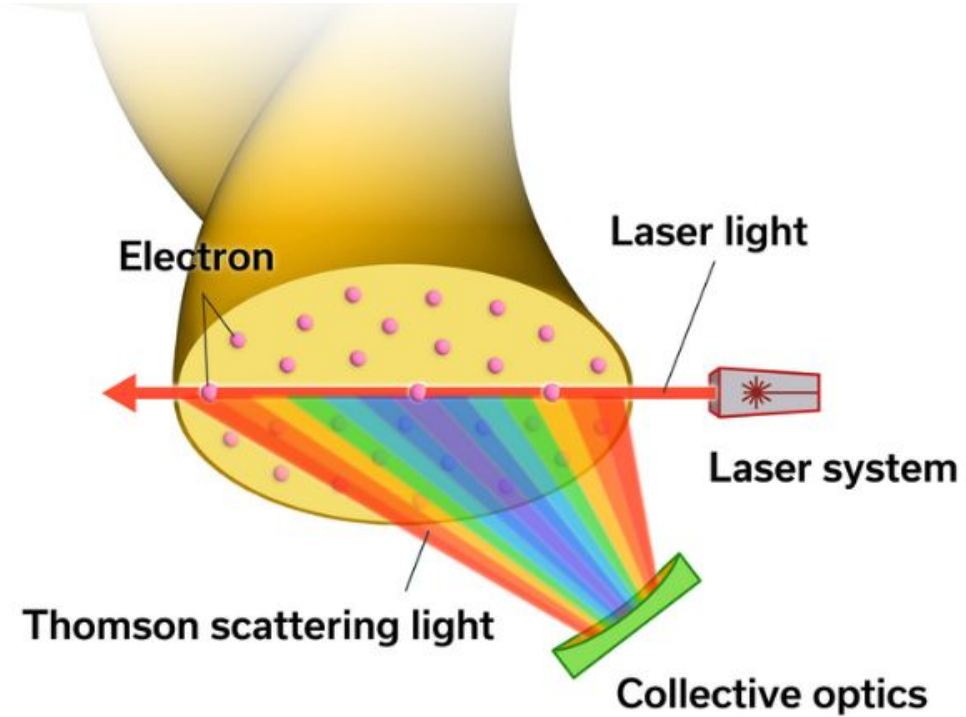
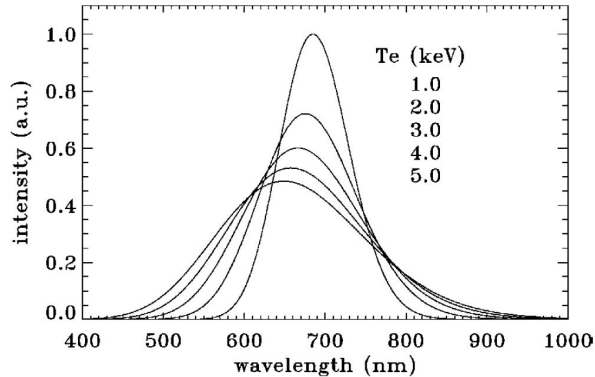
This difference in propagation can be measured as phase shift



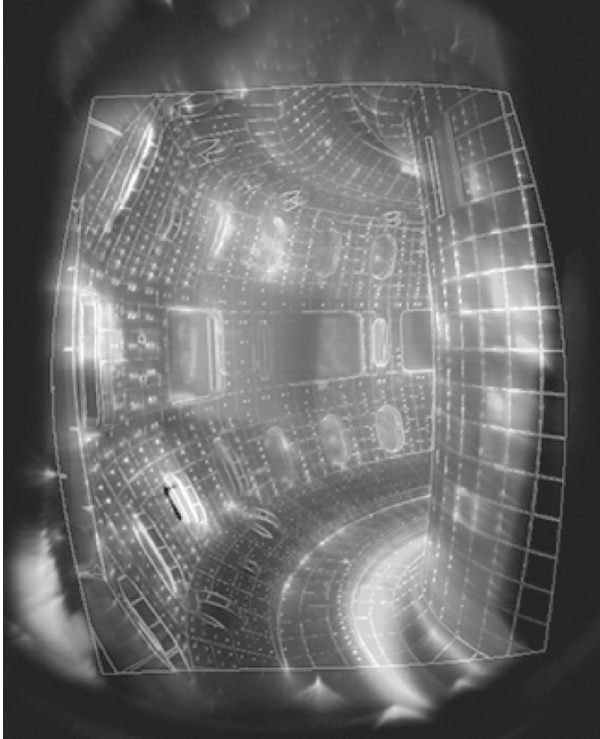
The Thomson scattering

Plasma electrons are accelerated in the E-field of a laser beam

The emitted light is measured and the wavelength distribution provides the electron temperature

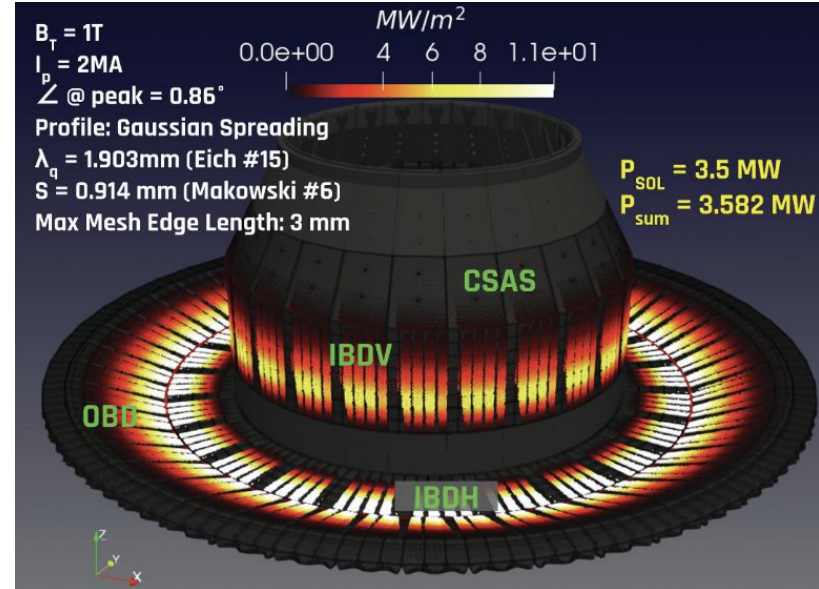


Heat fluxes to the plasma facing components



Camera looking at infrared emission to measure the heat at different locations.

Softwares are used to simulate it.



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How can I learn more? How can I get involved?

Public Engagement & Outreach

- Plasma Network for Engagement and Training
- APS Division of Plasma Physics
- Youth STEM Conference
- Regional Science Bowl Competition
- Ronald E. Hatcher Science on Saturday Series
- Plasma Demonstrations at Local Schools



Science On Saturday

LECTURE SERIES



Academic Programs

- Science Undergraduate Laboratory Internships (SULI)
- Community College Internships (CCI)
- Visiting Faculty Program
- Science Graduate Student Research Program
- Plasma & Fusion Undergraduate Research Opportunities
- High School Internships
- National GEM Consortium Fellowship
- Lab-wide Internship Programs

Undergraduate Program “SULI”

- Science Undergraduate Lab Internship
 - National program sponsored by DOE for U.S. citizens
- Solicited annually, three separate terms
 - Spring: 16 weeks (January – April)
 - Summer: 10 weeks (June – August)
 - Fall: 10 weeks (September – December)
- PPPL specific info www.pppl.gov/suli
- Apply <https://science.osti.gov/wdts/suli>



2026 summer SULI dates (10-weeks):

- Application: ~~Oct. 15, 2025 to Jan. 7, 2026~~
- Internship dates: June 1, through August 7, 2026

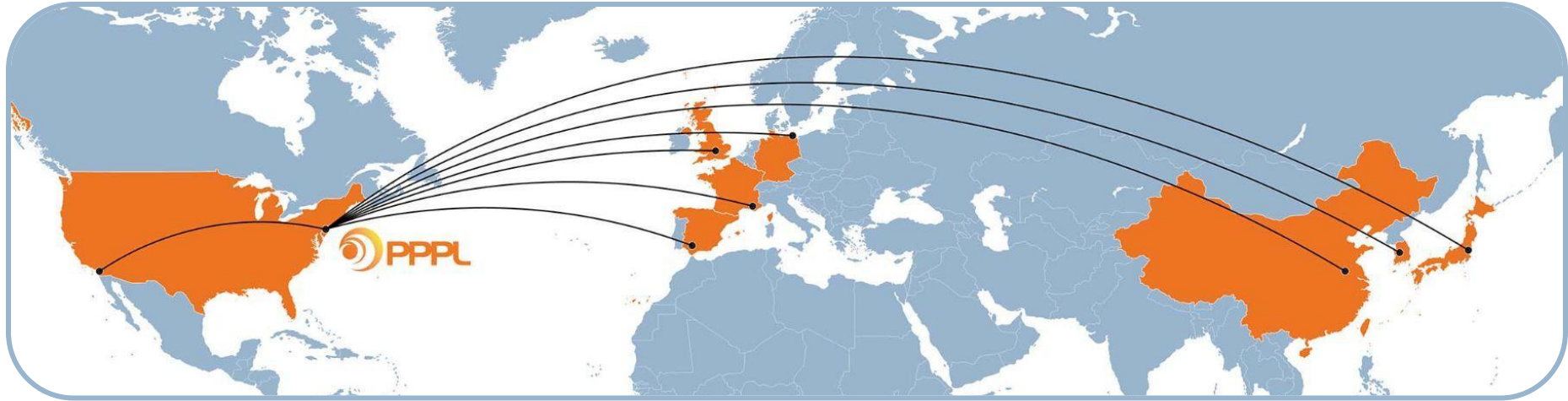
Graduate Program

- Department of Astrophysical Sciences
 - Based at PPPL
 - Top theoretical & experimental resources
 - Info <https://plasma.princeton.edu/>
- Department of Mechanical Engineering
 - Based at Princeton University
 - Top control & machine learning resources
 - Info <https://control.princeton.edu/>



Worldwide Fusion Facilities

We collaborate with experimental fusion facilities around the world, contributing to global scientific discovery.



Summary



- Fusion on earth can be achieved by containing a plasma with magnetic fields in a “doughnut” shaped container in order to have a large number of nuclei that move fast enough and stay in the same space for a long enough time
- At the Princeton Plasma Physics Laboratory, scientists are exploring the use of a “cored apple” shaped container like NSTX-U as an alternative concept for a future fusion power plant to reduce the fusion energy production cost
- A large set of diagnostics is deployed to both protect the device, control the plasma and evaluate and understand the plasma performances
- There are several opportunities for everybody to be involved! <https://www.pppl.gov/education>