Plasma, Fusion, and PPPL

Presented by:
Arturo Dominguez

PPPL: Princeton Plasma Physics Lab

- PPPL is one of 17 DoE national laboratories.
- We are managed by Princeton University but have a government mandate that focuses on fusion energy research and basic plasma science.

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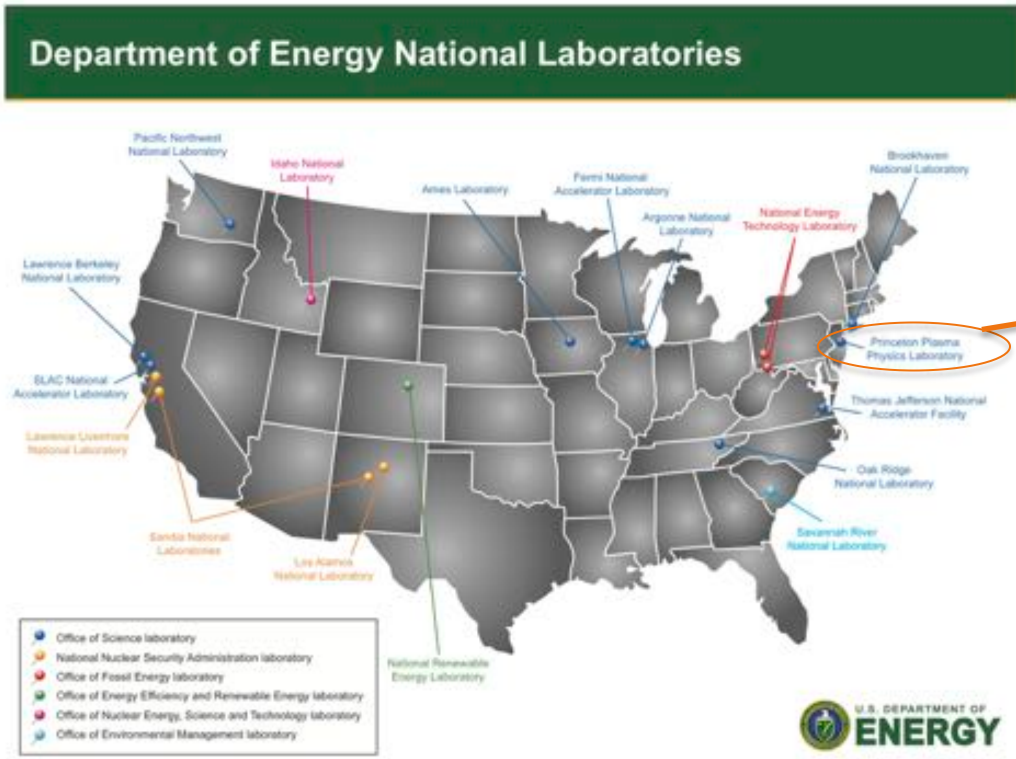
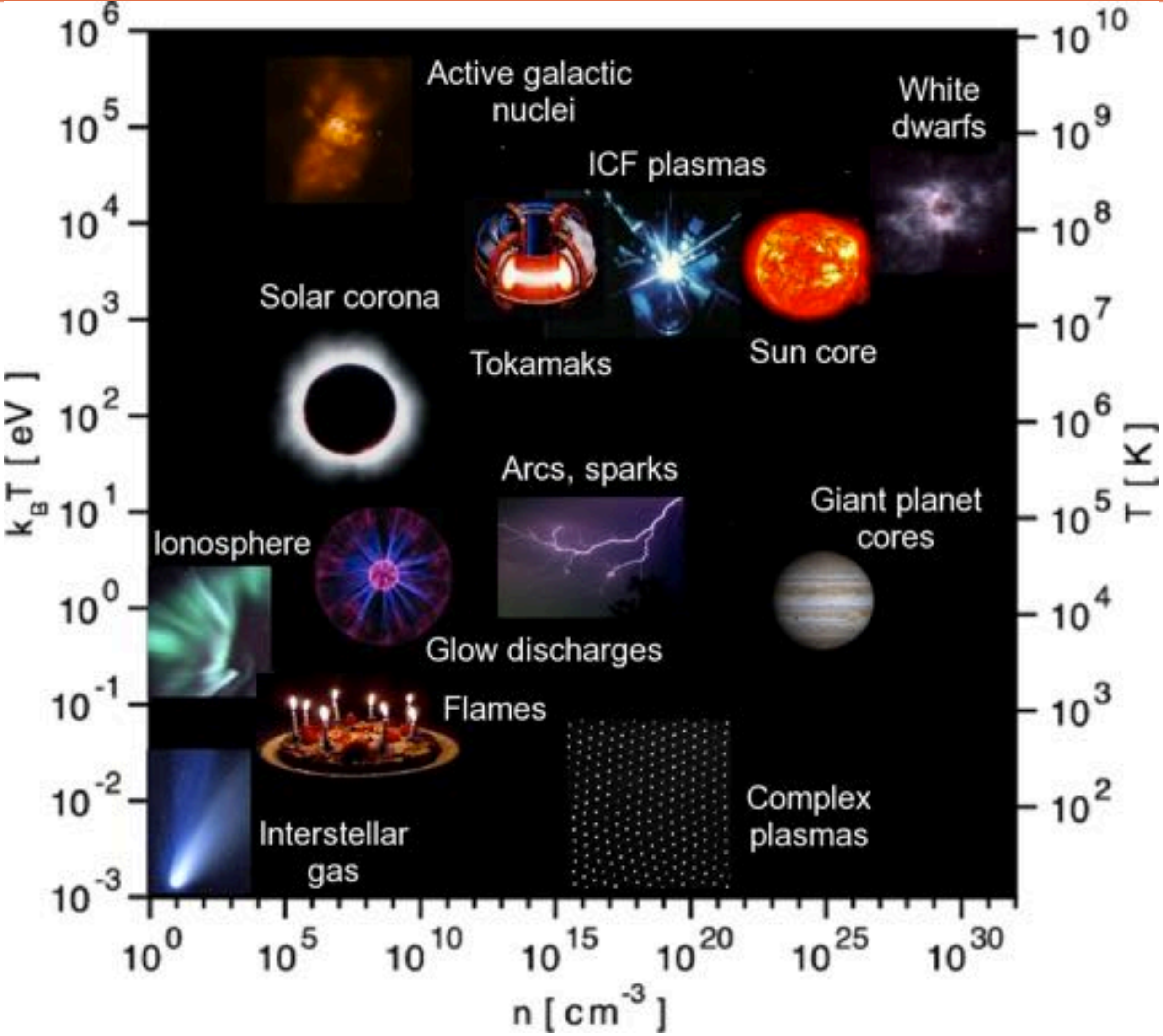
PLASMA PHYSICS
LABORATORY



Plasma: It's hot, but it's a dry heat

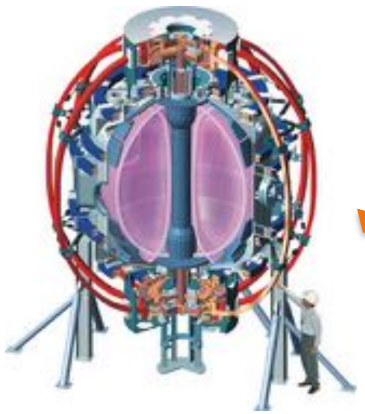
- **Plasma is the 4th state of matter:** It is qualitatively different than gas due to its collective behavior, particularly its interactions with E&M fields.

- **Plasmas cover a wide range of densities and temperatures** This makes the field rich in scope



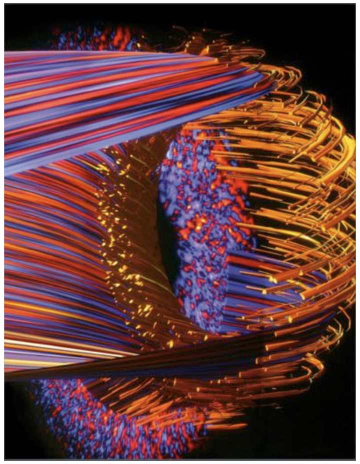
At PPPL, we try to understand many aspects of plasma

Fusion Research



Basic plasma physics

Plasma theory and simulation



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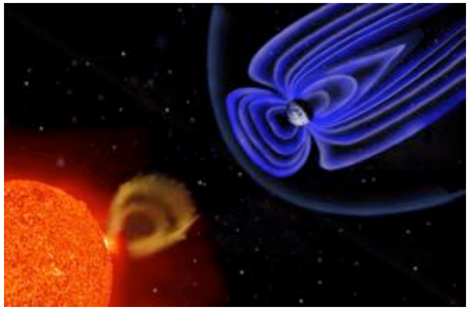
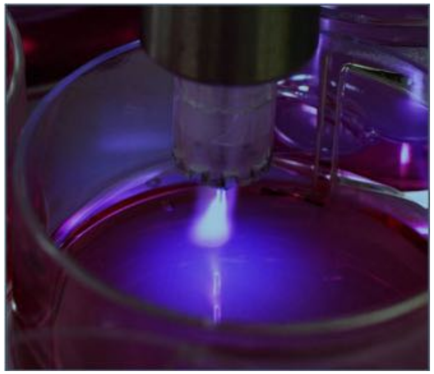
Astrophysical plasmas



Plasma in other fields (e.g. medicine)



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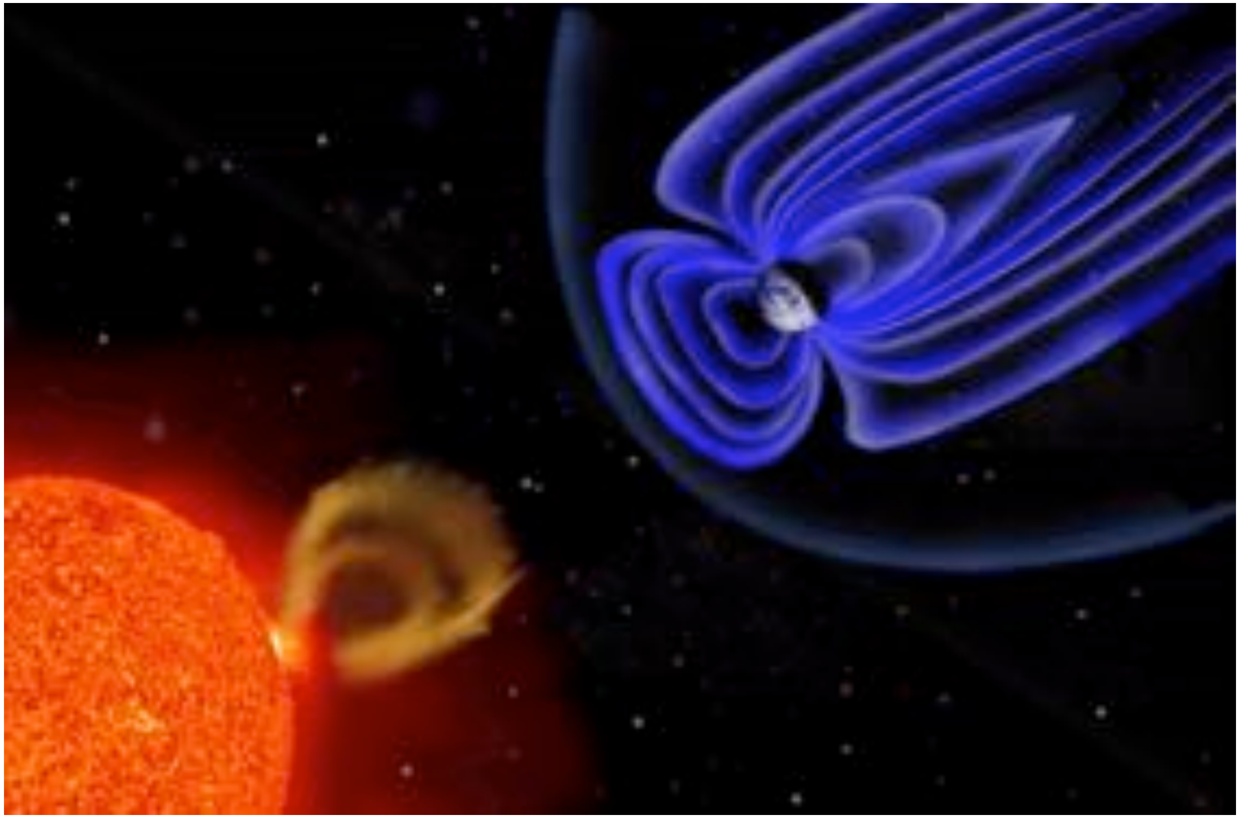
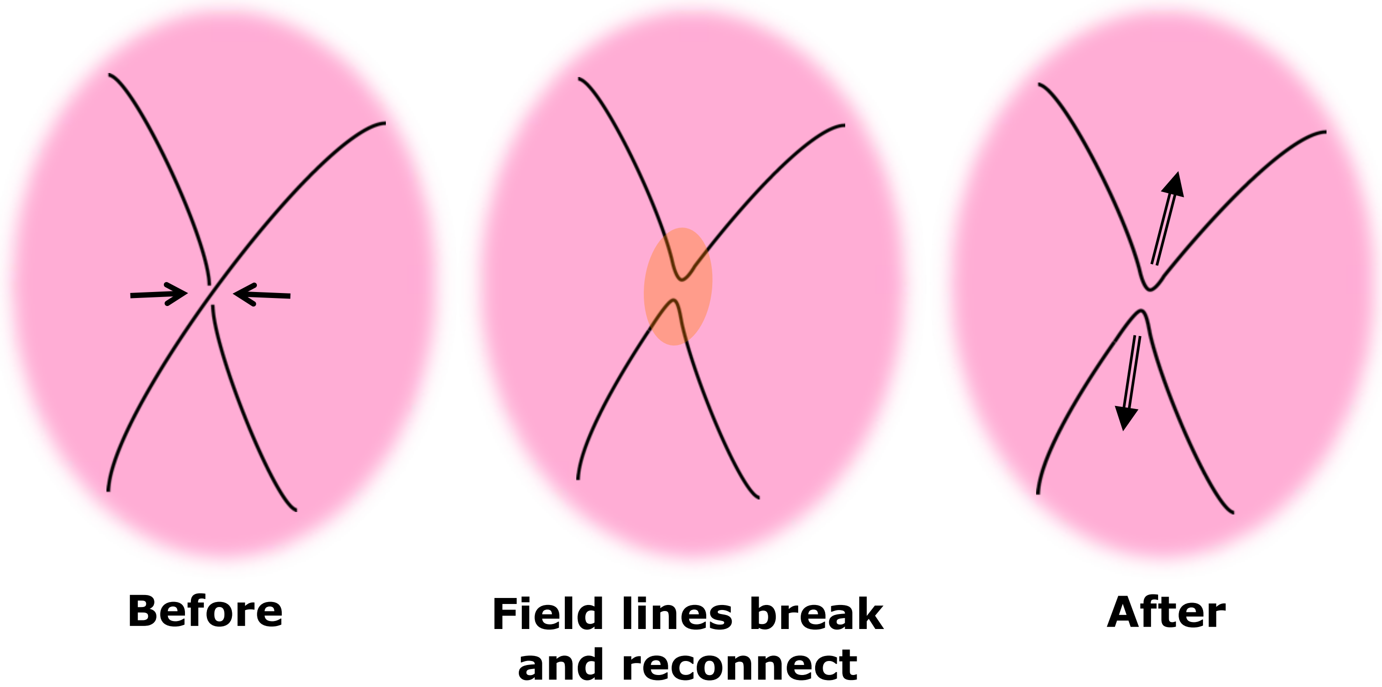
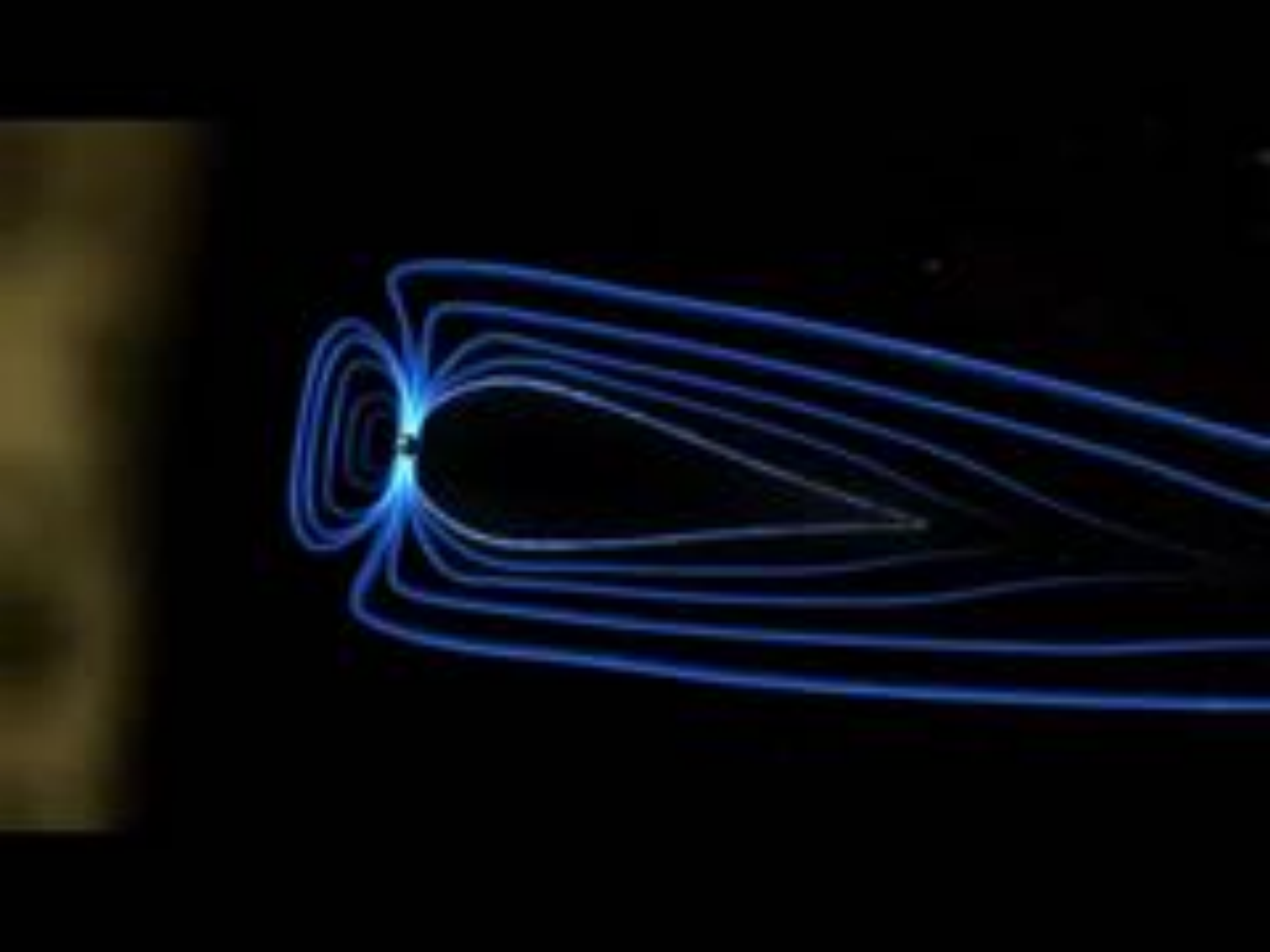


One large research topic is magnetic reconnection

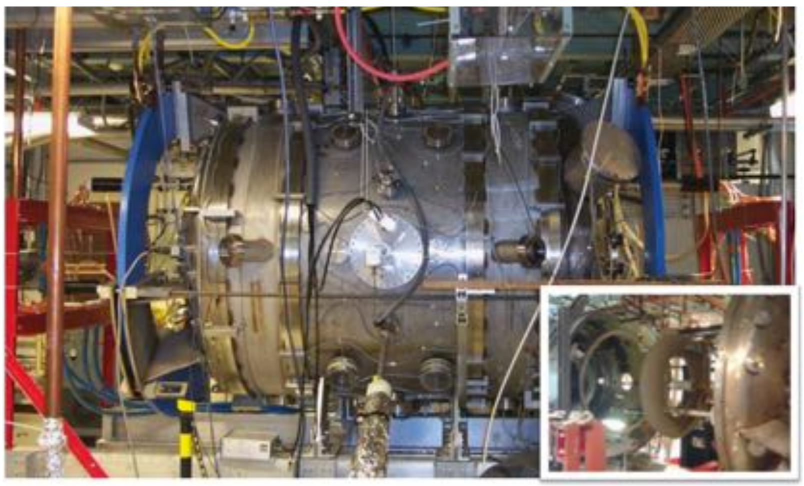


- **Topological rearrangement of the plasma** → breaks the "frozen in" condition on the magnetic field
- **Converts some magnetic field energy into particle energy** → the plasma charges a "toll" to the magnetic field

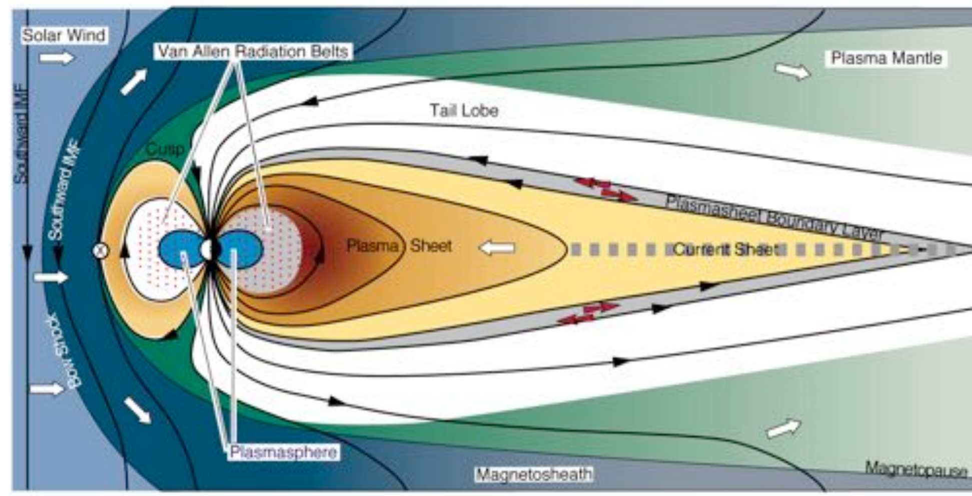


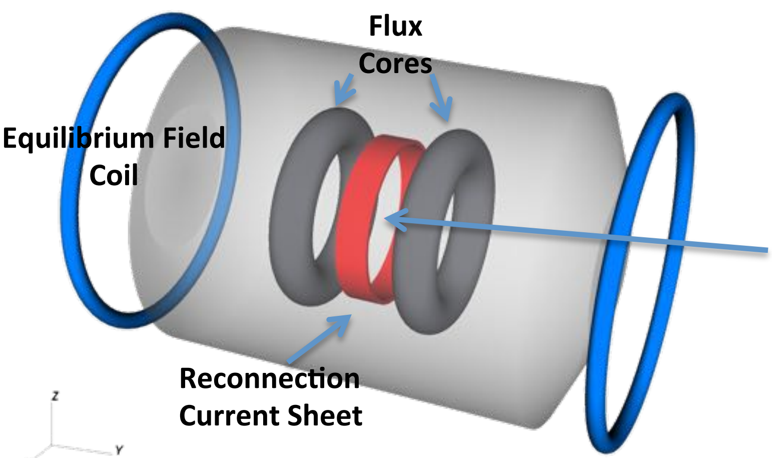
Magnetic Reconnection Experiment (MRX)

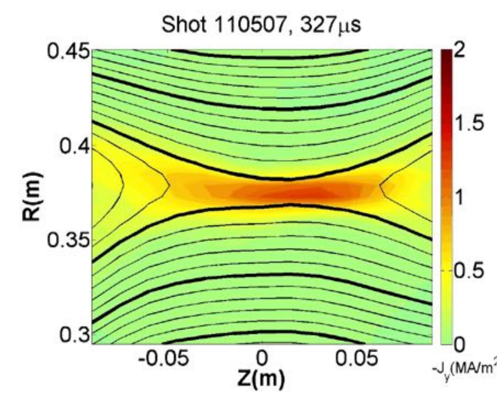
MRX Setup



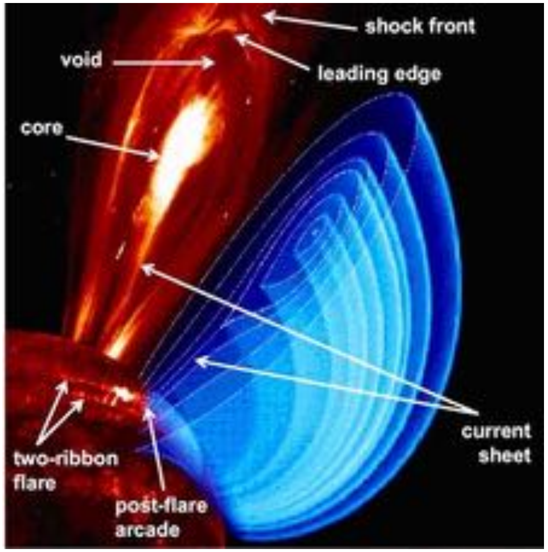
Current sheets in the earth's magnetosphere are one example of reconnection

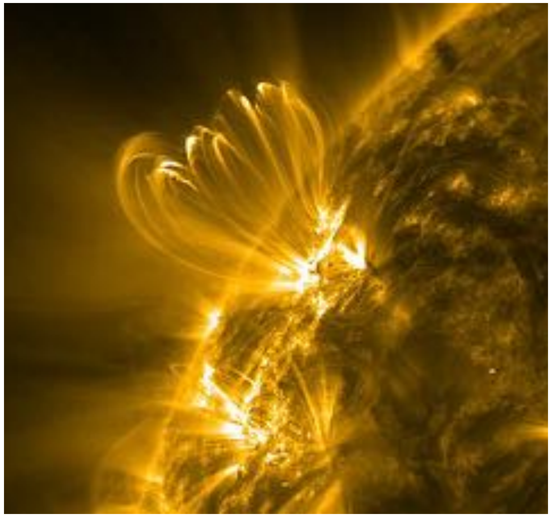


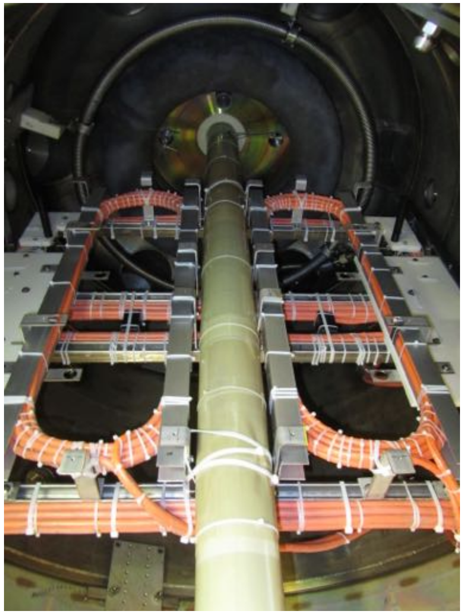


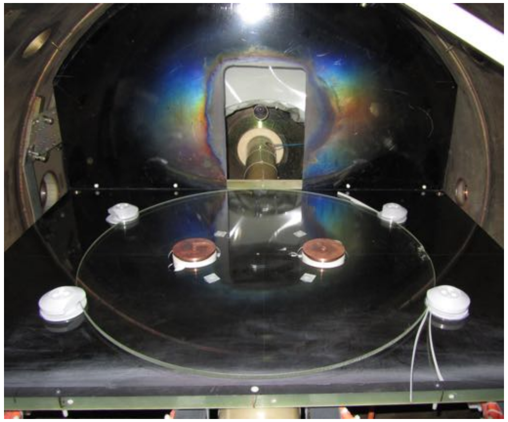


Coronal Mass Ejection on MRX

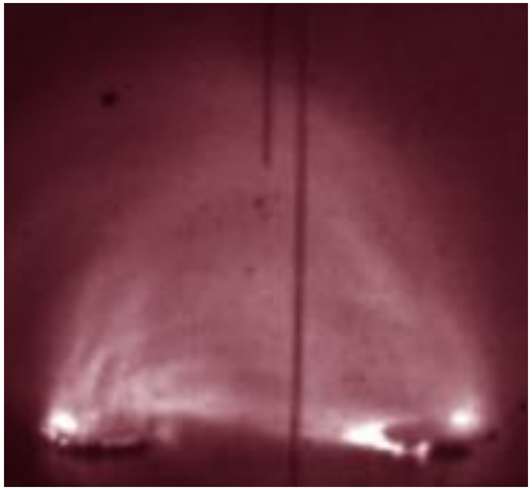




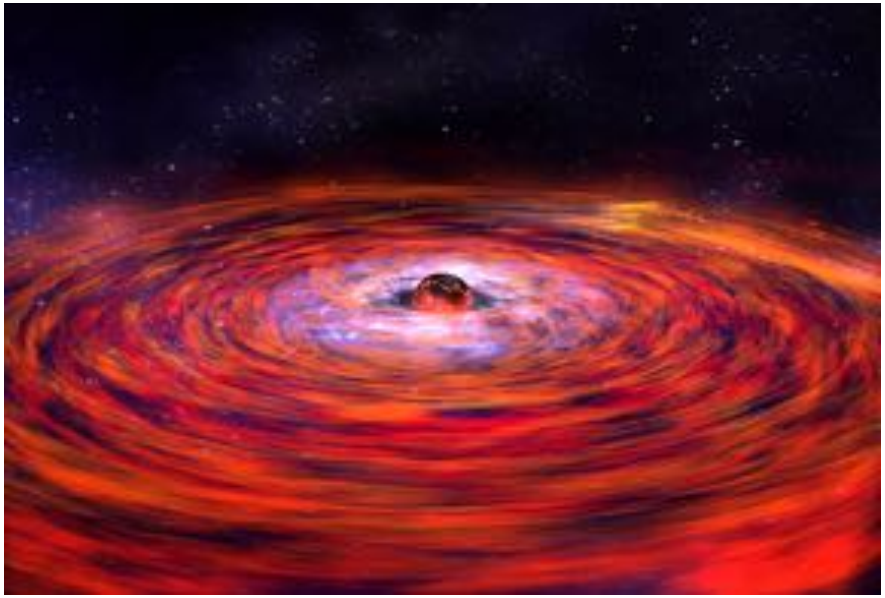


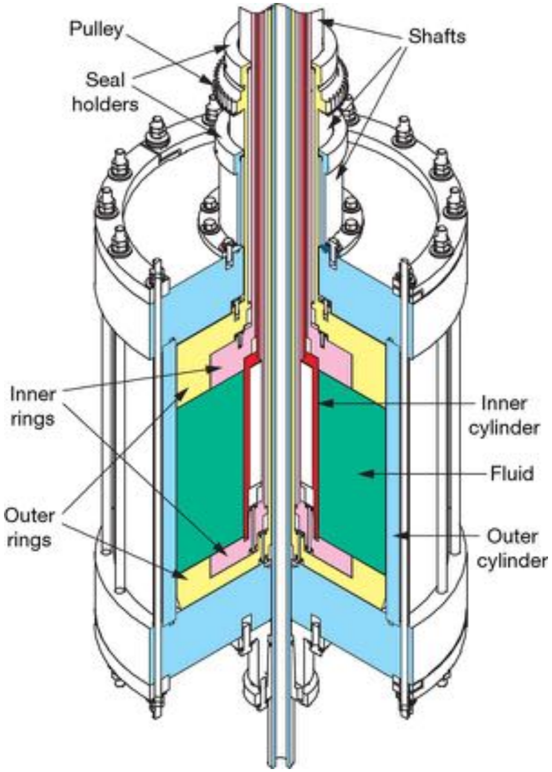


•Coronal mass ejections are being studied in the lab by reproducing their magnetic configuration in the MRX machine.



Experimental study of anomalous momentum transport in accretion discs

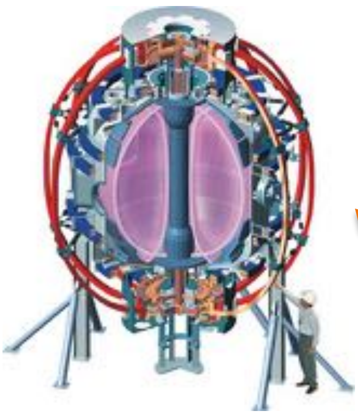




- Angular momentum measurements in accretion discs don't conform to current astrophysical models.
- The Magneto-rotational instability experiment (MRI) is testing the hypothesis of anomalous (turbulent) transfer of angular momentum.

At PPPL, we try to understand many aspects of plasma

Fusion Research



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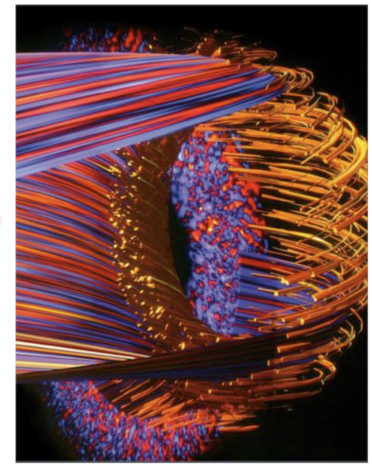

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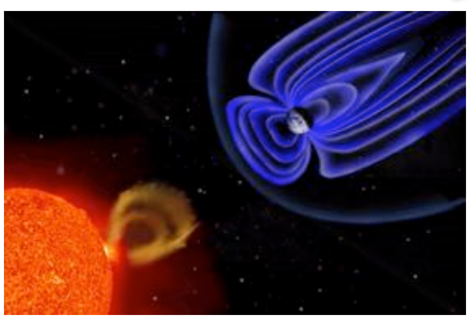

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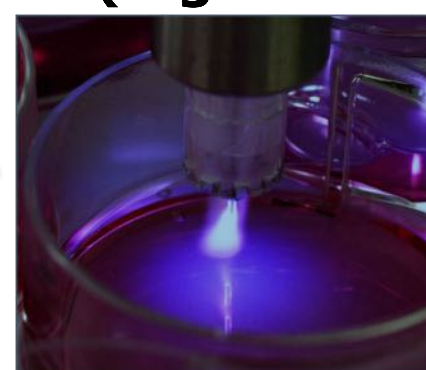
Plasma in other fields (e.g. medicine)



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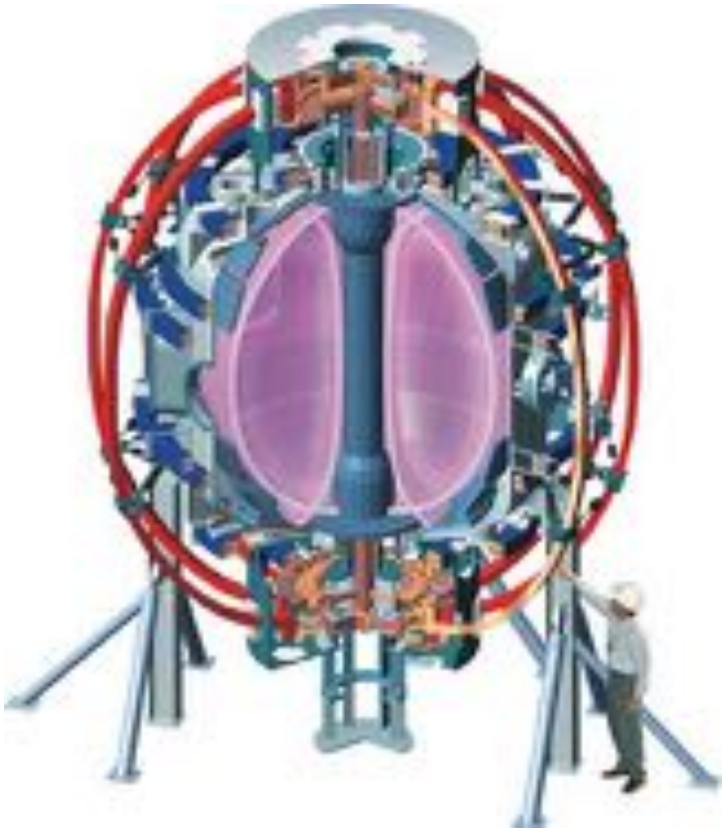
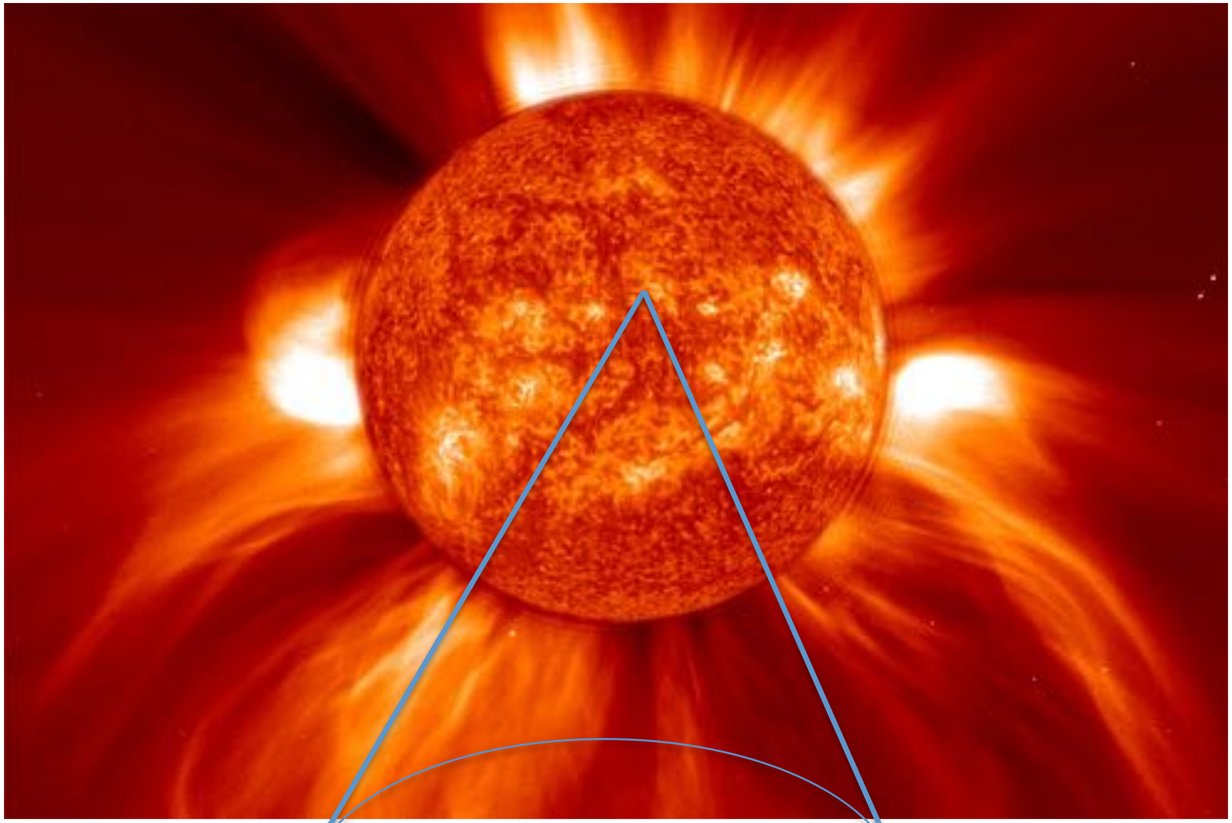
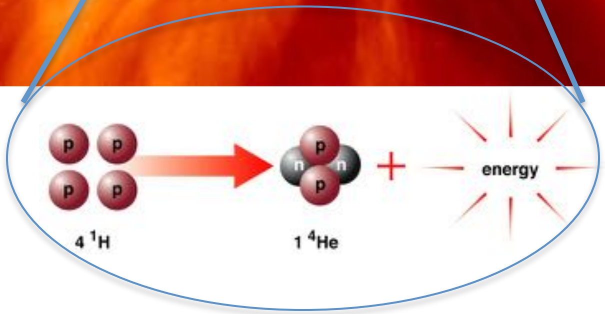


The sun’s energy comes from FUSION



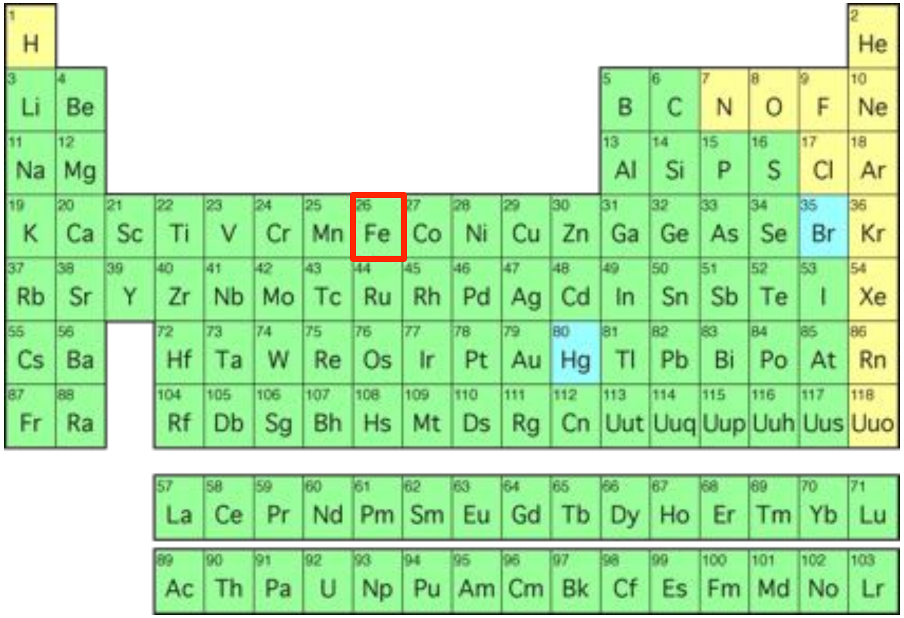
When small hot atoms (usually hydrogen) combine….

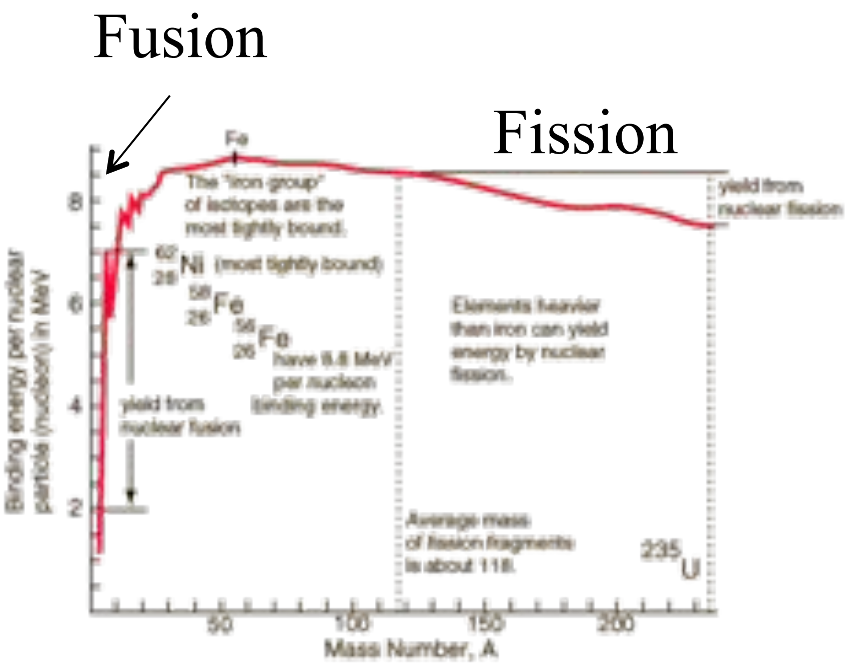


There is a lot of ENERGY produced!

This is FUSION

Fusion energy is the other side of the nuclear energy coin





We can get a LOT of power from the nuclei

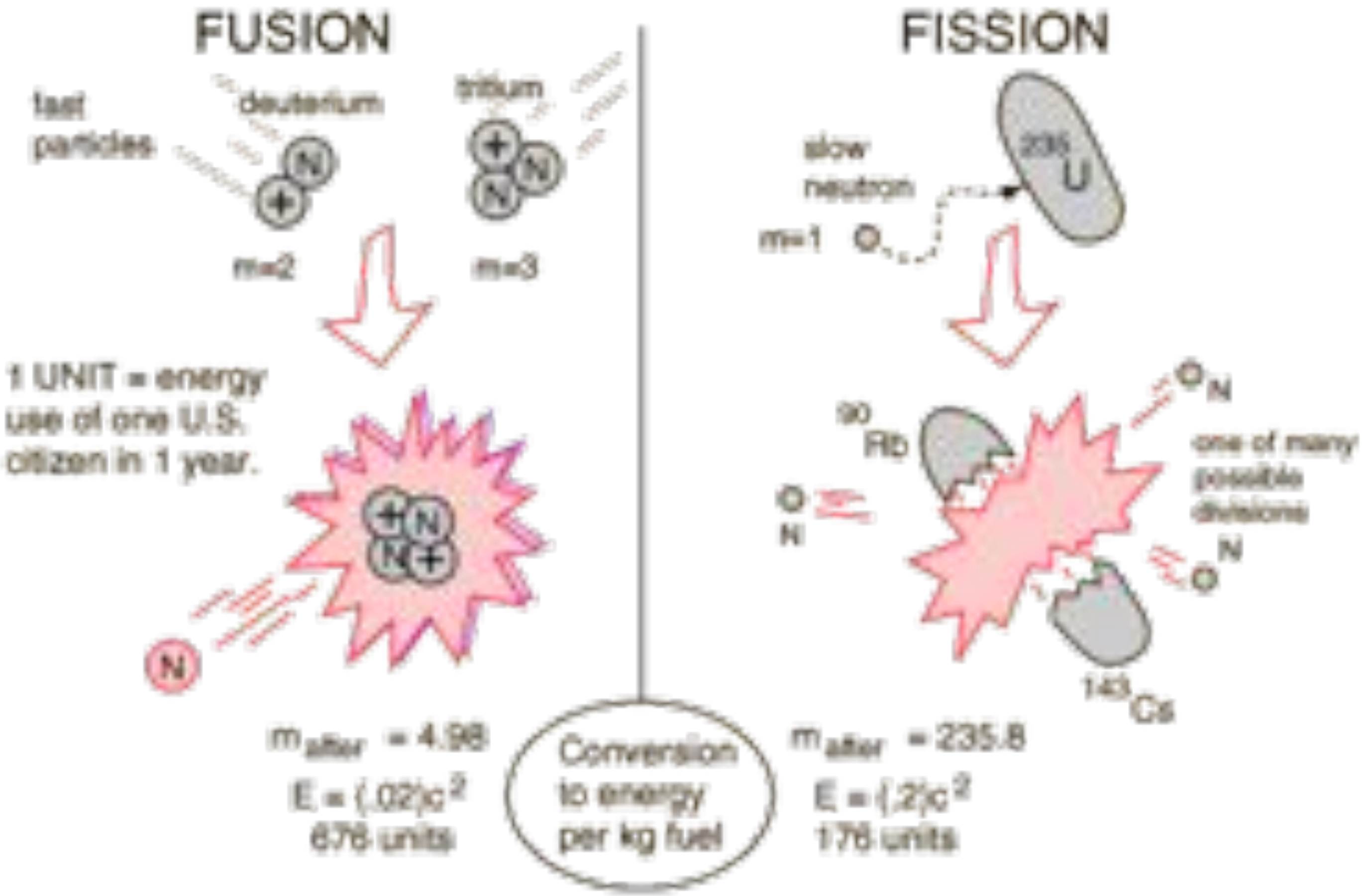
Protons and neutrons ("nucleons") are bound together in the nucleus of an atom by the strong nuclear force.
The mass can be converted to energy using….

$$E=mc^2$$

This is a LOT, lets say I, Arturo, turn into energy:

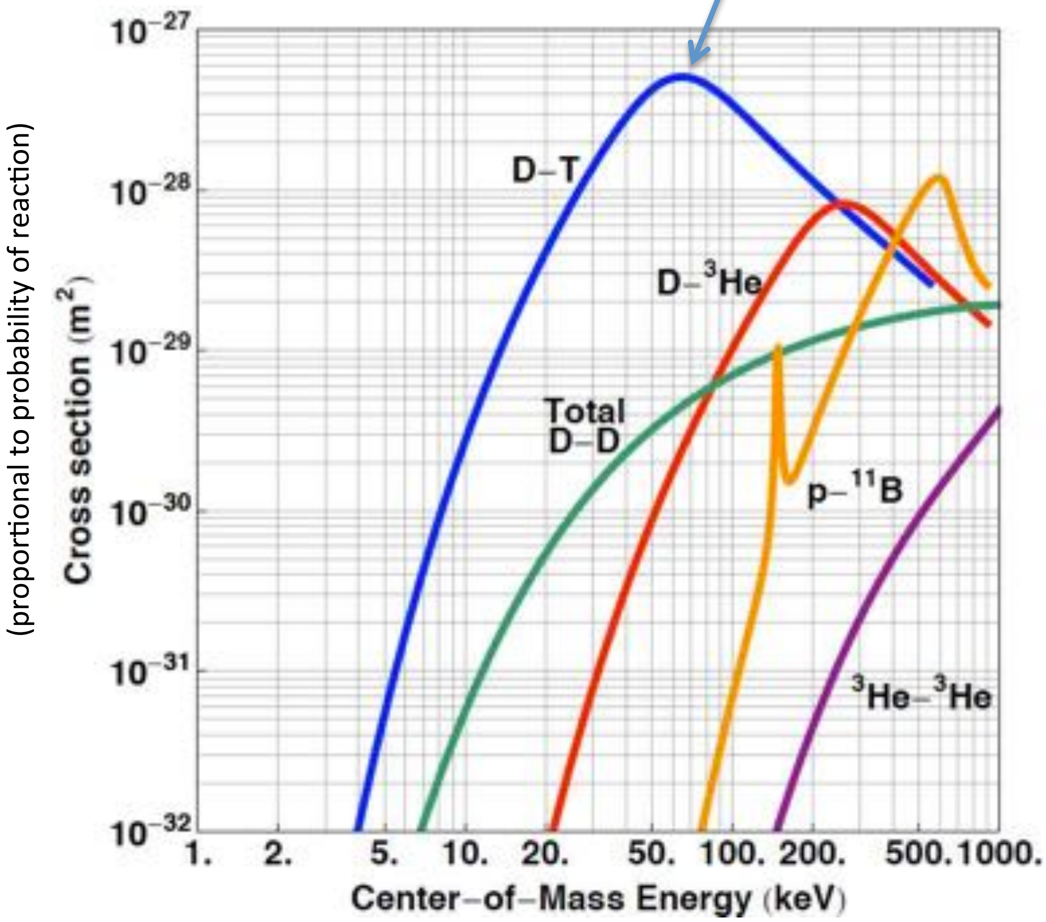
$E_{Arturo}=(90kg)(3x10^8 m/s)^2=8.1x10^{18} J \sim$ Energy consumed by the US in 1 day

For both fusion and fission, the energy comes from the mass



To overcome the repulsion, the plasma must reach extreme temperatures

Peak at 70keV~700Mill Kelvin!



The optimum temperature for Fusion devices is ~15keV ~150 Million Kelvin!

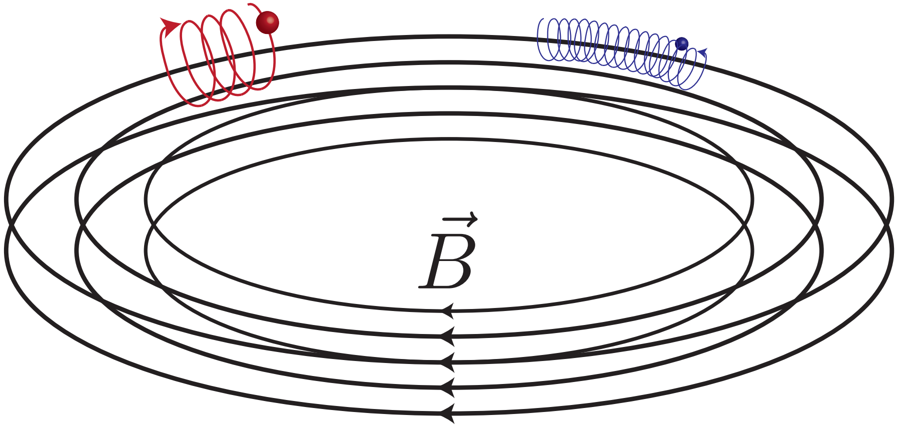
The center of the sun is ~15 Million Kelvin!

How can we contain such hot plasma on earth?

We use magnetic field to contain the plasma

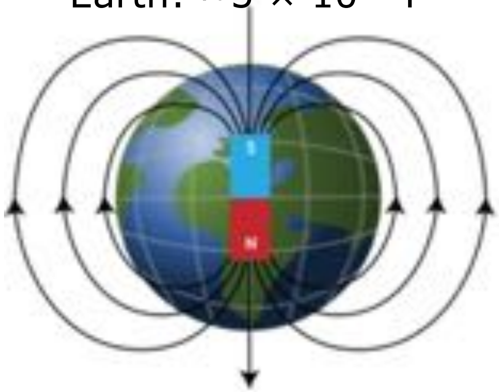
$$\vec{F} = q\left(\cancel{\vec{E}} + \vec{v} \times \vec{B}\right)$$

Lorentz Force will keep charged particles gyrating around the magnetic fields, so making a circular magnetic configuration confines the plasma



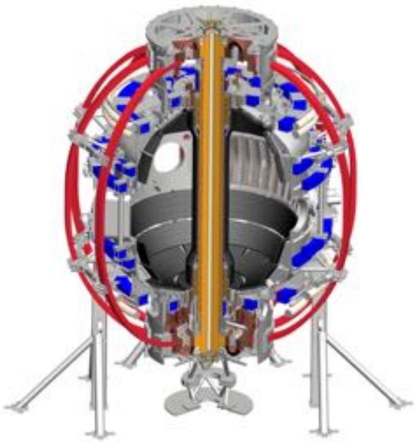
Magnet technology is crucial for our research

Earth: ~5 × 10^{-5} T



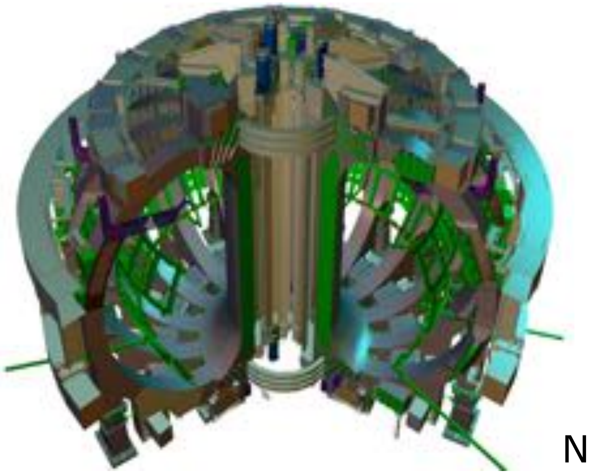
Refrigerator magnets
~1-5 × 10^{-3} T

PPPL's NSTX-U: 1 T

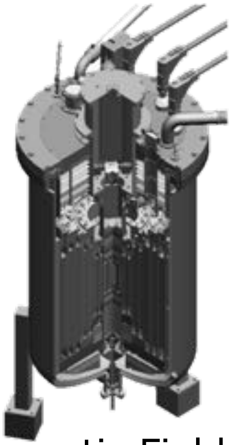


MRI: 0.5-3 T

ITER: 5.3 T

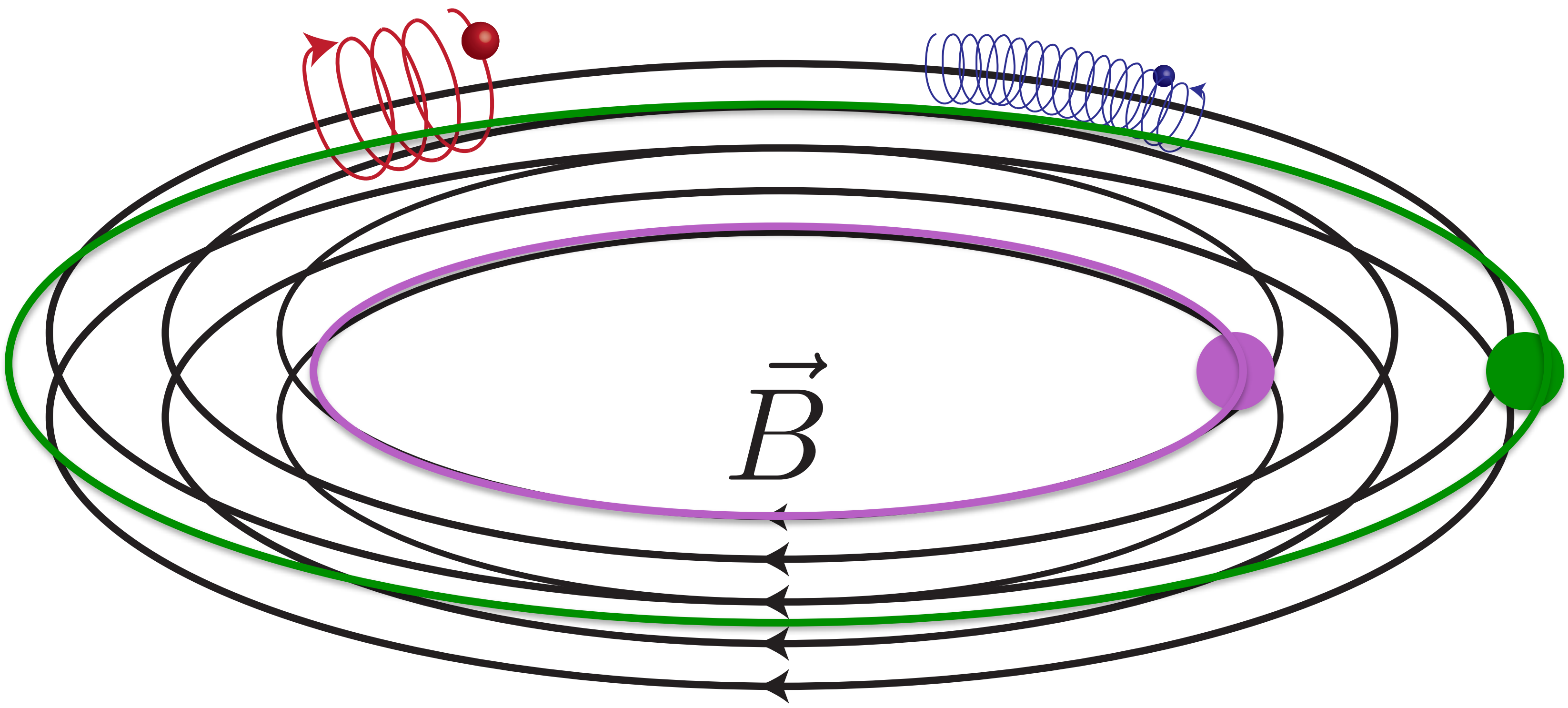


World Record: 100T
Non-destructive for a few milliseconds



National Magnetic Field Laboratory

Circular fields are not enough though



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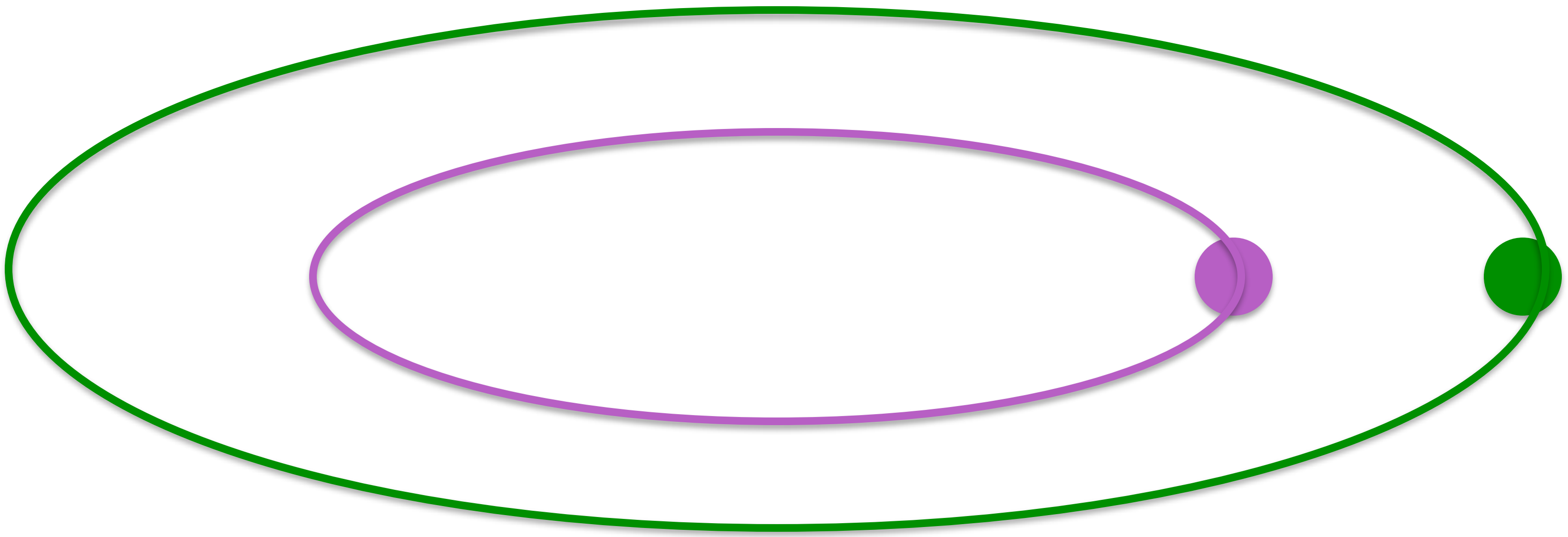

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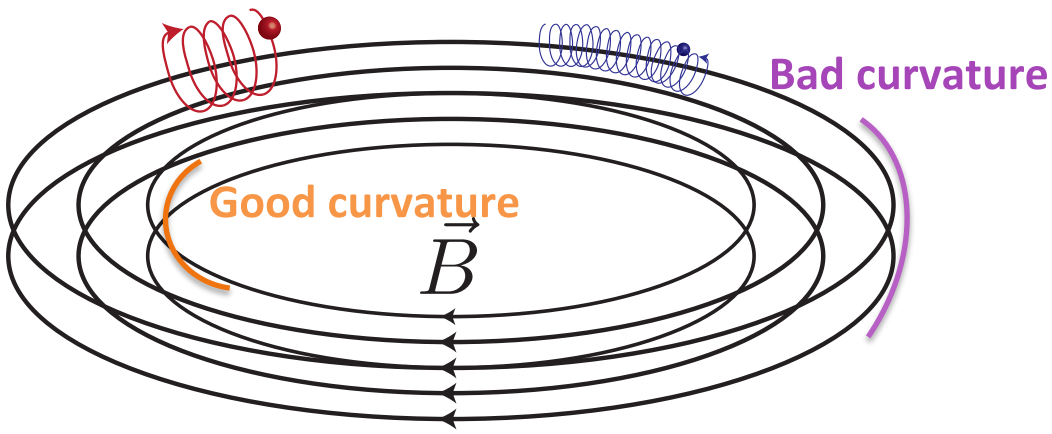

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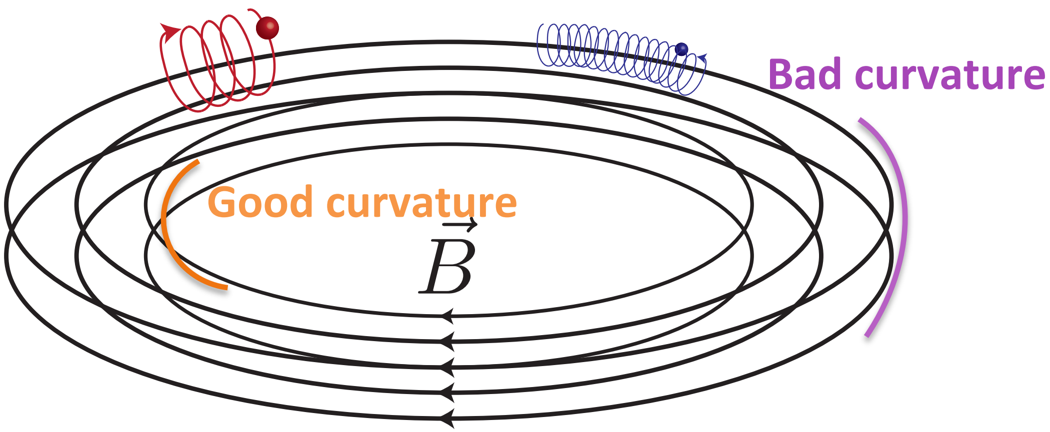

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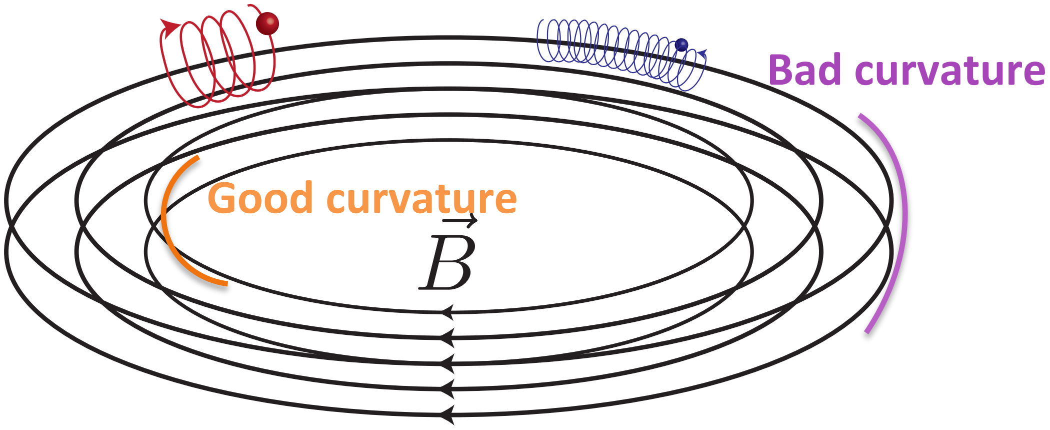

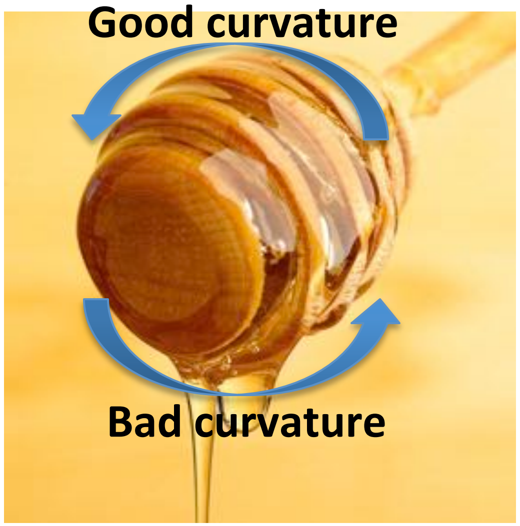

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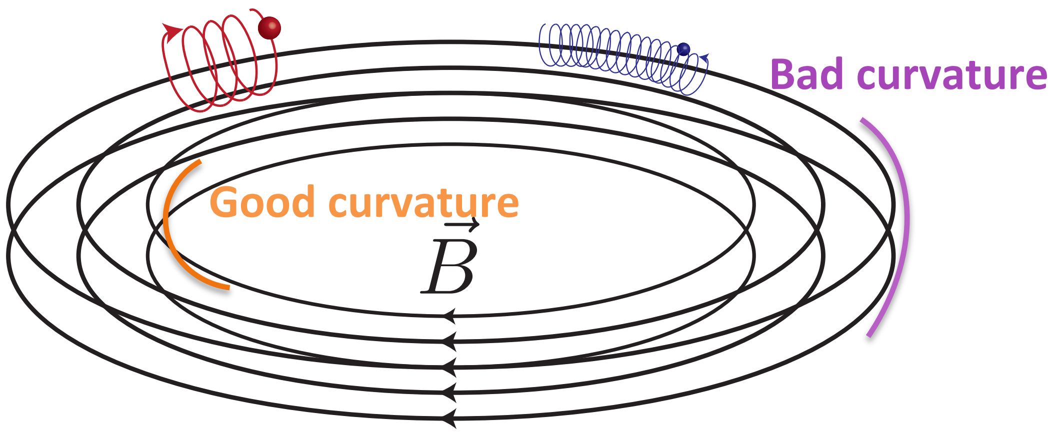

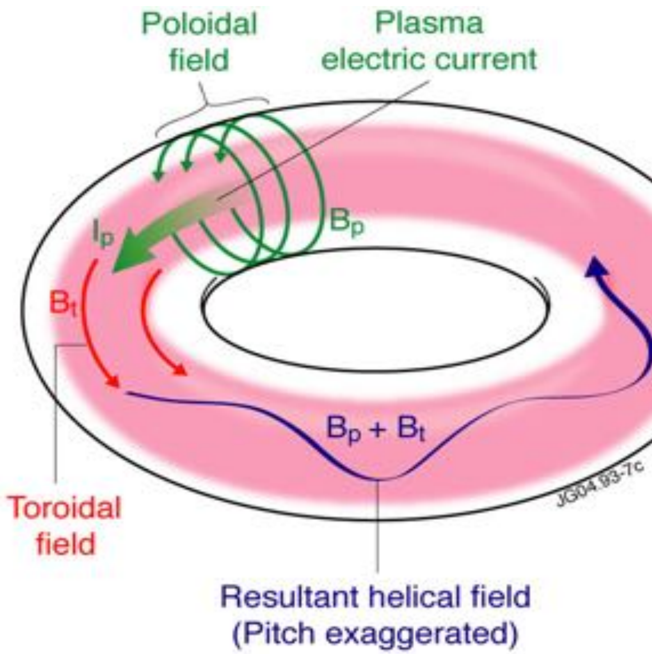

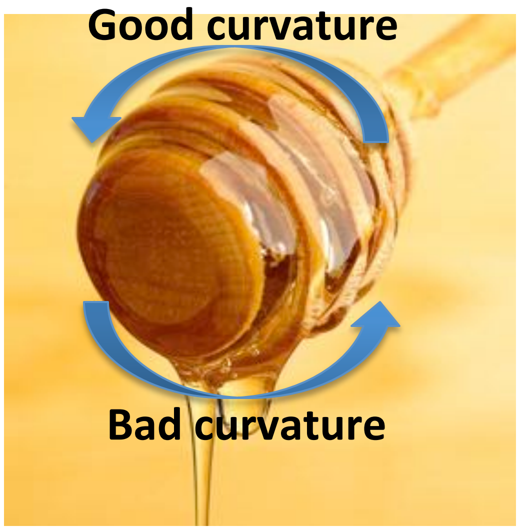

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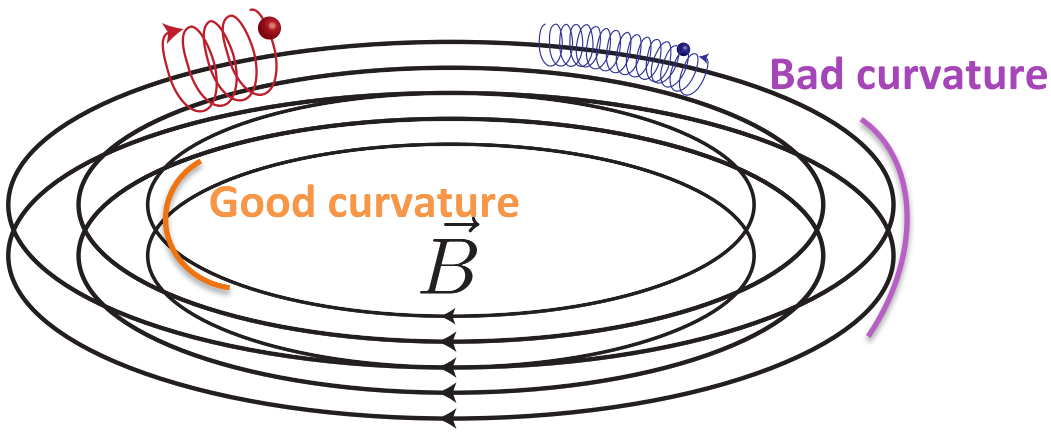
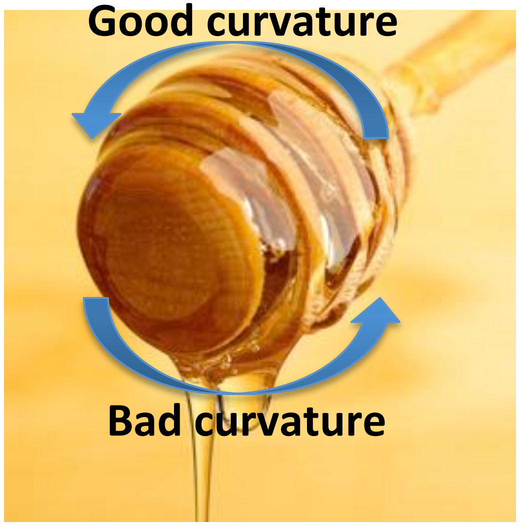
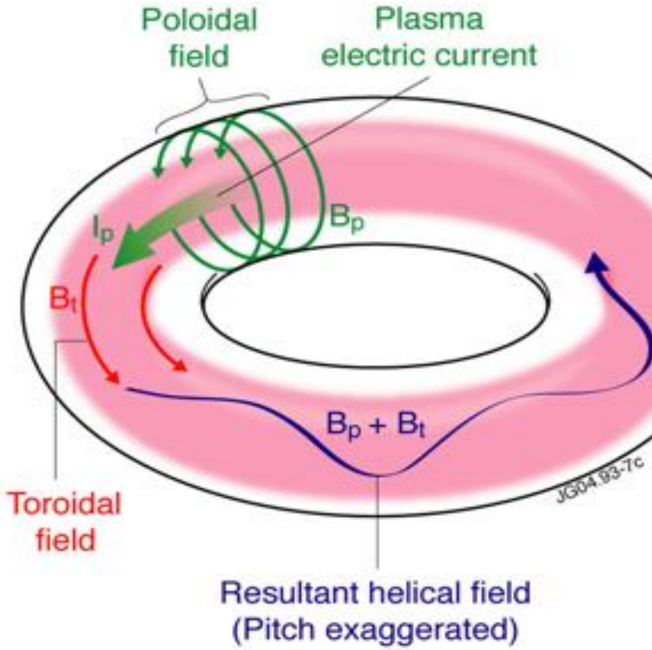
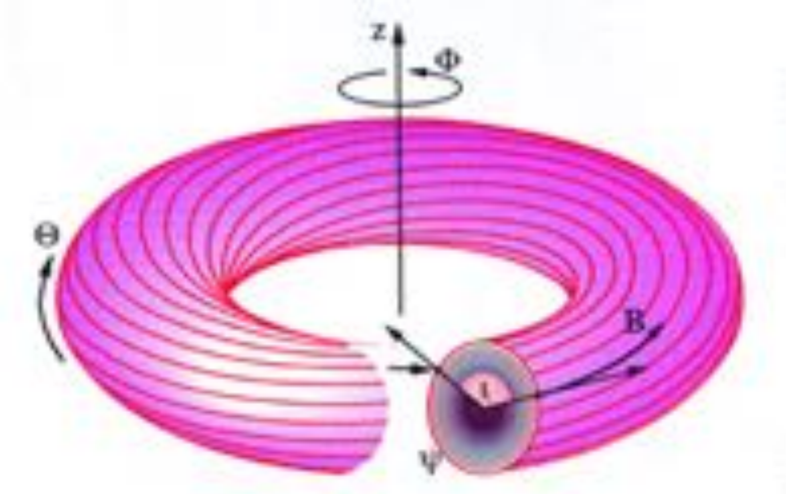


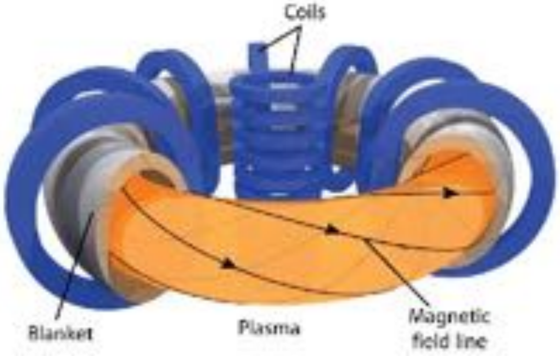




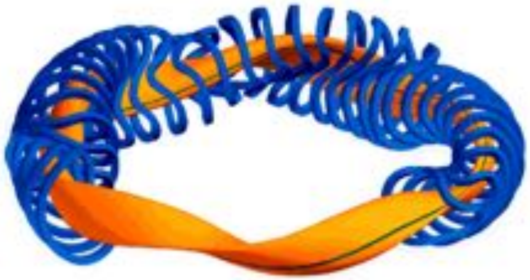


The two main configurations of magnetic confinement devices

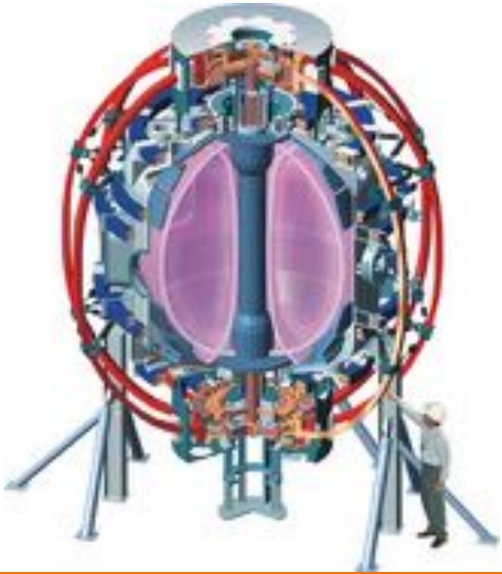
Tokamak



Stellarator



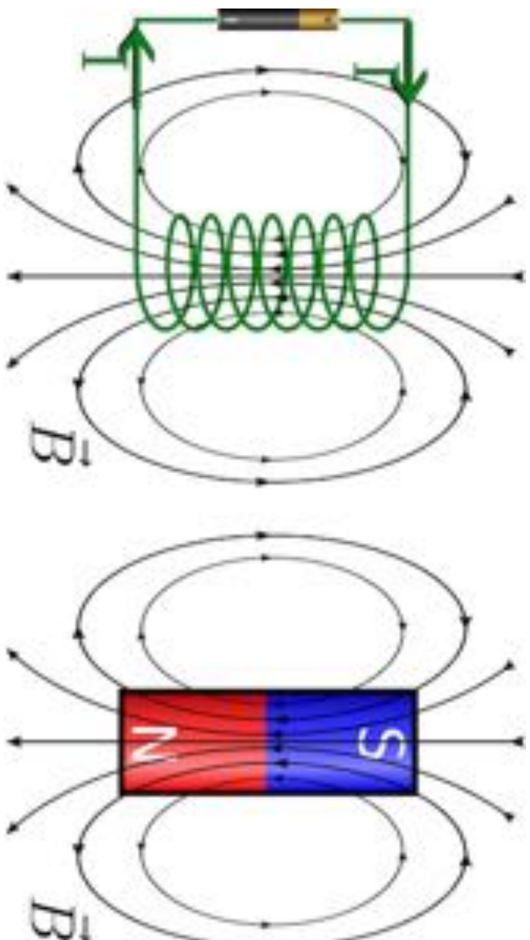
NSTXU @ PPPL

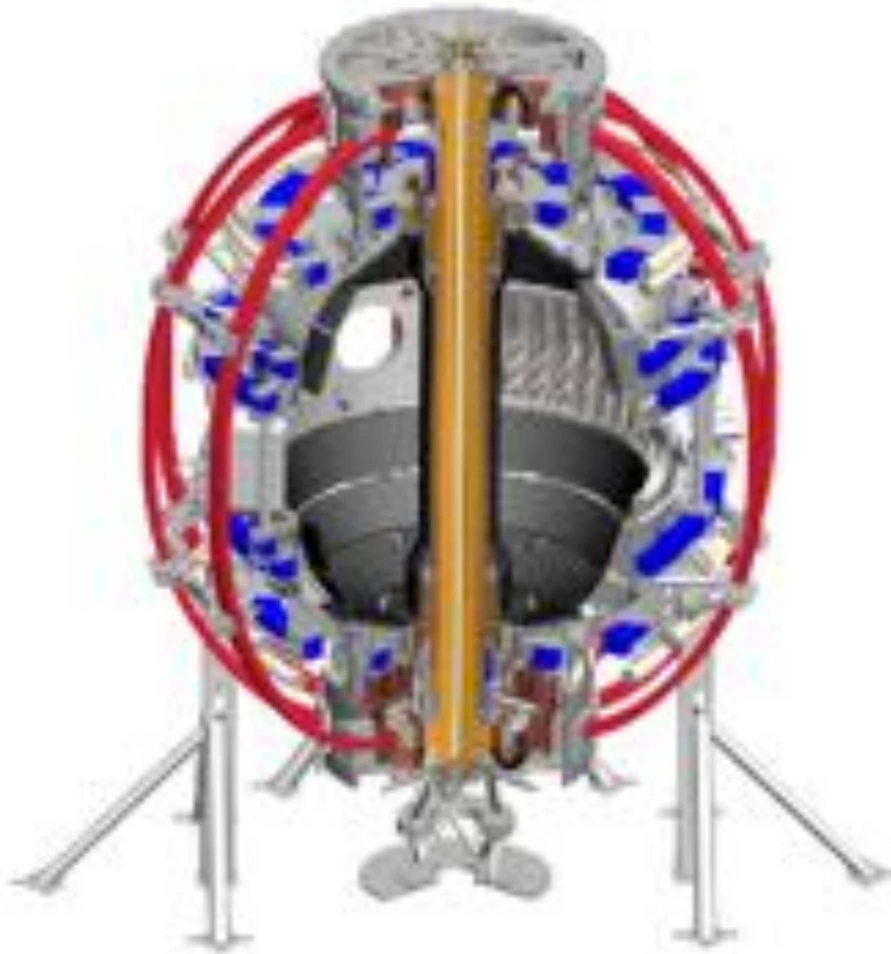


W7X @ Max-Planck / Germany

In a Tokamak the Toroidal Field is Easy

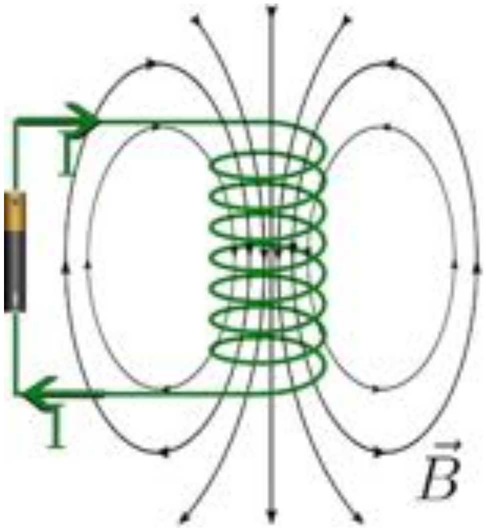
Electric currents create magnetic fields (Electromagnets)

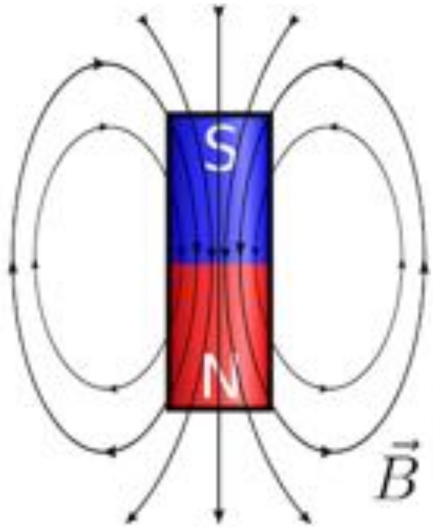


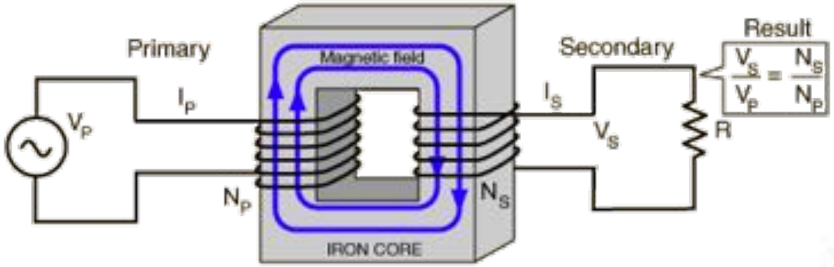


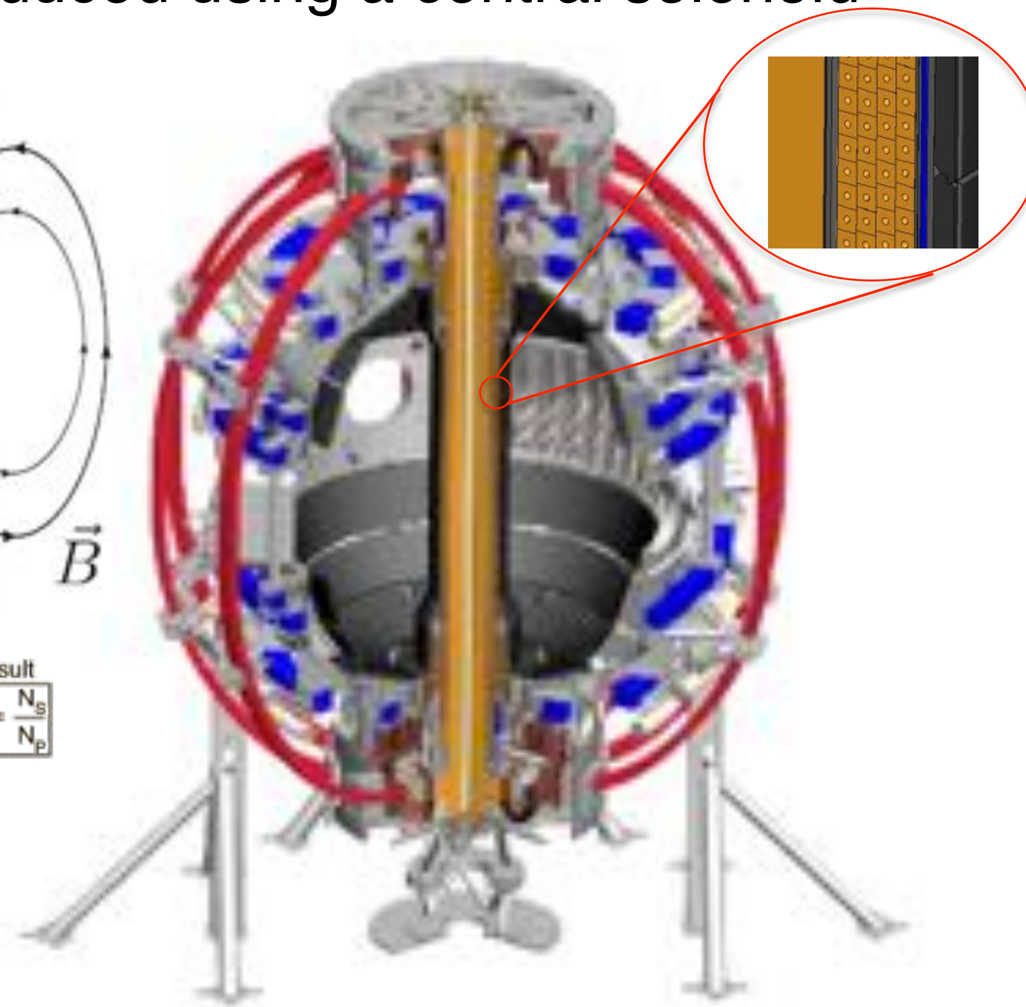
The Poloidal field is a bit harder

The poloidal field is induced using a central solenoid









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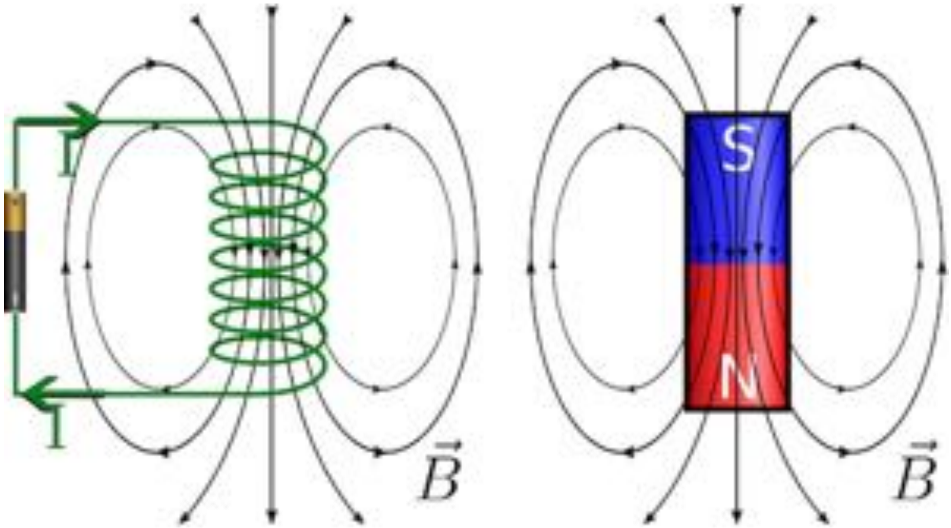

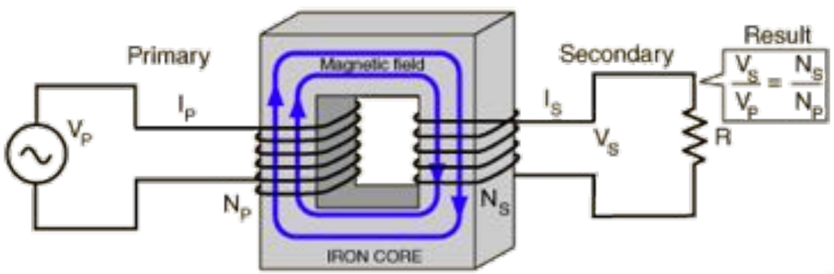

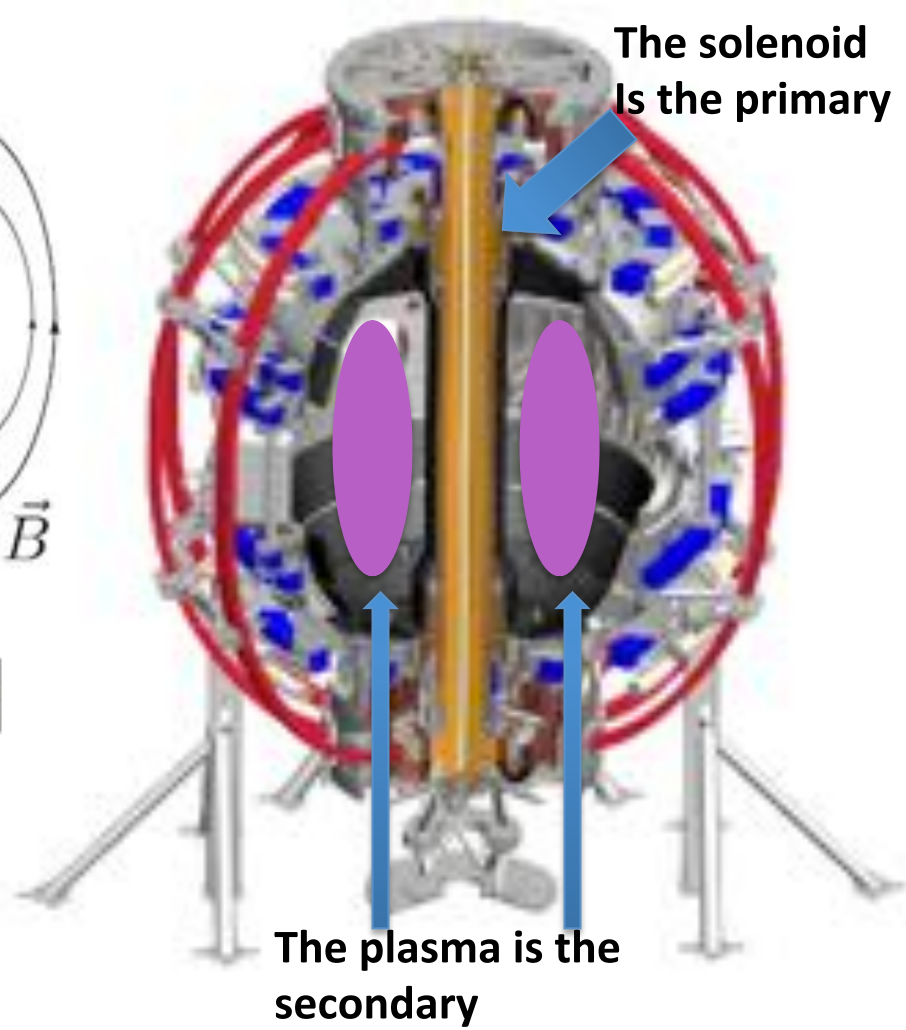

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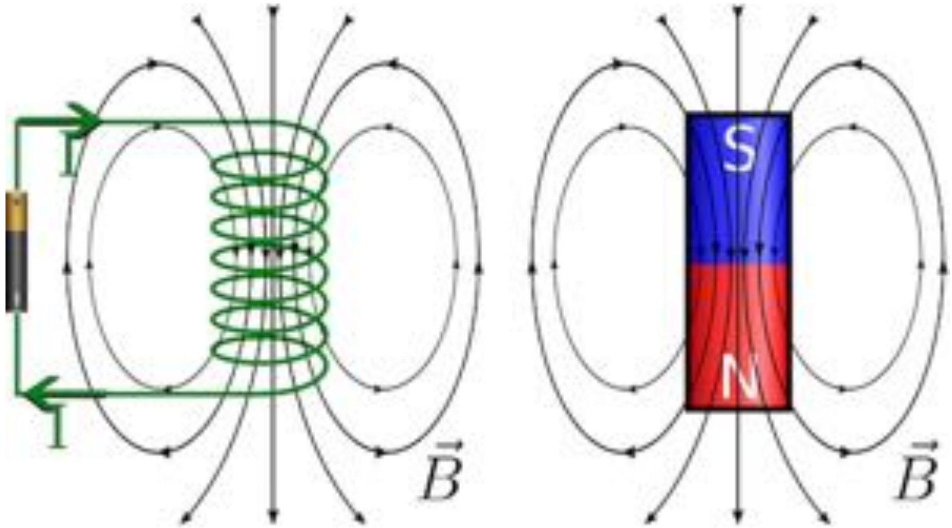
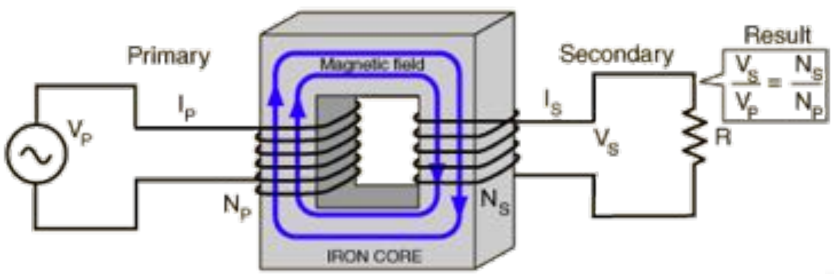
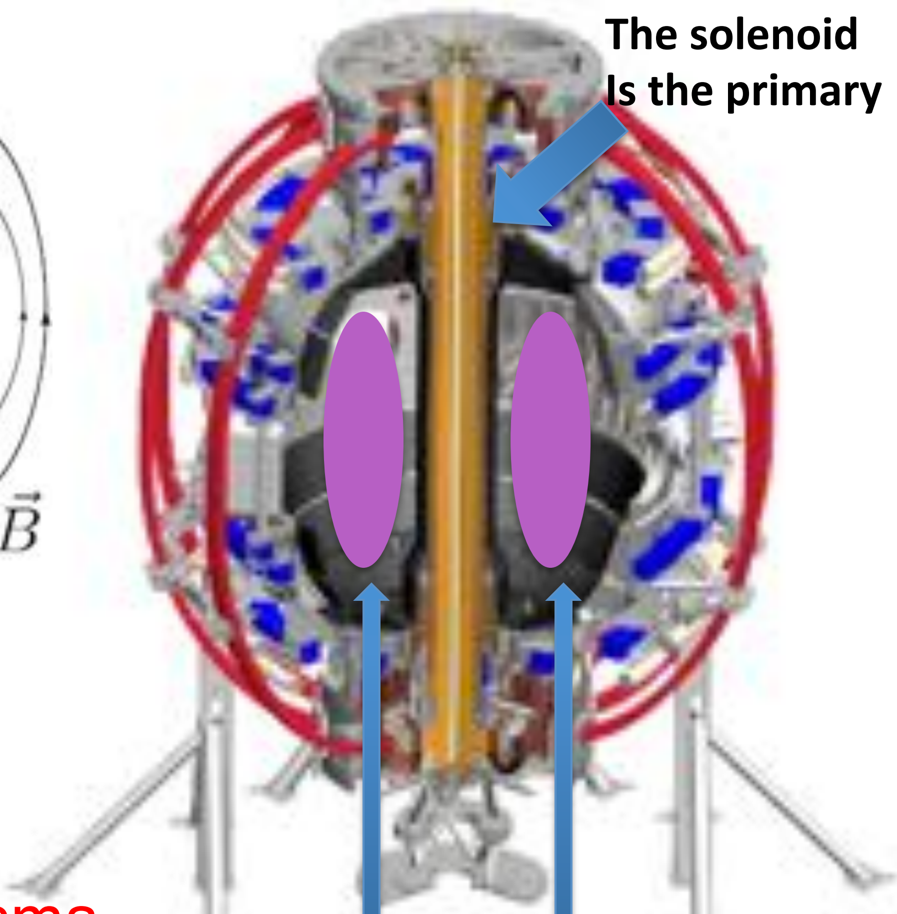






The solenoid
Is the primary

The plasma is the secondary

Added benefit: you heat the plasma with the current

The U in NSTX-U is the Upgrade that just finished

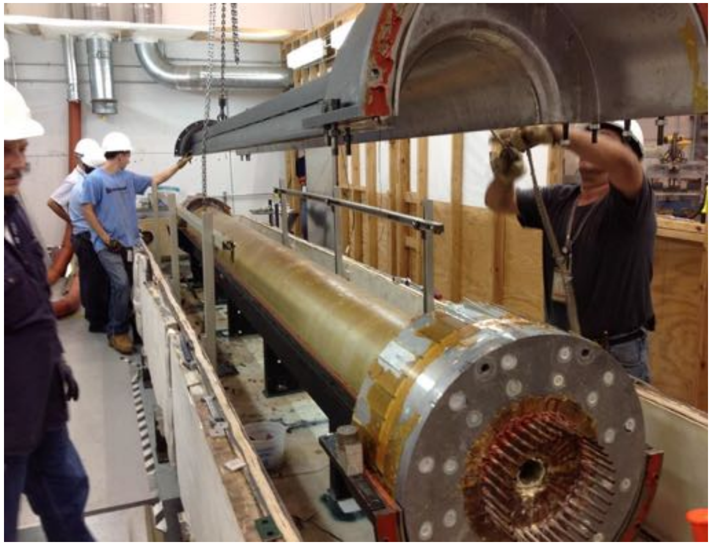
•In 2012, NSTX went down for the upgrade

•The main change was the improvement of the center stack

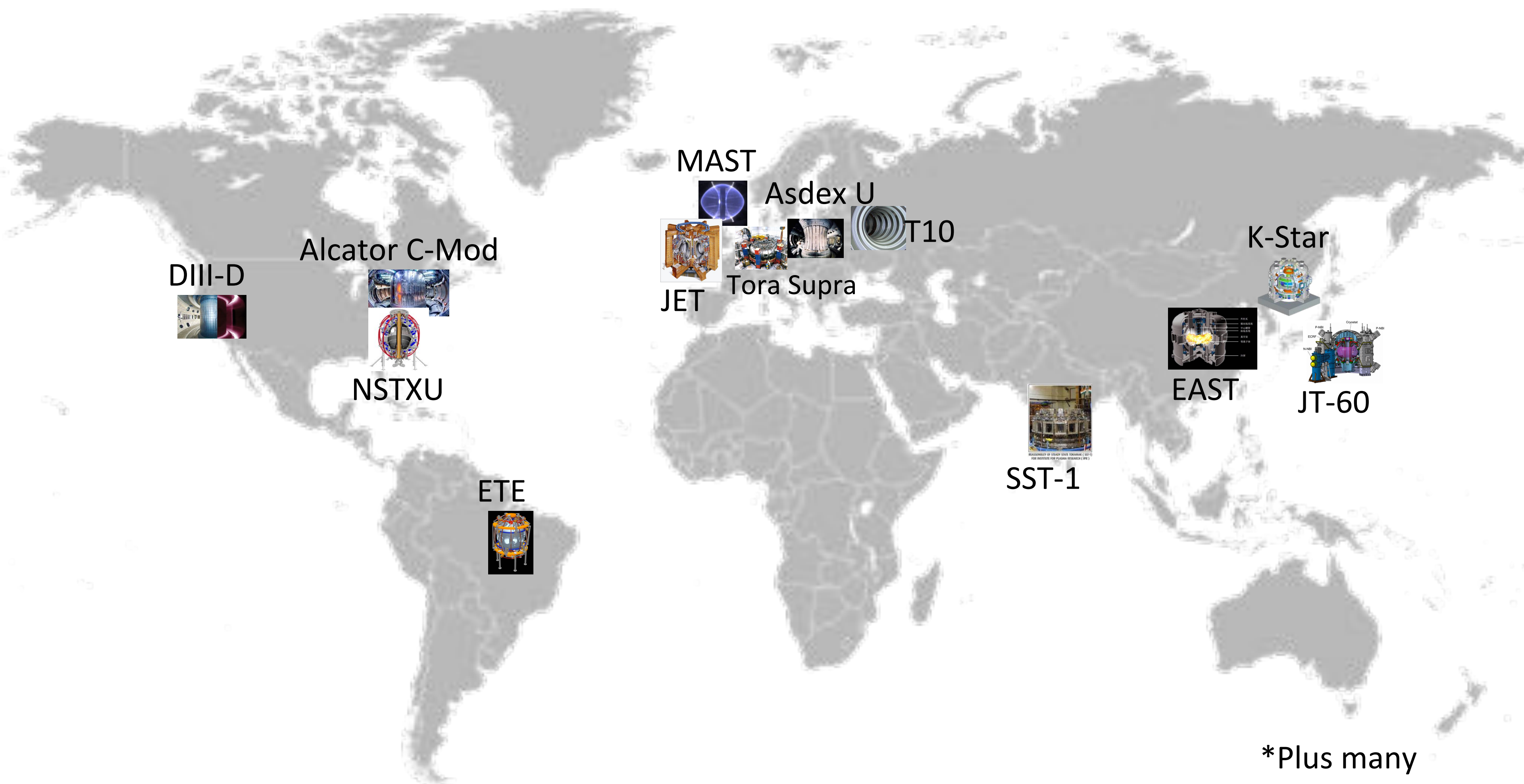
•With the new changes, NSTXU will have:
- •x2 toroidal field
- •x2 plasma current
- •x5 Pulse length

•Upgraded operation has begun

•Pulse length is now constantly >2s and increasing

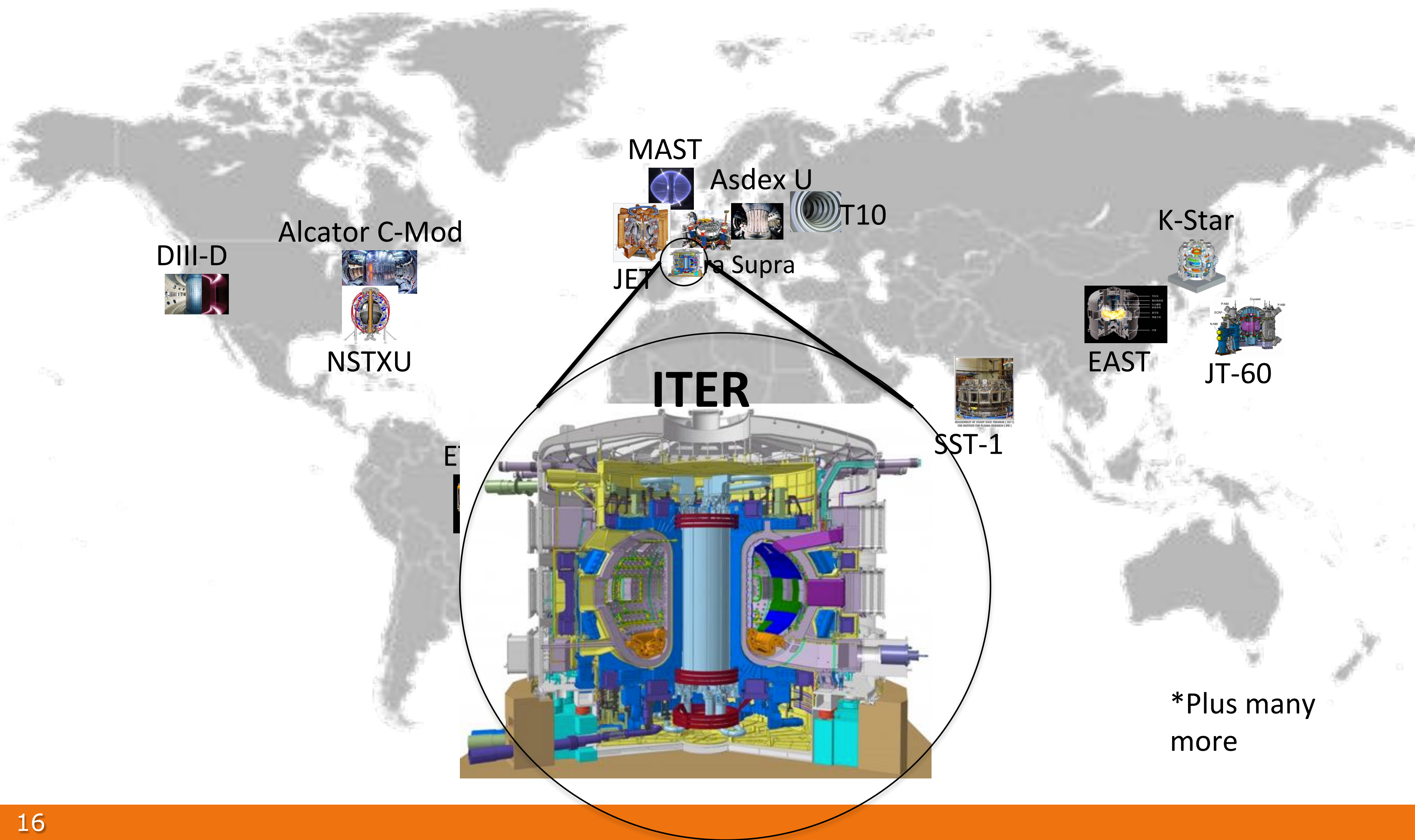


There are many tokamaks around the world studying different plasma parameters and shapes



*Plus many more

There are many tokamaks around the world studying different plasma parameters and shapes



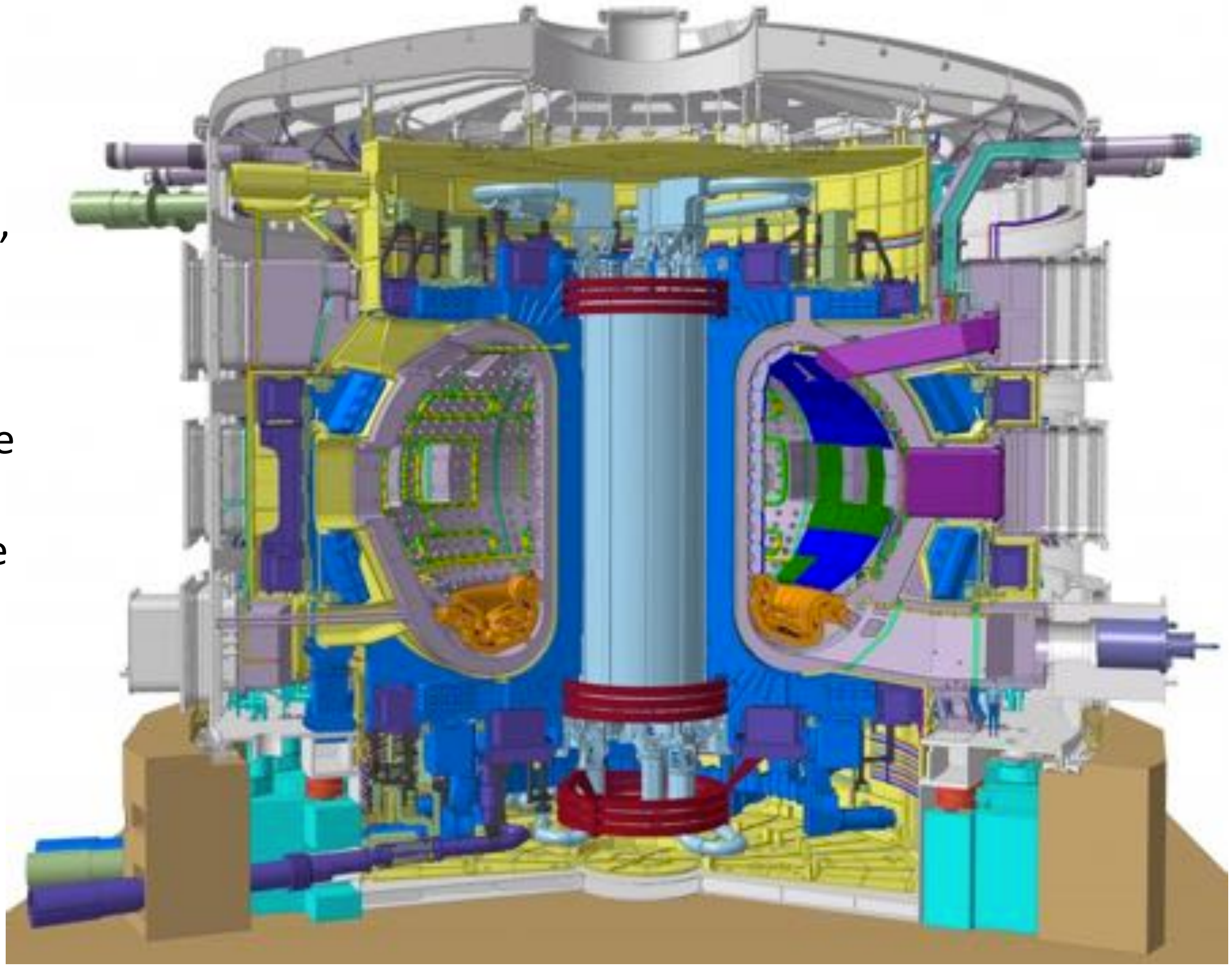
*Plus many more

ITER will be the first time we have more energy OUT than IN

•ITER is a collaboration between USA, EU, China, Japan, Korea, India and Russia

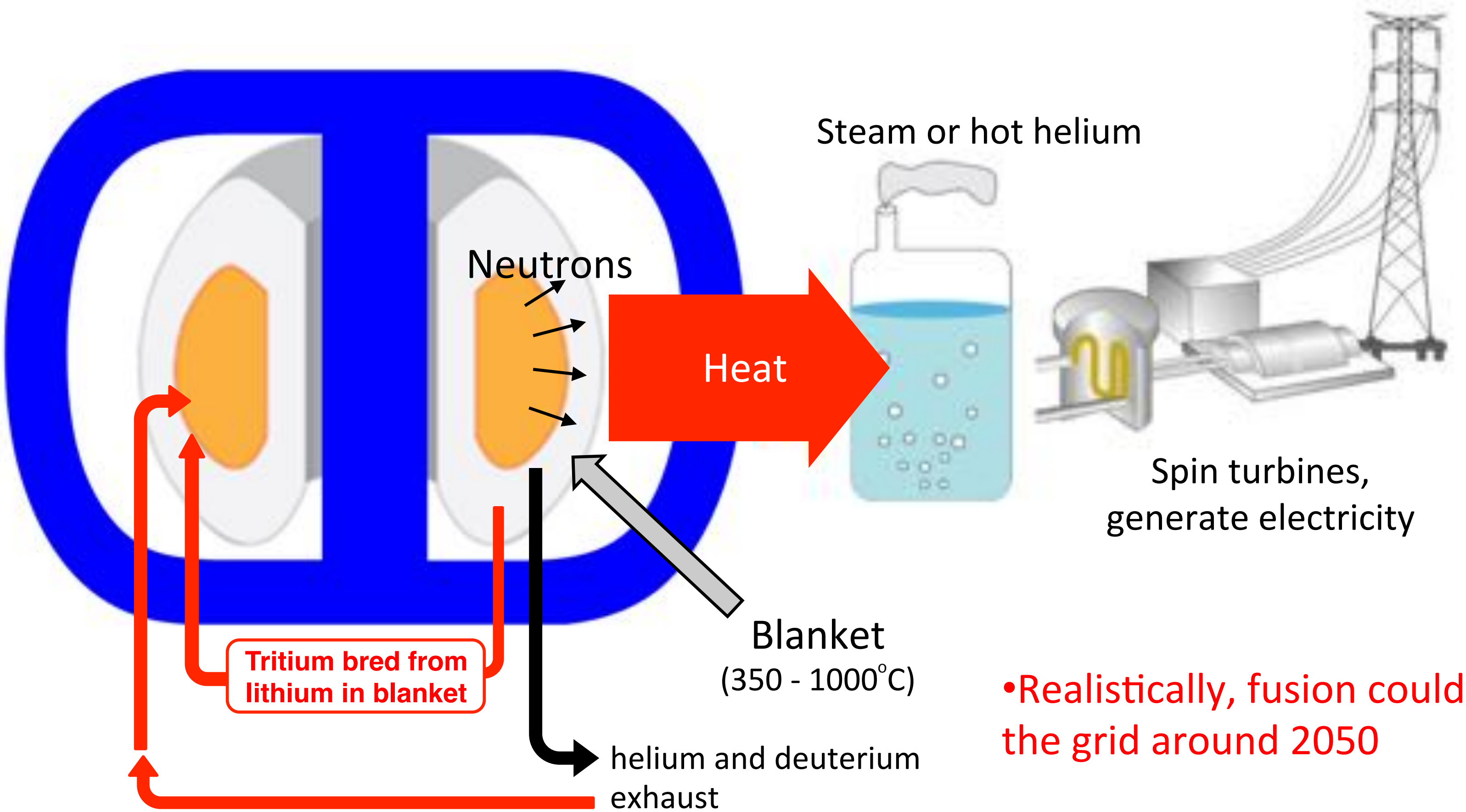
•It's expected to produce 500MW of power using 50MW to run…this is the 1st time in history where **$P_{out}>P_{in}$**

•First plasmas expected by 2020



There's one more step to produce electricity

- ITER will still not produce electricity…a working reactor will need a Lithium blanket that heats up, boils water and turn turbines.
- After ITER, a demonstration reactor would be built.



- Realistically, fusion could be in the grid around 2050

The challenges are many, but the rewards are immense

•Fusion energy only requires Deuterium (from sea water) and Lithium to run. There are reserves for hundreds of thousands of years.

•There's no chance of a meltdown because fusion can't have chain reaction events.

•The only byproduct is Helium (no greenhouse gases).

•There's no long term radioactive waste. Tritium is radioactive but it's half live is ~16 years.

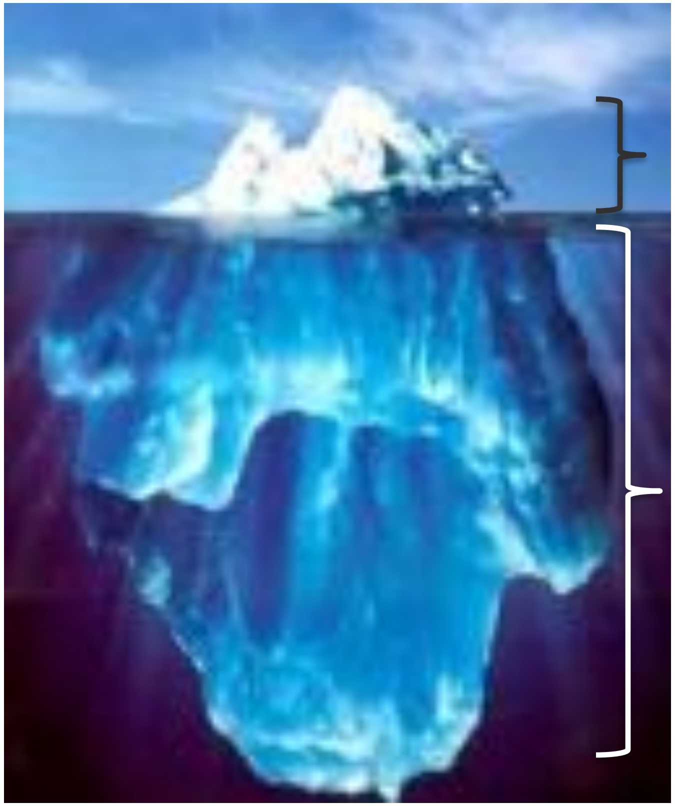
•It would run continuously.

Research opportunities

- PPPL has a wide range of research activities, many opportunities for novel, impactful projects

- New projects coming
  - NSTX-U
  - FLARE
  - W7X collaboration
  - ITER
  - Theory core codes
  - Liquid walls
  - Plasma-nano

  …



What I just showed

Active research topics at PPPL

SULI Internship

- **Summer Undergraduate Laboratory Internship (SULI)**
  - Paid summer internship program
  - 1 week course intro to plasma/fusion
  - 8 week project based internship
  - Also available for fall/spring semester long internship
  - Summer 2017 applications open up in October!

Faculty and Lecturer opportunity: ALPhA immersion

ALPhA immersion is an NSF, AAPT funded 3 day workshop for college faculty and lecturers to develop “beyond first year” labs. We run 3 workshops to develop low cost plasma physics experiments using a DC discharge apparatus (total cost <$5k).

July 12–14, 2016, at the Princeton Plasma Physics Laboratory
Princeton, NJ

- Low Cost Plasma Physics: Electrical Breakdown and the Paschen Curve
- Low Cost Plasma Physics: Spectroscopy
- Low Cost Plasma Physics: Plasma Probes and the Electron Temperature

Arturo Dominguez, Andrew Zwicker, and Jeremiah Williams show how to teach experimental plasma physics on a very low budget.

APS Conference for Undergraduate Women in Physics

- **CUWiP at Princeton University**
  - APS sponsors 10 CUWiPs in the US and Canada
  - January 13-15, 2017
  - 200 participants expected at Princeton
  - Workshops, speakers, panels, tours, student poster session, career expo, networking opportunities

  - **APPLY BY OCTOBER 14!**

APS Conference for Undergraduate Women in Physics

- **CUWiP Goals**
  - Increase diversity and inclusiveness of physics community
  - Exposure to exciting subfields and careers in physics
  - Practical tools to succeed in STEM
  - Network with peers and leaders in the field
  - Combat the negative effects of bias and create a sense of belonging

APPLICATION CLOSES OCT. 14!!

Find Princeton CUWiP on:

OR at cuwip.princeton.edu

APS Conference for Undergraduate Women in Physics

- **CUWiP Details**
  - Lodging and meals are covered by CUWiP host site
  - Participants must seek travel and registration fee assistance from their department
  - Some funds are available for those whose department cannot provide support
  - Preference to women, physics majors, and first-time attendees, but all are welcome
  - Contact Shannon Swilley Greco at cuwip@princeton.edu

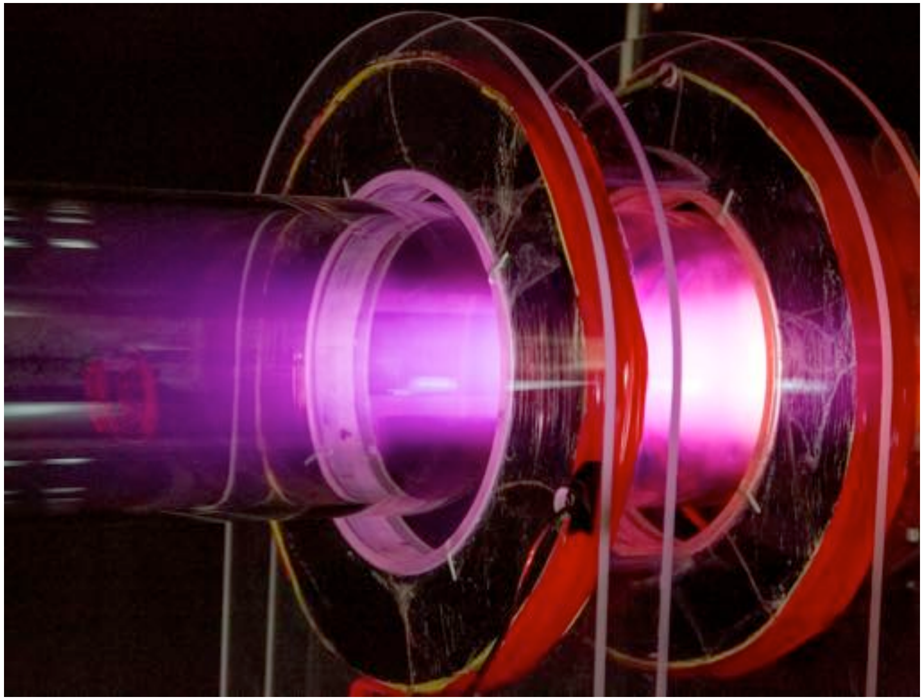
APPLICATION CLOSES OCT. 14!!

Find Princeton CUWiP on:

OR at cuwip.princeton.edu

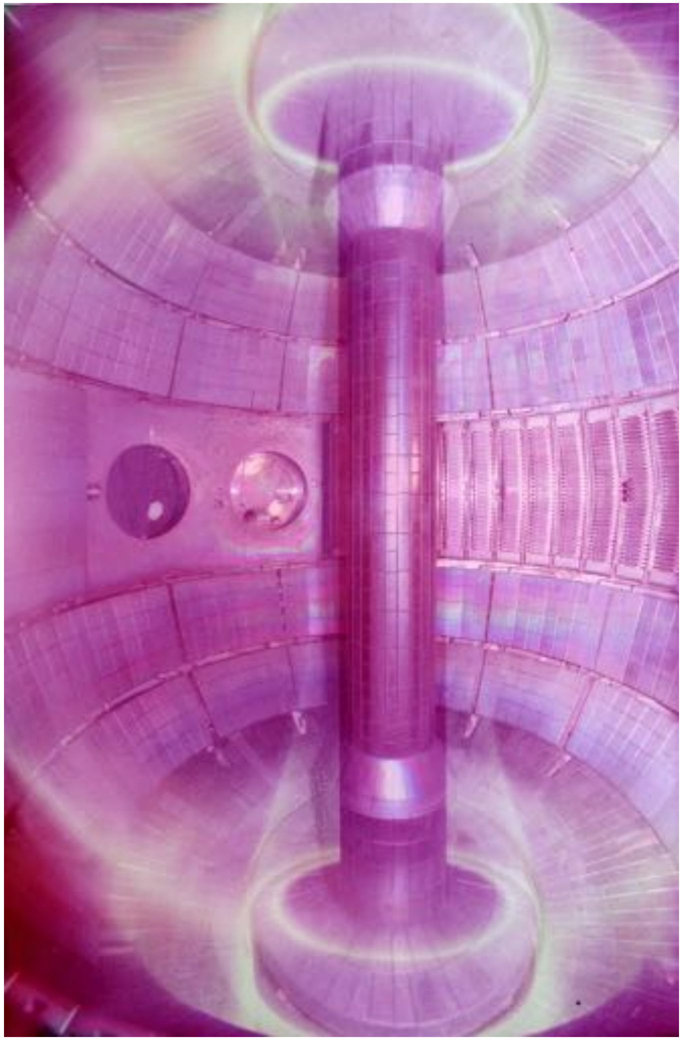
CUWiP+ Workshops

- **CUWiP+ Workshop in Plasma Physics**
  - Extension of CUWiP for those interested in plasma physics
  - January 15-17, 2017
  - Held at Princeton Plasma Physics Laboratory, a DOE National Lab
  - Up to 20 participants
  - Hands-on lab experiments and short course
  - Hotel and meals provided



More info on cuwip.princeton.edu

National Spherical Torus eXperiment Upgrade (NSTX-U)



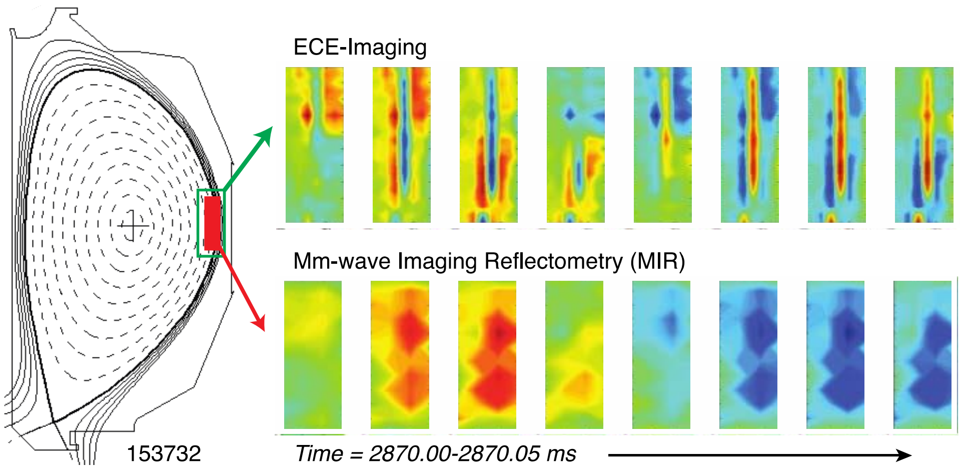
- Our flagship experiment is NSTX-U
- Research focuses on understanding particular "spherical tokamak" geometry
- Studying particle and energy confinement, crucial for reactor regimes
- Developing solutions for plasma-material interfaces
- Implementing diagnostic techniques to measure temperature, density, magnetic fields, etc.

Diagnostic development

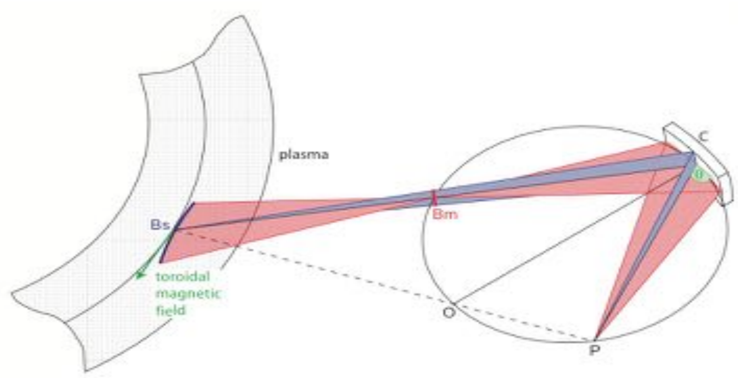
•One of the main challenges of fusion reactors is the implementation of tools to measure plasma parameters.

•At PPPL, many of the projects are centered around individual diagnostics and their development. This is critical for next generation reactors.

Imaging techniques

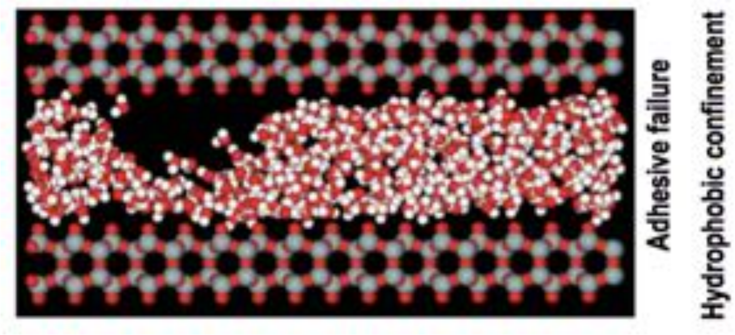


Novel X-ray diagnostic

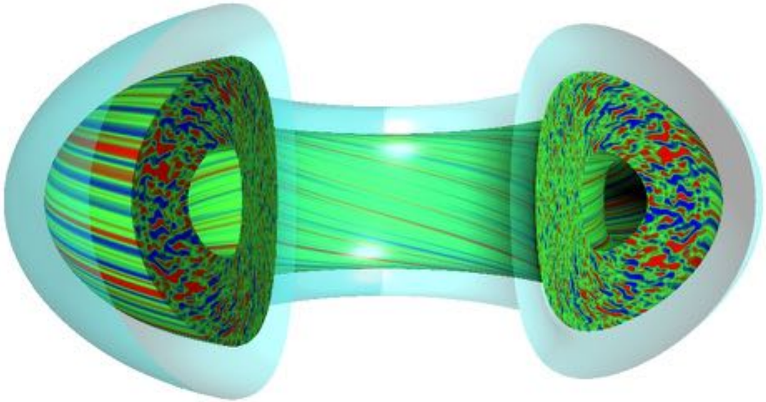


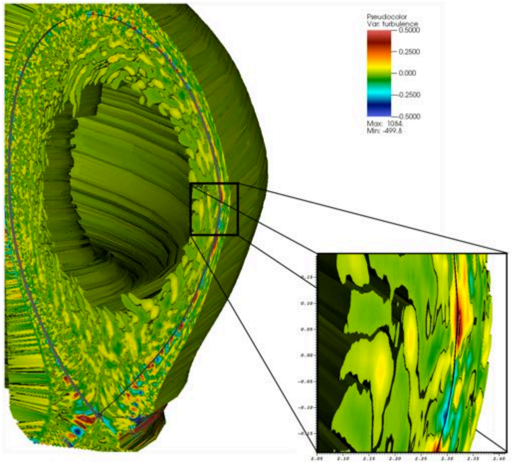
Modeling is essential in all fields of plasma physics

Model of first wall physics

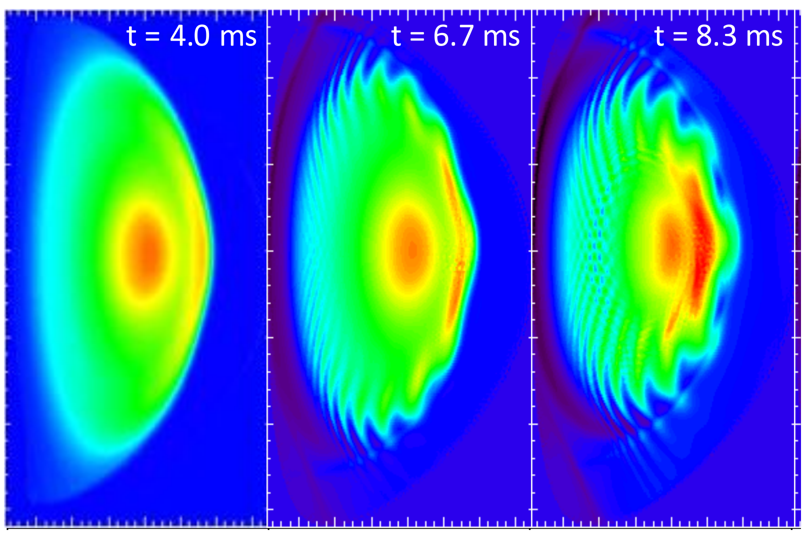


Evolution and destruction of turbulence





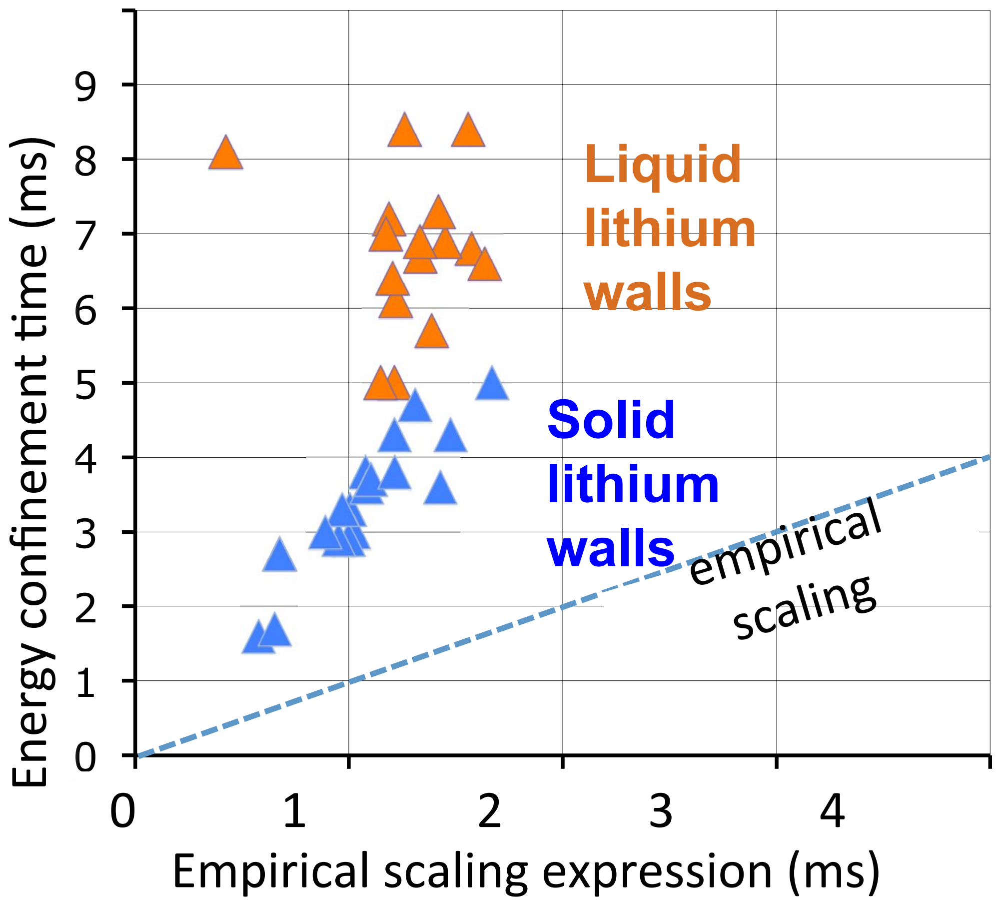
Simulation of a disruption event



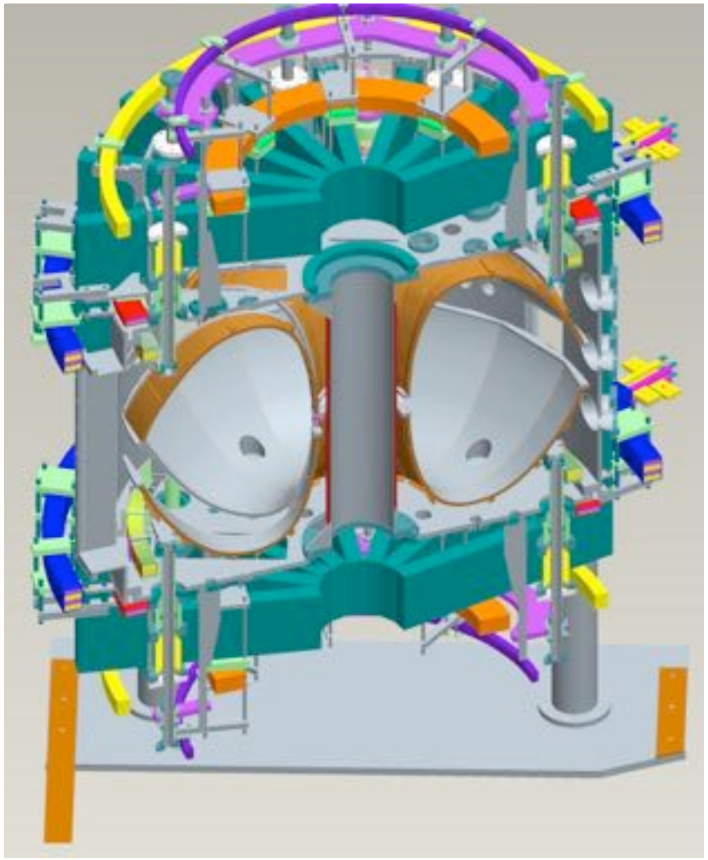
Lithium walls have shown improved confinement

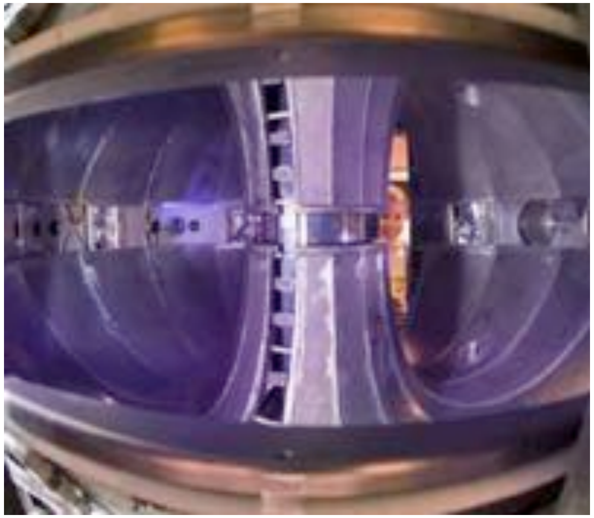
•Liquid lithium walls are actively being studied to try to reduce excess power to the walls and to improve energy confinement.

•Results have been very positive



Lithium Tokamak Experiment (LTX)





•The Lithium Tokamak Experiment (LTX) focuses exclusively on testing the effects of liquid lithium in a high temperature magnetic confinement device