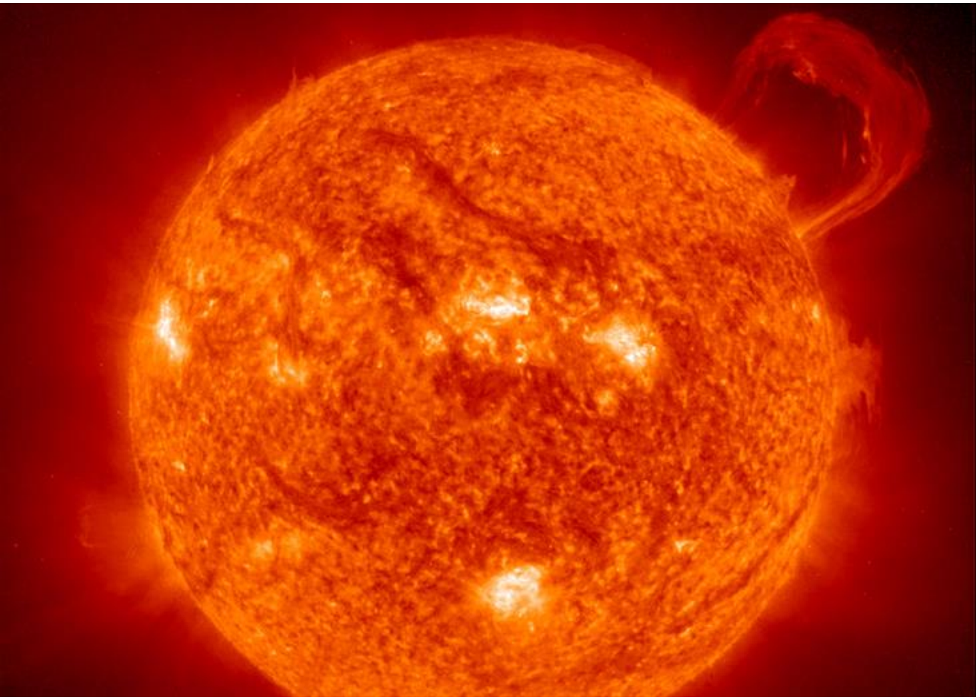
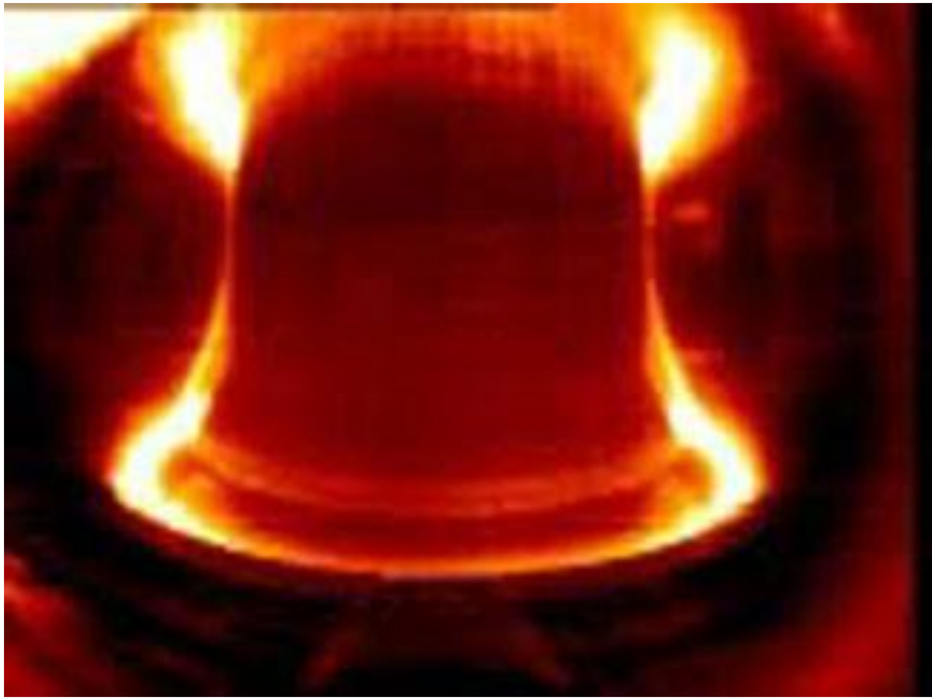
# Containing a star on earth: the promise of fusion energy





**Walter Guttenfelder**

*Princeton Plasma Physics Laboratory (PPPL)*

Portland State University, Physics Dept. seminar
Nov. 5, 2018

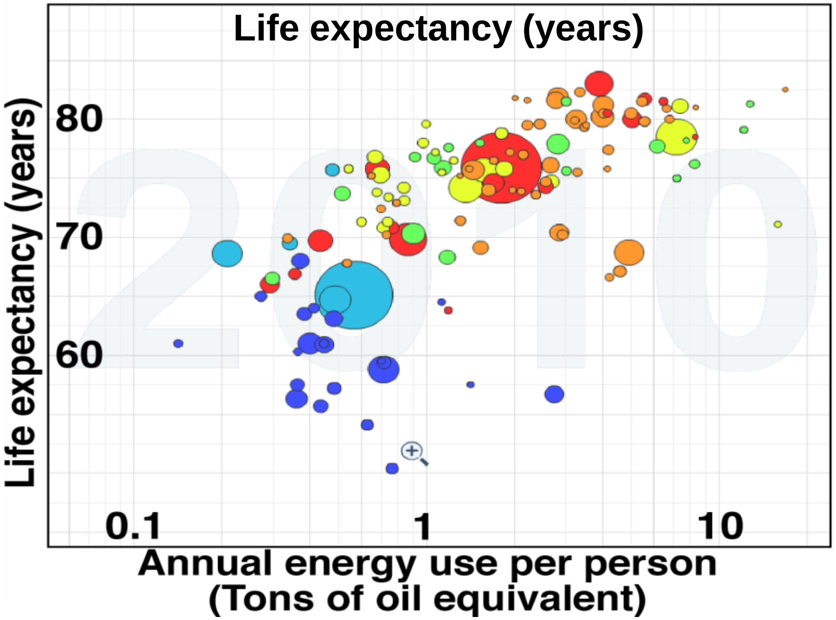
U.S. DEPARTMENT OF ENERGY | Office of Science

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

# OUTLINE

- Nuclear fusion for energy (what & why)
- Plasmas
- Magnetic confinement of fusion plasma
- Achievements in fusion energy research
- Challenges and opportunities

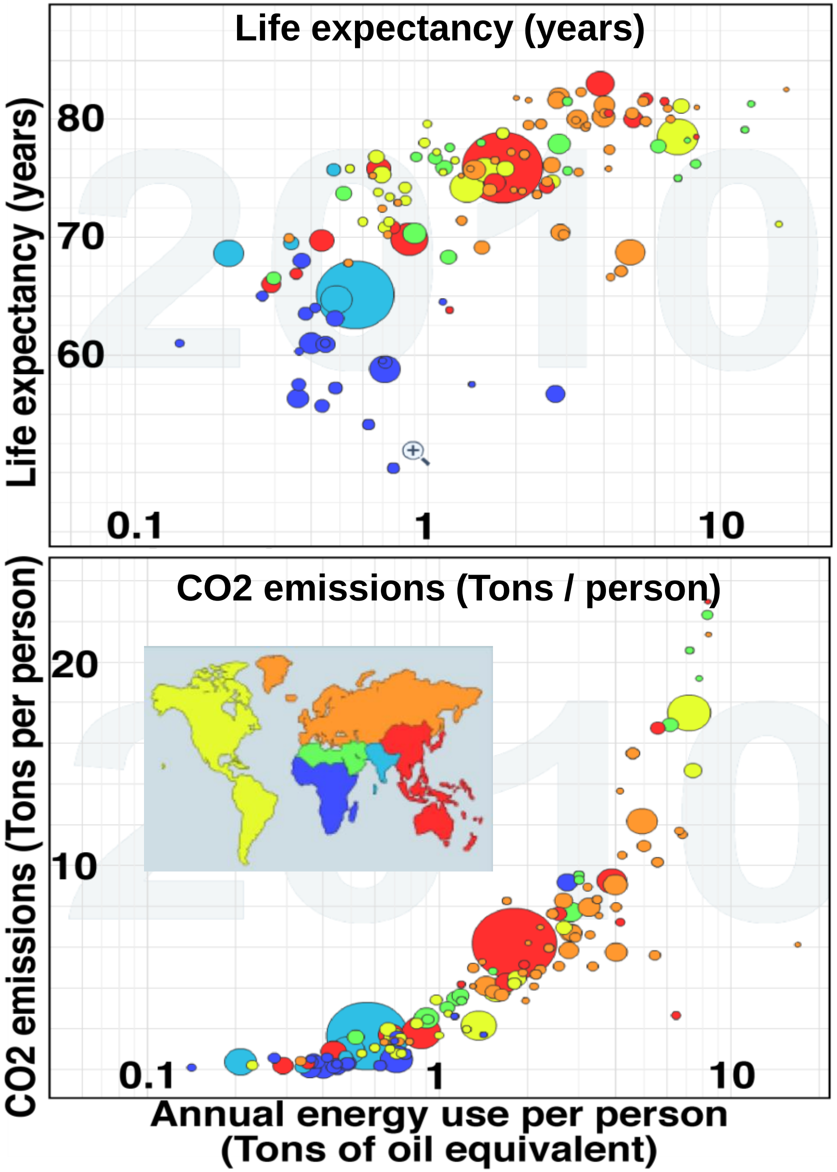
# Many quality-of-life metrics correlated with energy use



- Similar trends for
  - UN human development index
  - Income, average wage
  - Literacy, years in school
  - Reduced child mortality
  - …

**Free material from www.gapminder.org**

# Many quality-of-life metrics correlated with energy use

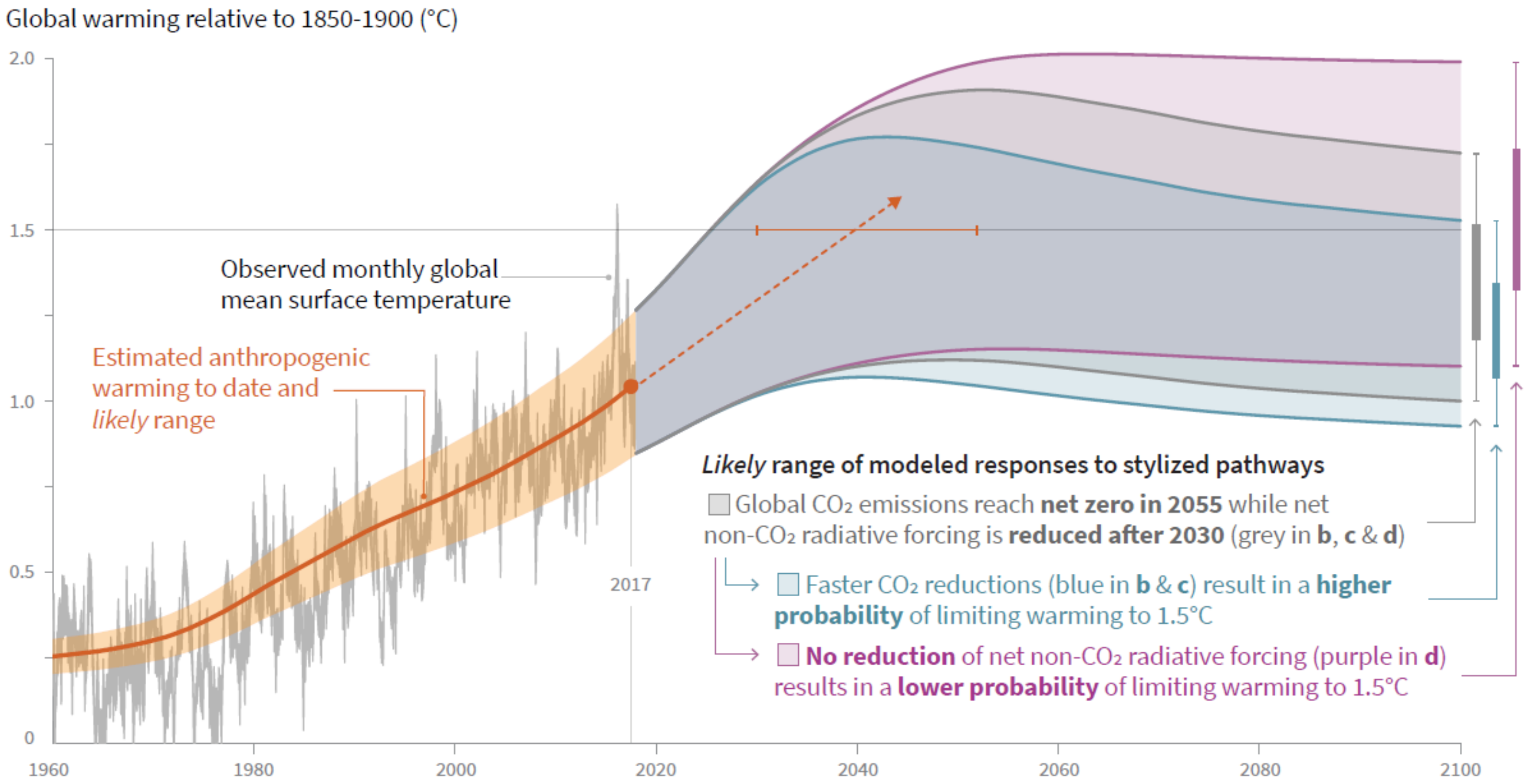


- Similar trends for
  - UN human development index
  - Income, average wage
  - Literacy, years in school
  - Reduced child mortality
  - …

- **Increased energy consumption in the industrial era has increased CO2 emissions**

**Free material from www.gapminder.org**

# Increased CO2 emissions → increased CO2 concentration → elevating global temperatures

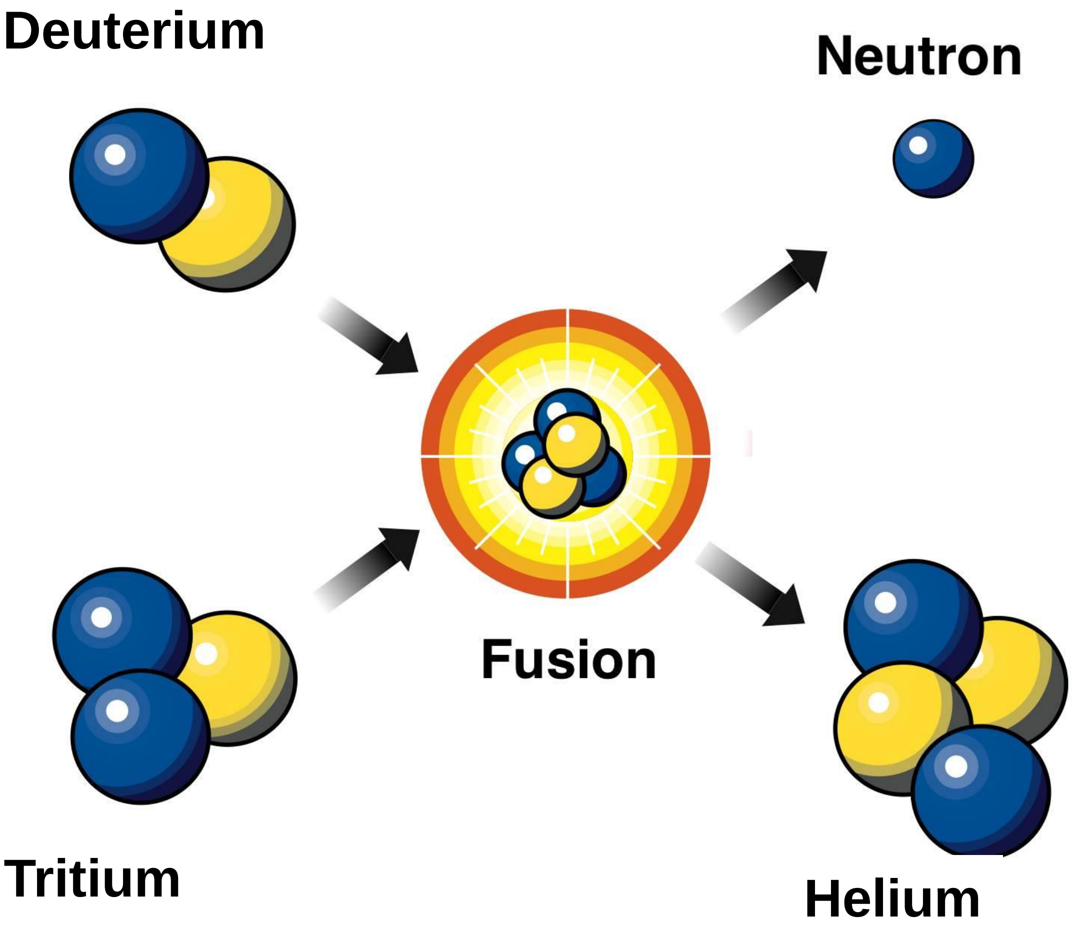


**Source: IPCC Special Report on Global Warming of 1.5°C (Oct. 6, 2018)**

- **Climate concerns & growing *global* energy demand drives pursuit of a portfolio of alternative / renewable, non-carbon energy sources:**
  - solar, wind, nuclear fission, hydroelectric, geothermal … and **nuclear fusion (this talk)**

# Nuclear Fusion: Energy release occurs due to fusing two small nuclei

| mass of<br>deuterium + tritium | > | mass of<br>Helium + neutron |
|---|---|---|



# Nuclear Fusion: Energy release occurs due to fusing two small nuclei

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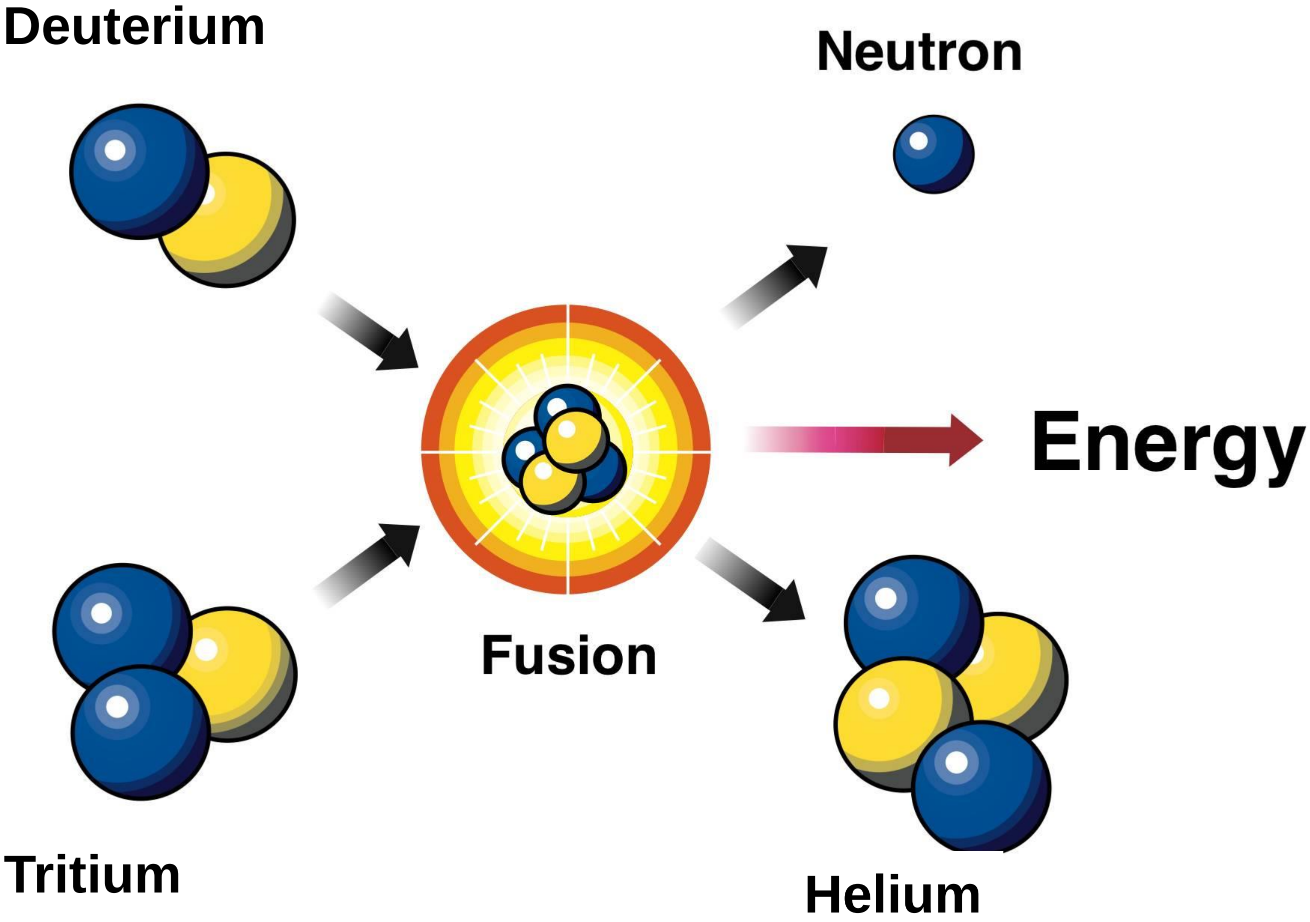
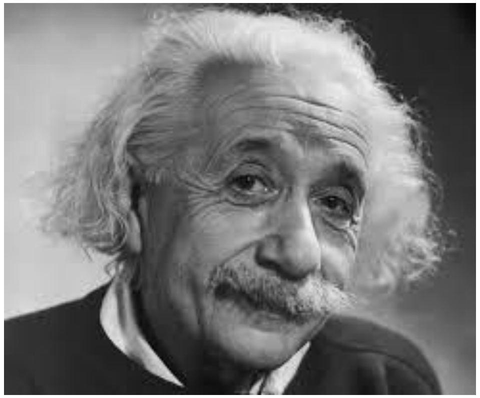


Tiny difference in mass is converted into energy

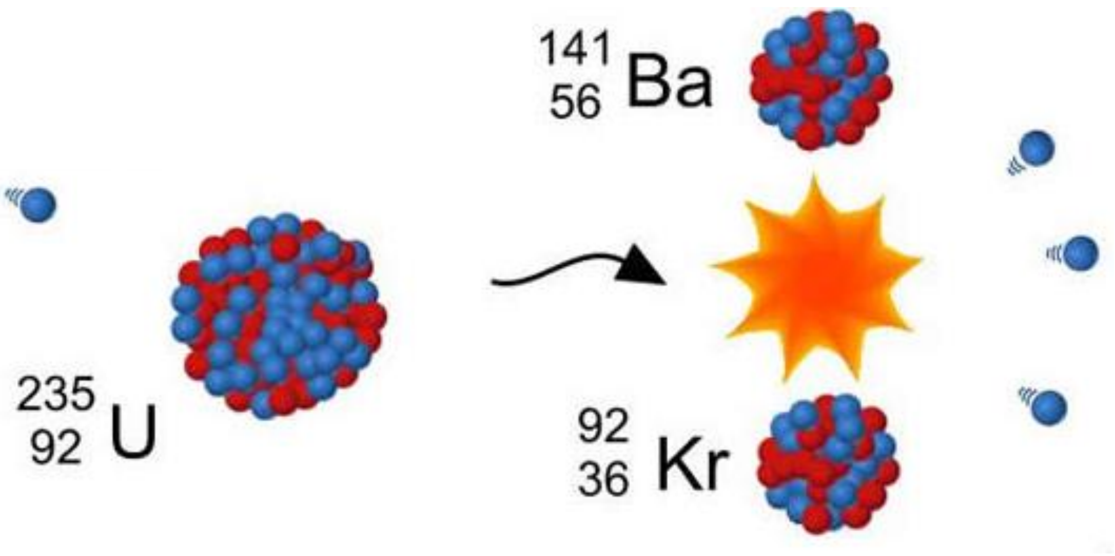
$$\boxed{E = mc^2}$$



# Opposite of nuclear fission that powers today's "nuclear" reactors

- Splitting large atoms also leads to energy release

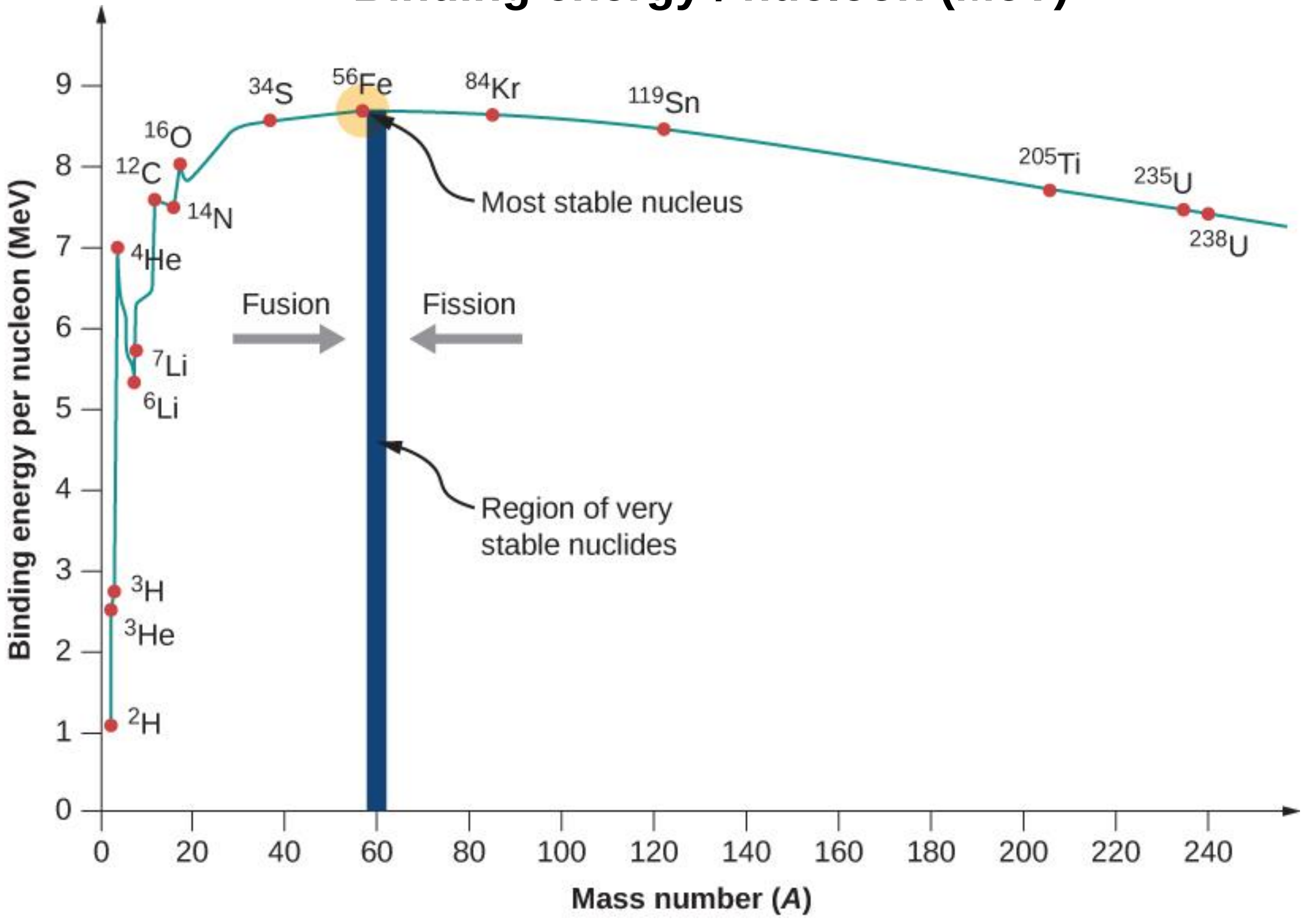
mass of Uranium + neutron > mass of Products



Columbia Generating Station
(Richland, WA)

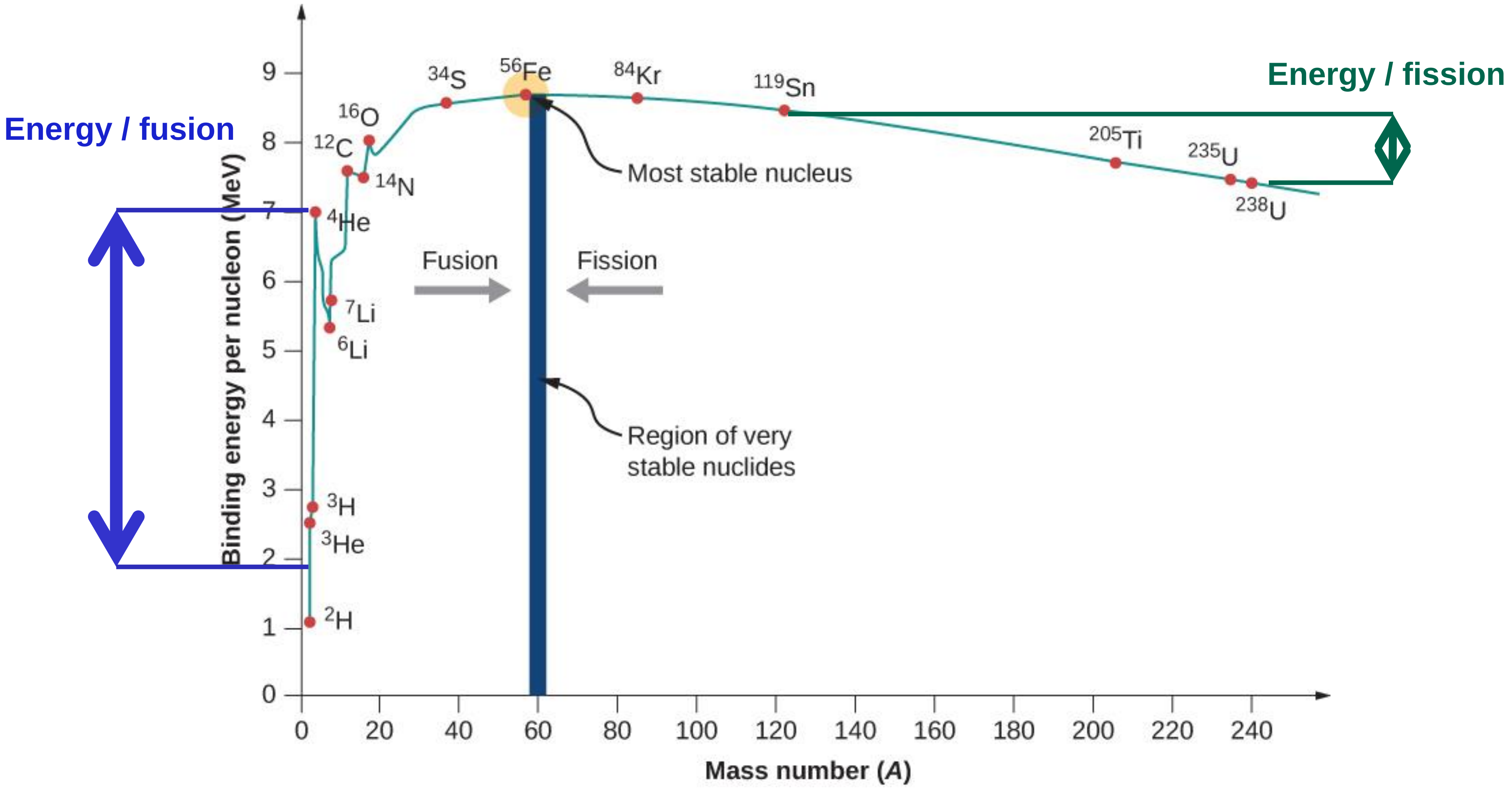
# Energetics governed by binding energies / strong nuclear force

**Binding energy / nucleon (MeV)**



# Energetics governed by binding energies / strong nuclear force

- Gain for fusion can be much larger than fission (both are far larger than chemical reactions)



# Fusion with deuterium & tritium (D-T) is easiest

**Potential Candidates:**

D + D → $^3$He + n + 3.27 MeV (50%)

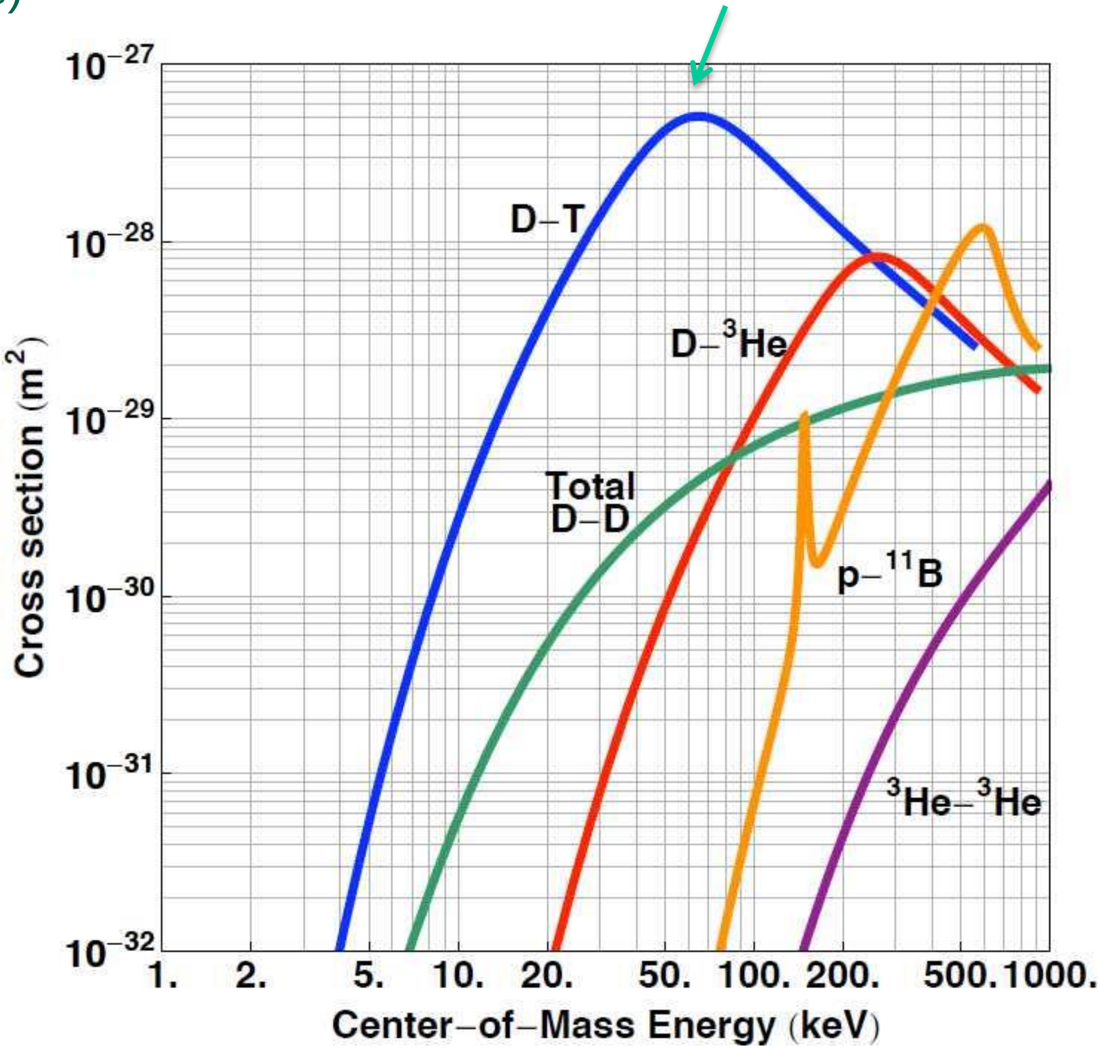
D + D → T + p + 4.03 MeV (50%)

**D + T → $^4$He + n + 17.59 MeV**

D + $^3$He → $^4$He + p + 18.3MeV

- **Optimal temperature for D-T "thermonuclear" fusion ~ 150 M °C (15 keV)**
- **~10 × hotter than the center of the sun!**

**Peak at 70 keV ~ 700 M °C!**



# Deuterium is abundant in seawater, but tritium half-life ~12.3 years (only ~50 kg on the planet) → breed tritium from lithium

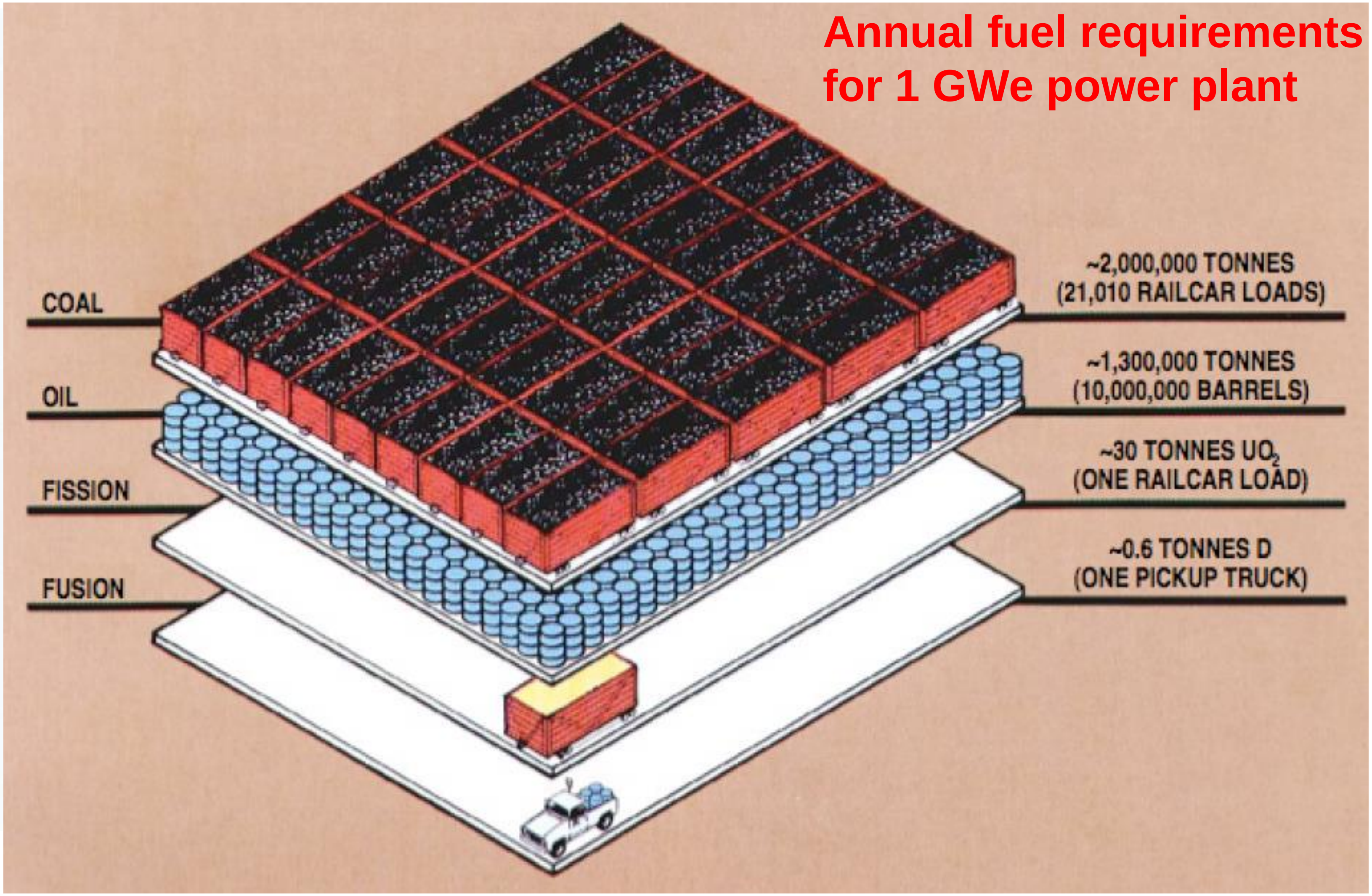
$$
\begin{aligned}
{}^7Li + n &\rightarrow He + T + n - \text{energy} \\
{}^6Li + n &\rightarrow He + T + \text{energy}
\end{aligned}
$$

- Reserves in South America
- Potential abundant source of Li also in seawater (via desalination / dialysis)

$$
\begin{array}{ll}
 & \mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV} \\
+ & \mathrm{Li} + \mathrm{n} \rightarrow {}^4\mathrm{He} + \mathrm{T} + 2.3\ \mathrm{MeV} \\
\hline
\approx & \mathbf{D + Li \rightarrow 2\,{}^4He + 20.0\ MeV}
\end{array}
$$

# Why study fusion energy research?

- No carbon emission
- Fuel is abundant (~thousands of years)



Annual fuel requirements for 1 GWe power plant

# Why study fusion energy research?

- No carbon emission
- Fuel is abundant (~thousands of years)

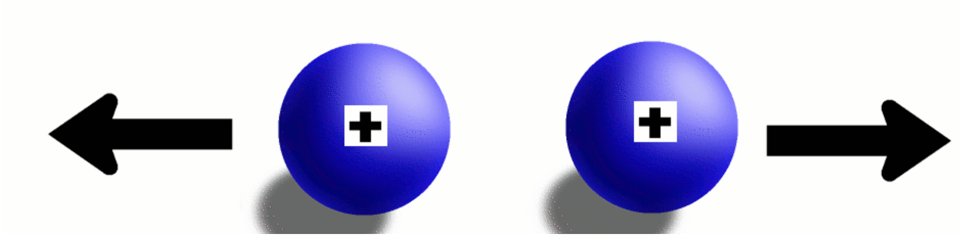
- Inherently safe – only grams (<minute) of fuel in the device
  - no melt down/runaway concerns
- Very little (and short lived, low-level) radioactive material compared to nuclear fission

- Compared to non-carbon renewables (solar, wind) fusion is compact and continuous (not intermittent)

- **Disadvantages: Hard to do!**

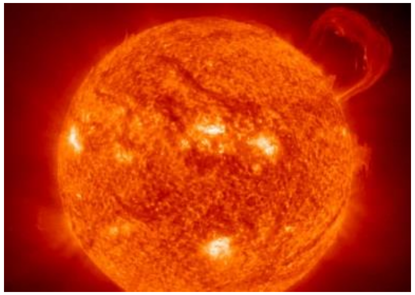
# Must overcome repulsive electrostatic force to fuse atomic nuclei

- Force between two charged particles increases as they get closer



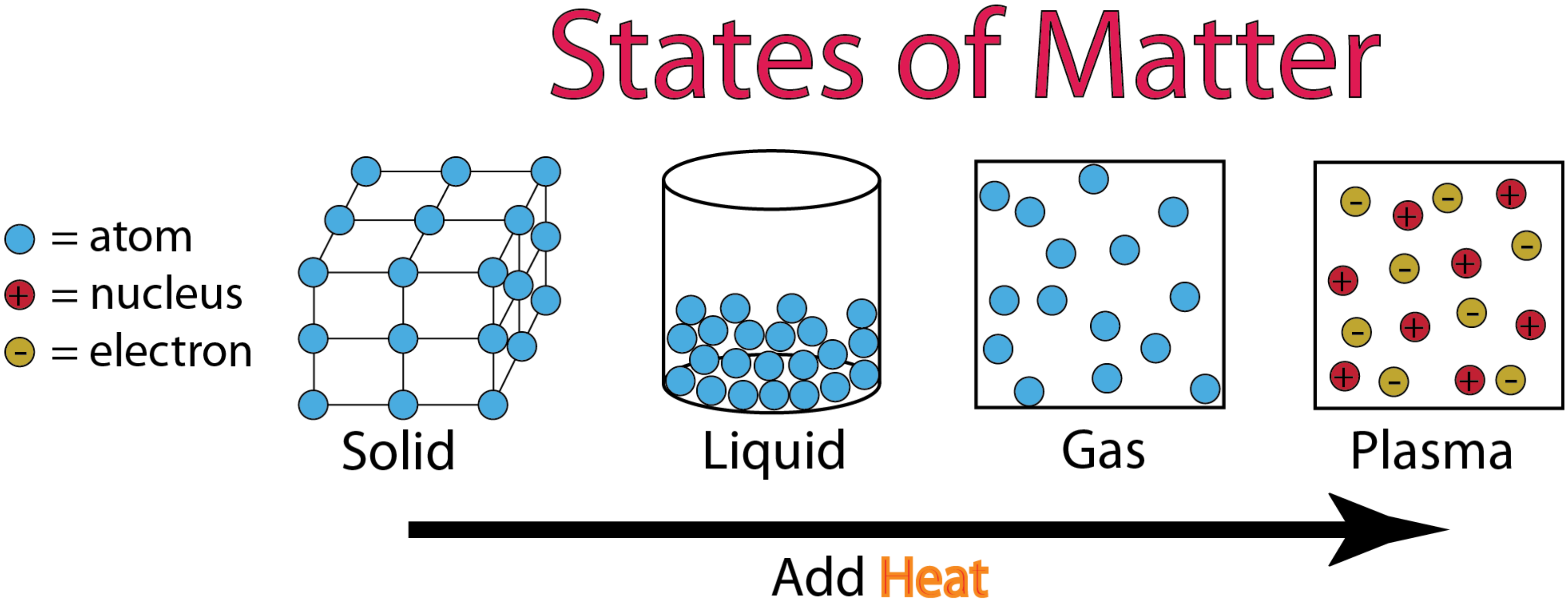
$$F = \frac{1}{4\pi\epsilon_0}\frac{Q_1Q_2}{r^2}$$

- **Temperatures must be ~150 million degrees Celsius**
  **→ no longer a gas, but a <u>plasma</u>**
  **(Core of the sun ~15 million C)**



# What is plasma?

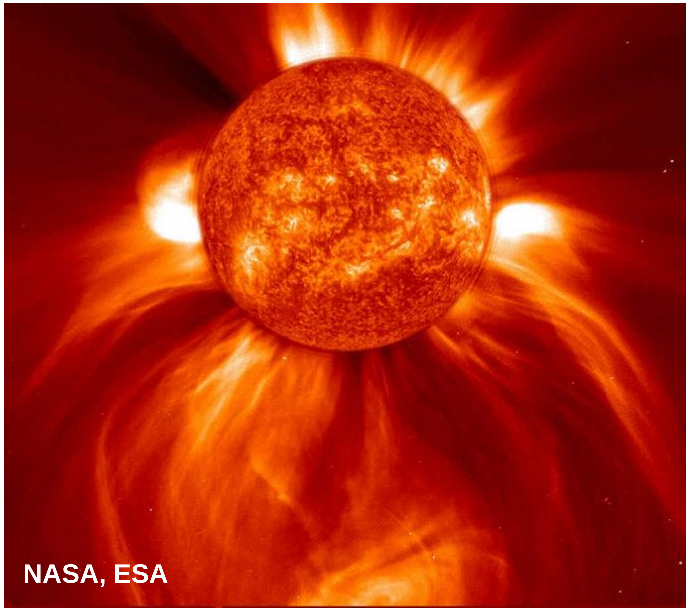
# Plasma: a gas of charged particles (the fourth state of matter)



- **Plasma behaves qualitatively different than neutral gas due to collective (Coulomb) interactions & interactions with electric (E) & magnetic (B) fields** $\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$

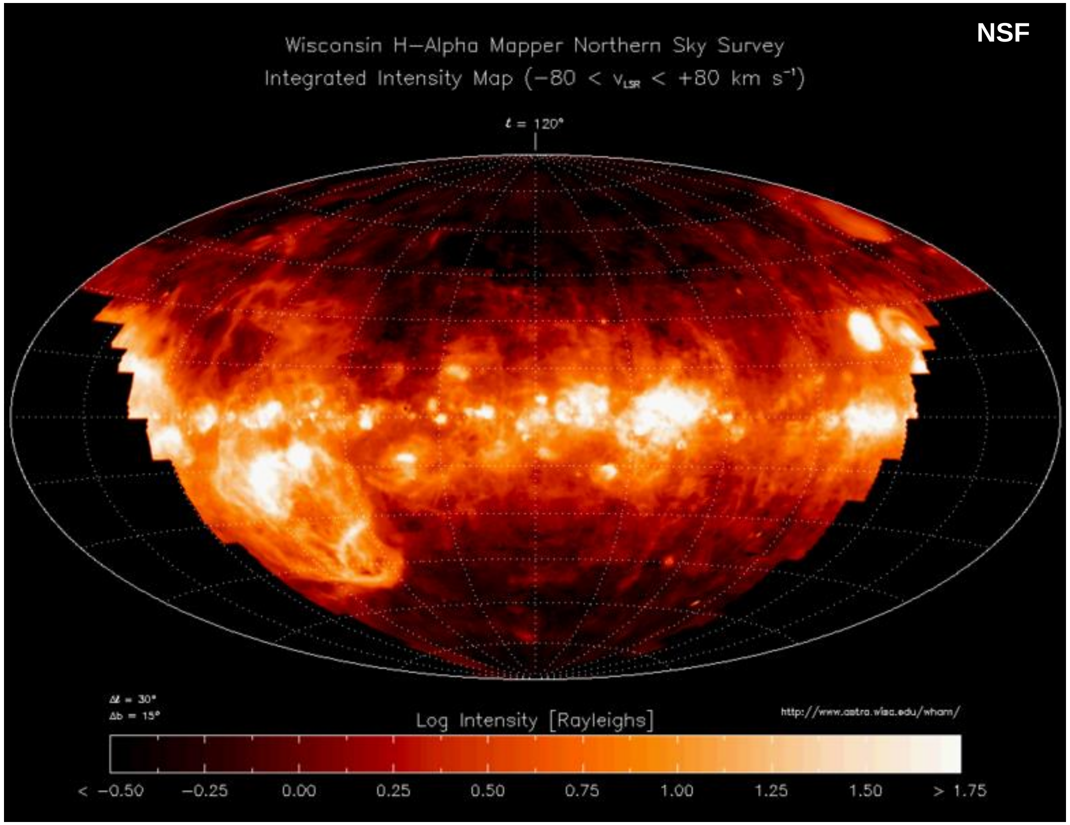
# 99% of (known) matter in universe is plasma

- Sun, stars, interstellar and intergalactic medium account for most mass and are largely plasma

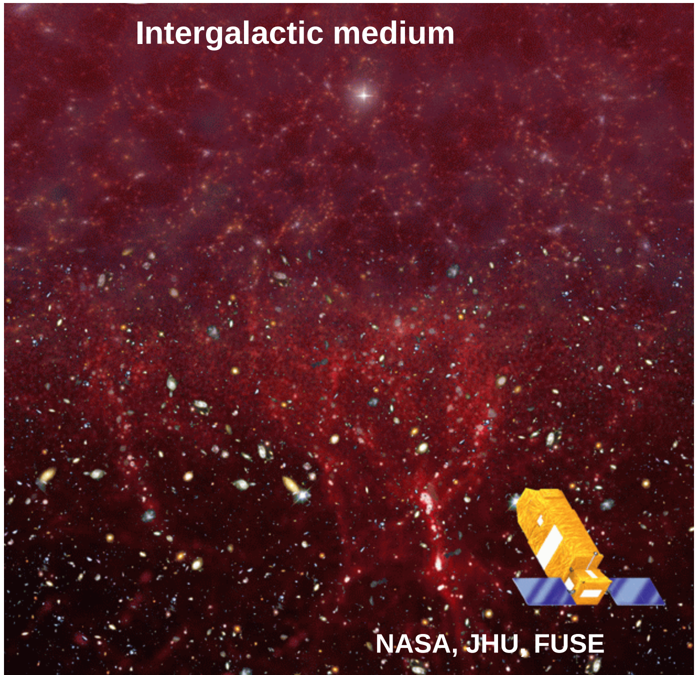


NASA, ESA

**Ionized gas in the Milky Way**



NSF



**Intergalactic medium**

NASA, JHU, FUSE

# Numerous examples of plasmas on or near earth

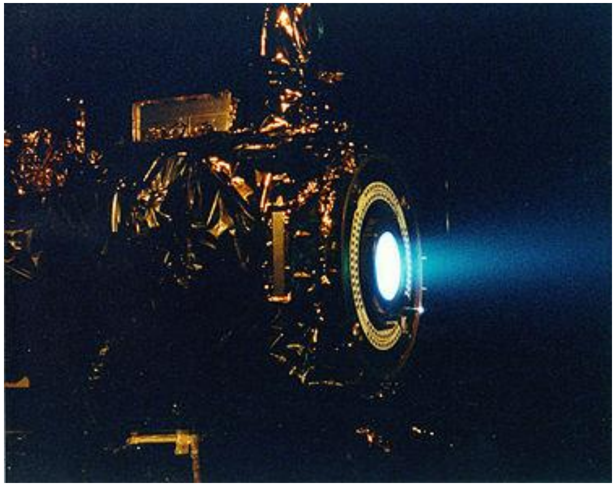
lightning

neon signs

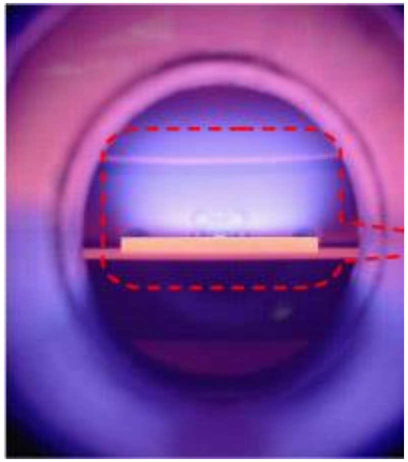
tv

aurora

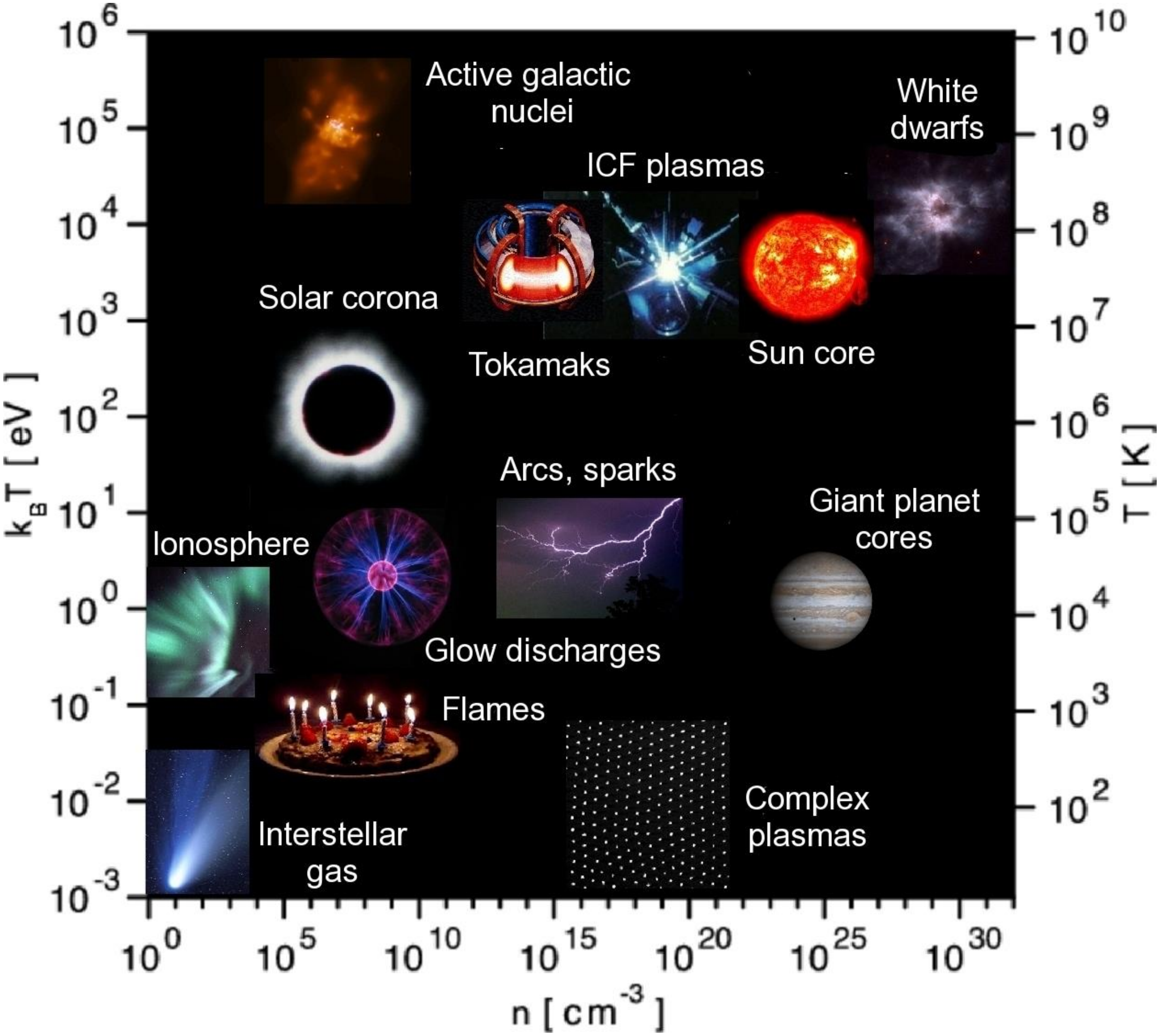
satellite plasma thrusters



semiconductor processing



# Plasmas exist over broad range of density and temperature → wide range of physics phenomenon!



# How do we create and contain a *hot* plasma on earth?

# Recipe to create a fusion plasma

1. **Establish an appropriate magnetic field**

2. **Inject appropriate gases (in a container at vacuum pressure)**

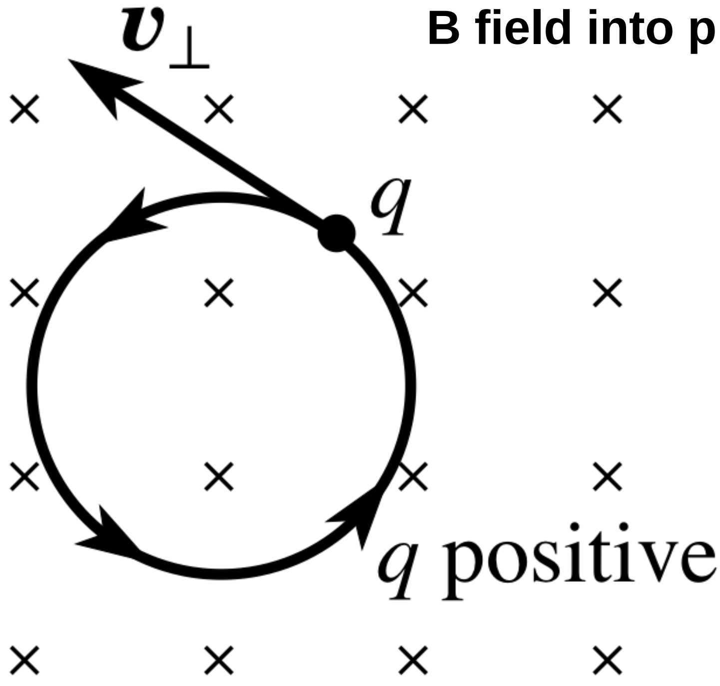
3. **Heat the gases**

# Charged particles experience Lorentz force in a magnetic field → gyro-orbits

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

- Magnetic force acts perpendicular to direction of particle

→Particles follow circular gyro-orbits



**B field into plane**

$$\mathbf{f_{gyro}} = \frac{\mathbf{1}}{\mathbf{2\pi}}\frac{\mathbf{eB}}{\mathbf{m}}$$

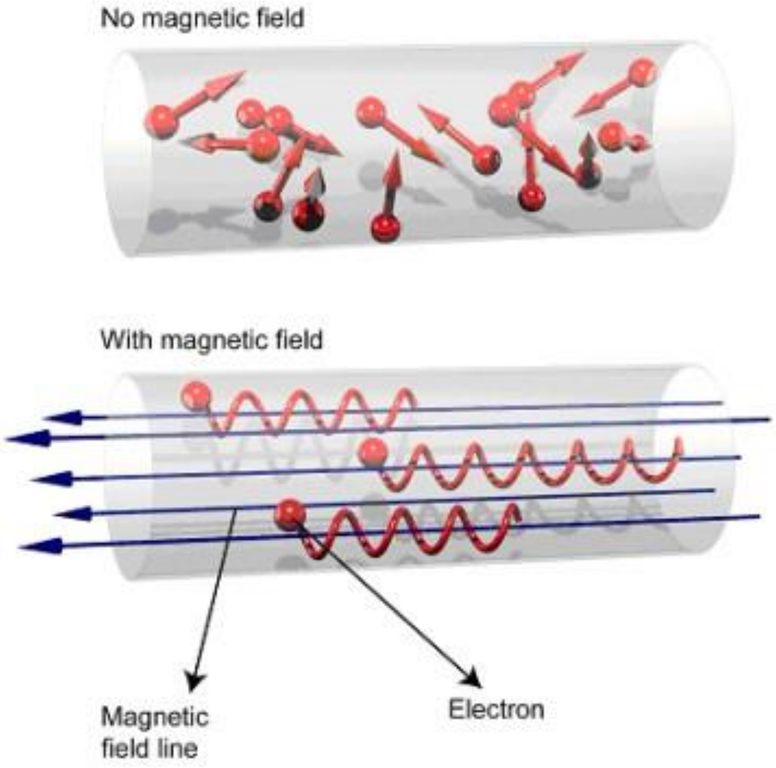
**$f_{gyro}$ ~ $10^7$ / $10^{10}$ Hz**

**(for deuteron / electron, B=5 T)**

# Magnetic field confines particles away from boundaries

For a 5 Tesla magnetic field,
100 million C plasma

**ion radius ~ 3 mm**
**electron radius ~ 0.05 mm** << **1-2 meter device size**



# Magnetic field confines particles away from boundaries

For a 5 Tesla magnetic field,
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**ion radius ~ 3 mm**
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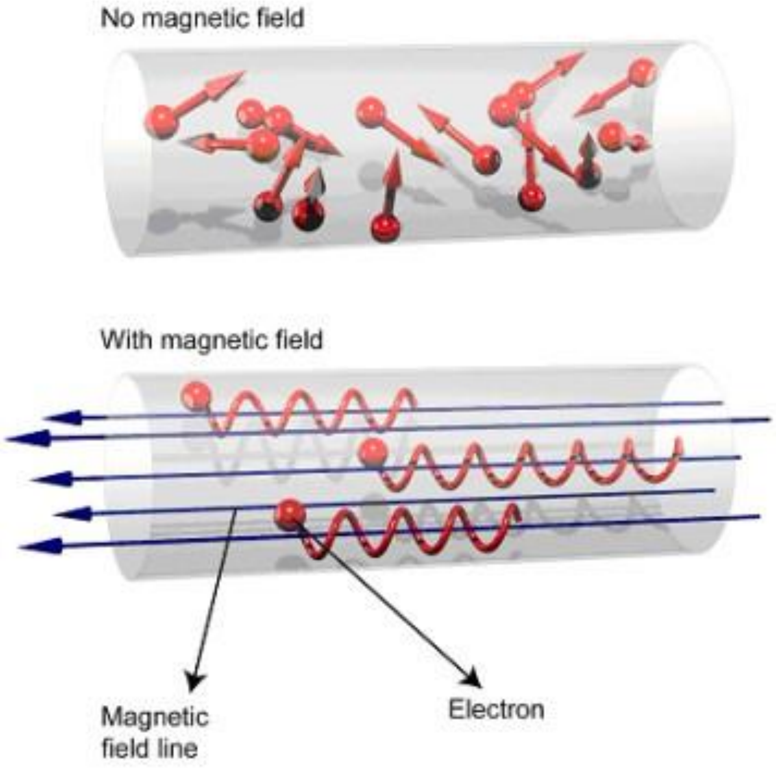
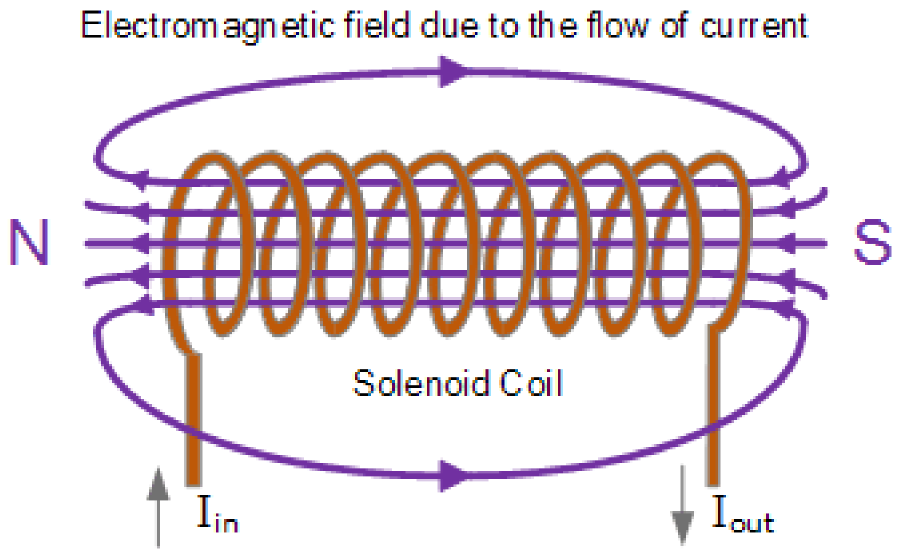
For comparison

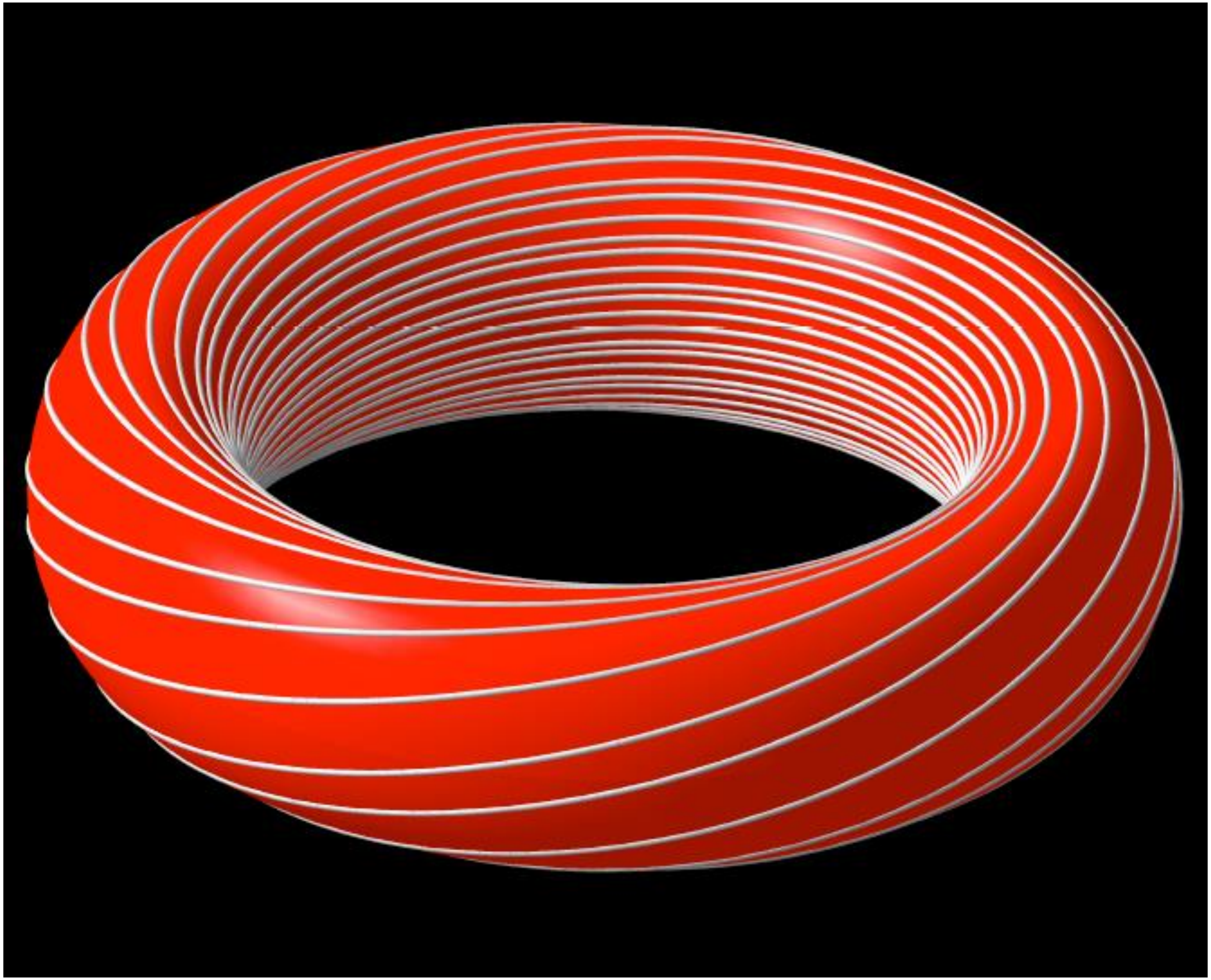
- Earth's magnetic field – 50 $\mu$T
- MRI – 1-5 T
- Junkyard magnet – 1-2 T





**But particles easily lost from ends (very low collision frequency~1/$T^{3/2}$, $\lambda_{MFP}$~ km's >> device size)**

# Solution: bend the field into a donut-shaped torus

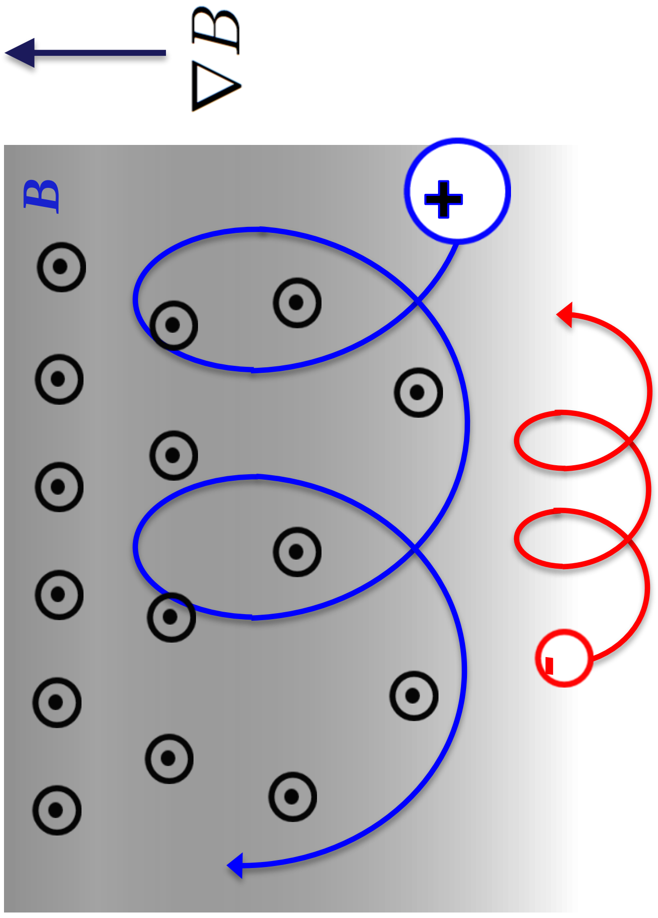


# But toroidicity leads to vertical drifts from ∇B & curvature

$$B \sim \frac{1}{R}$$

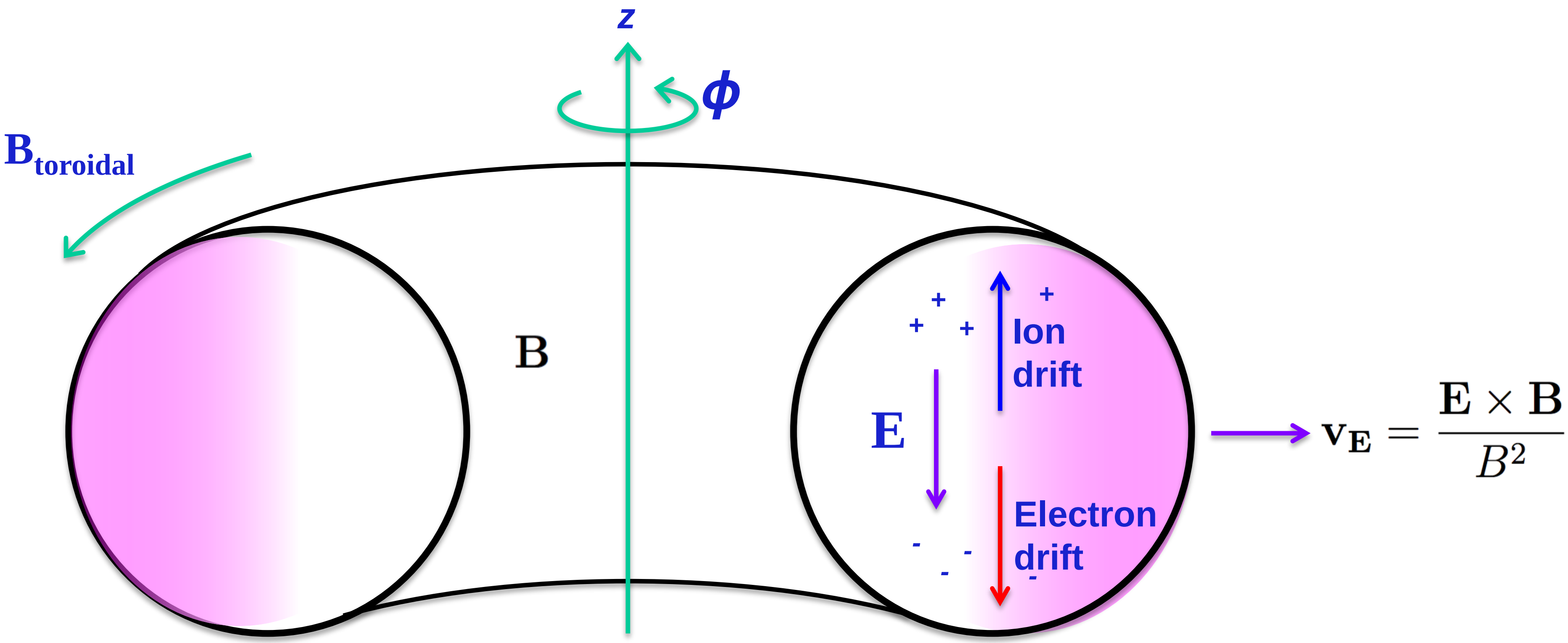
$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

$$v_{\nabla B} \approx \frac{T}{qBR}\left(\hat{z}\right)$$



$\tau_{loss}$ ~ 5 ms from vertical drifts (B~5 T, R~5 m, T~15 keV)

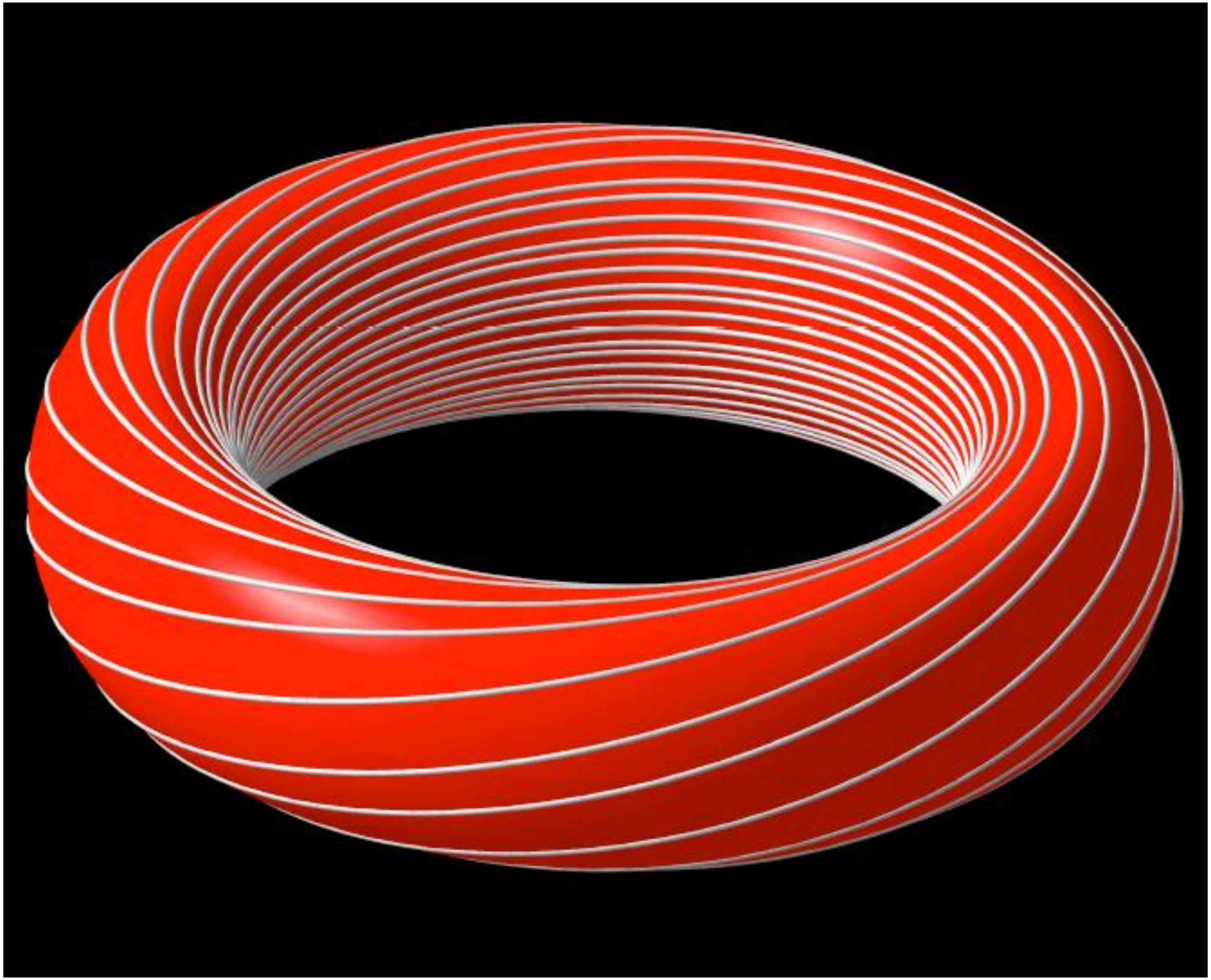
# Even worse, charge separation leads to faster E×B drifts out to the walls



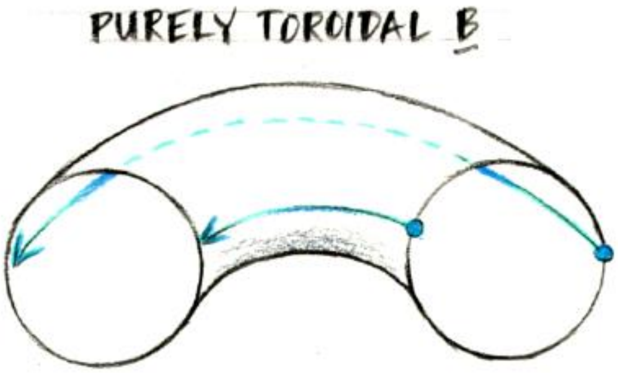
$$\mathbf{v_E} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

$\tau_{\text{loss}}$ ~ μs from E×B drifts (due to charge separation from vertical drifts)

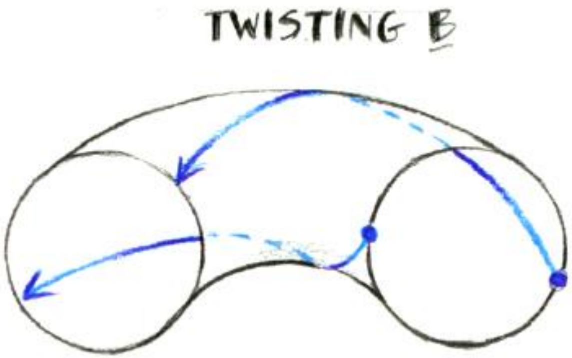
# Solution: need a helical magnetic field for confined particle orbits



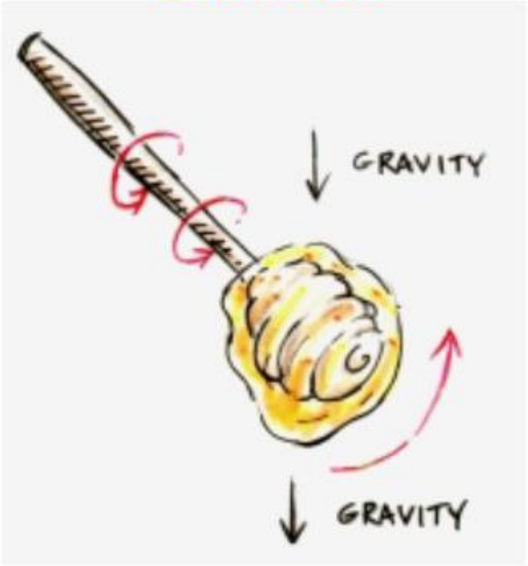
# Helical B field carries plasma from “bad curvature” region to “good curvature” region



Unstable



Stable

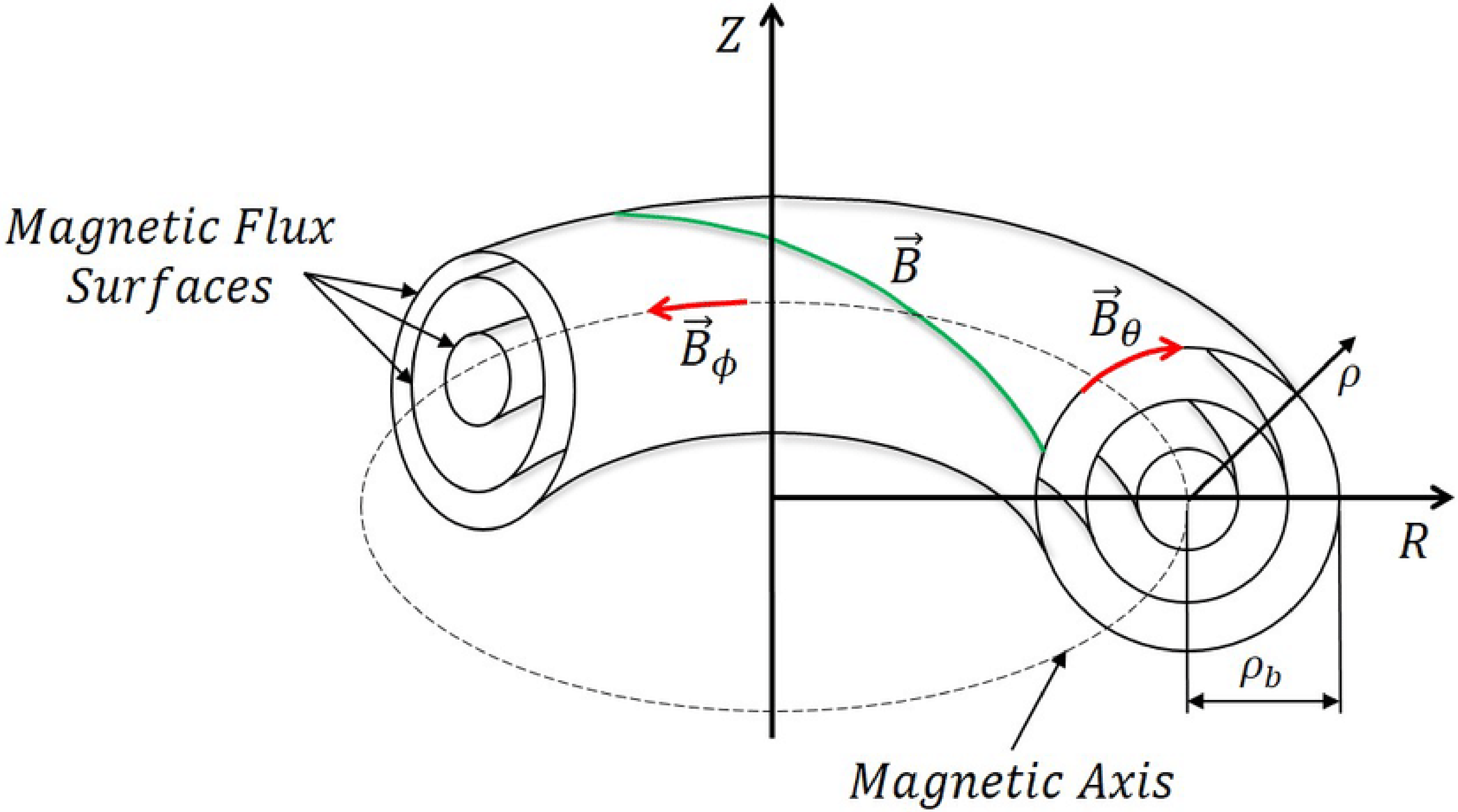


**Similar to how honey dipper prevents honey from dripping**

# Equilibrium establishes closed, nested magnetic "flux surfaces"

**Governed by magnetic hydrodynamic (MHD) force balance:**

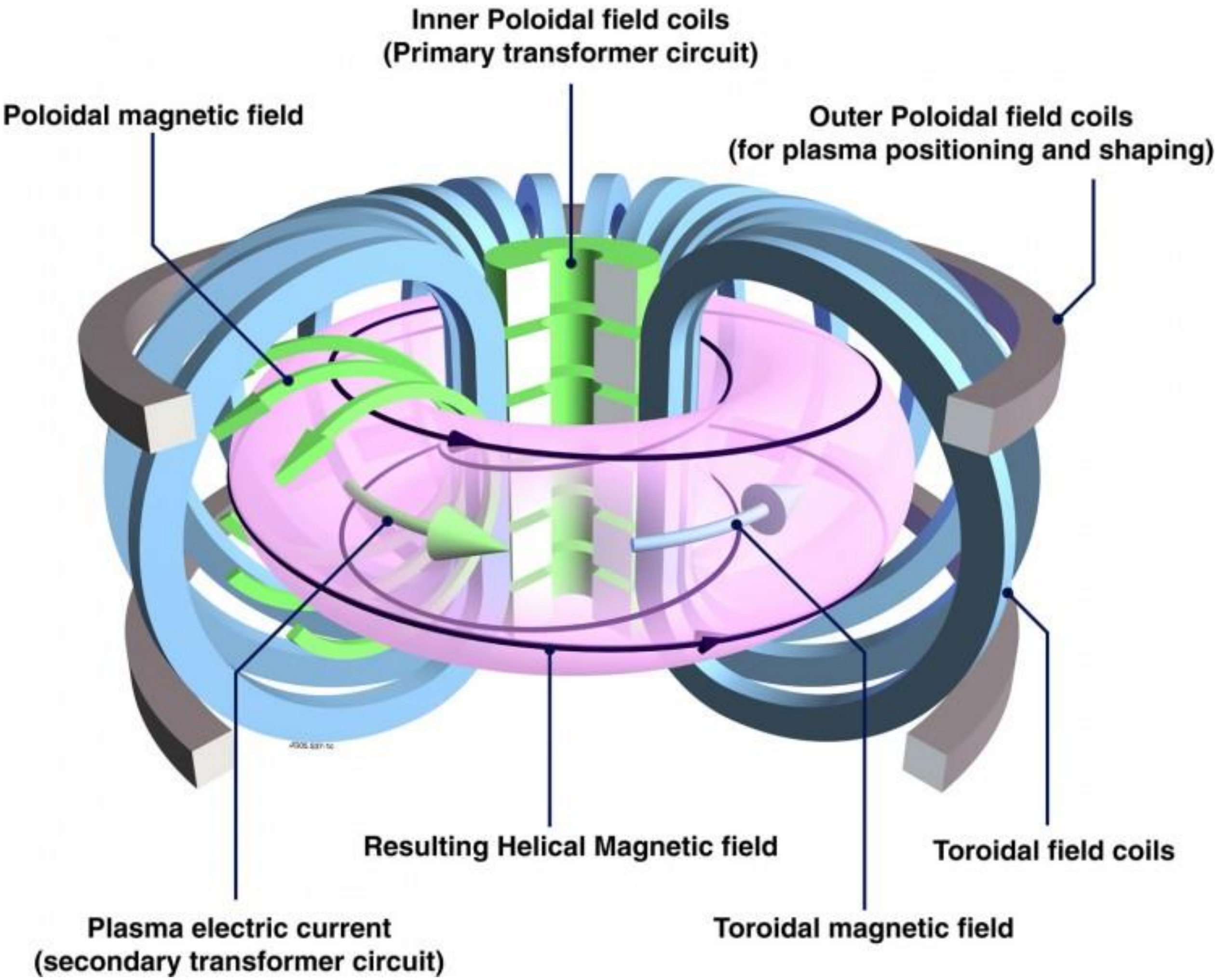
$$\mathbf{J}\times\mathbf{B} = \nabla P$$



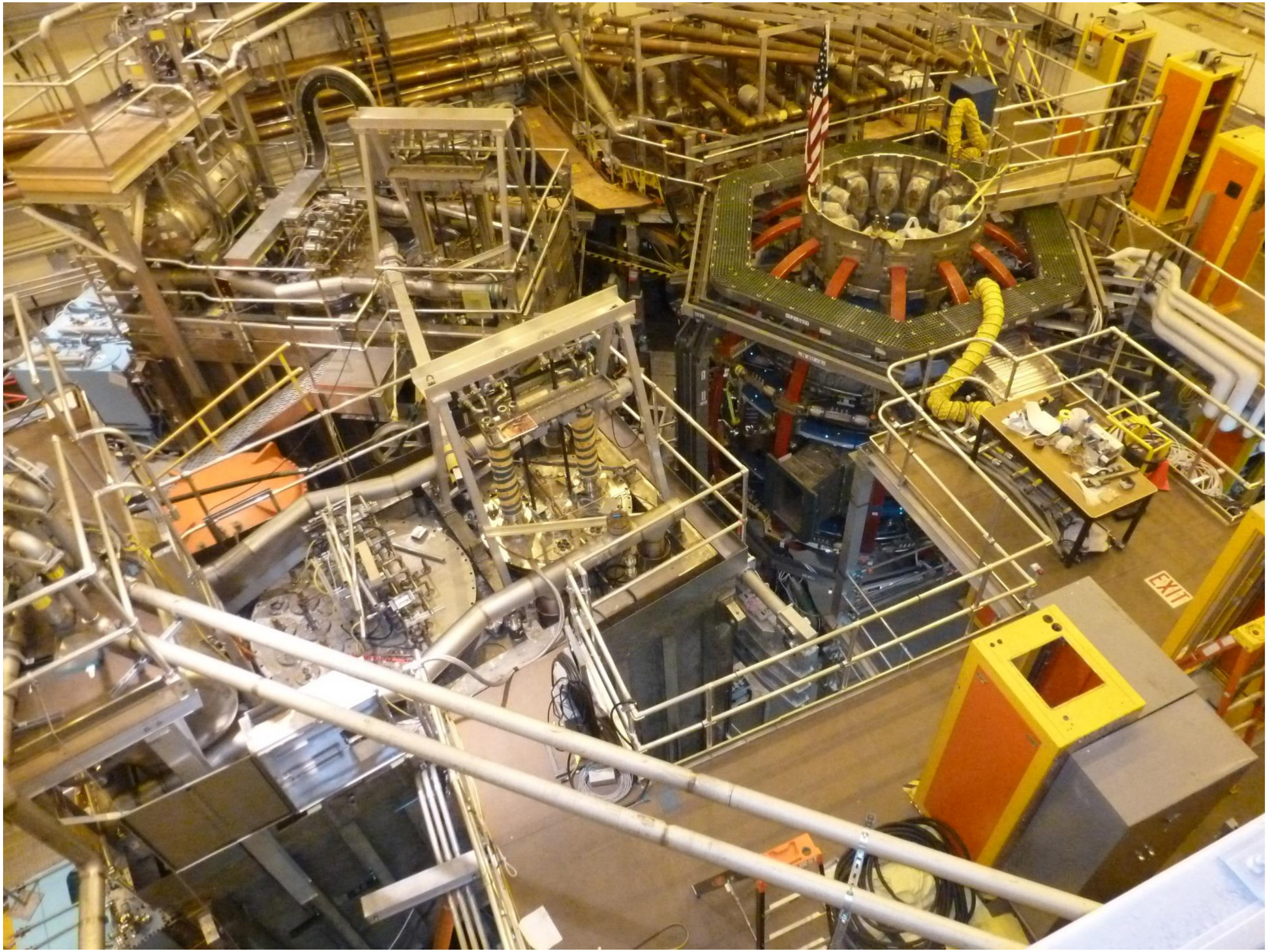
# How do we create the helical magnetic field?

# The Tokamak (Russion acronym ~ “toroidal chamber with magnetic coils”)

- Toroidal field from external coils + poloidal field from plasma current → helical field



# At Princeton Plasma Physics Lab (PPPL): National Spherical Torus Experiment-Upgrade (NSTX-U)



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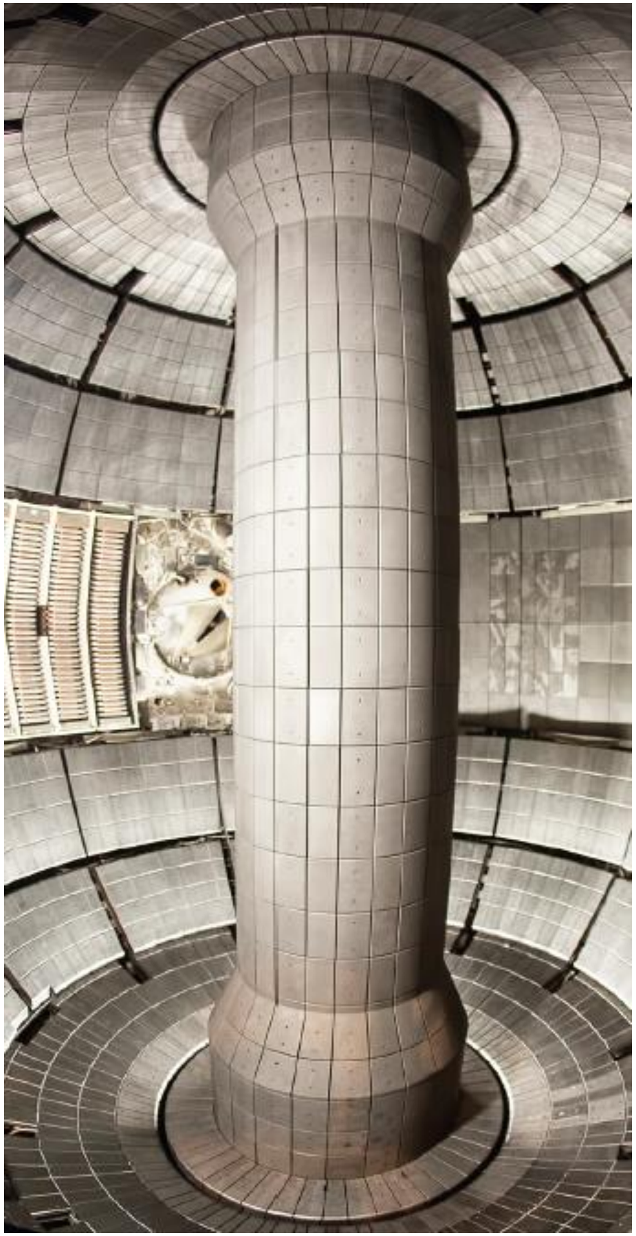

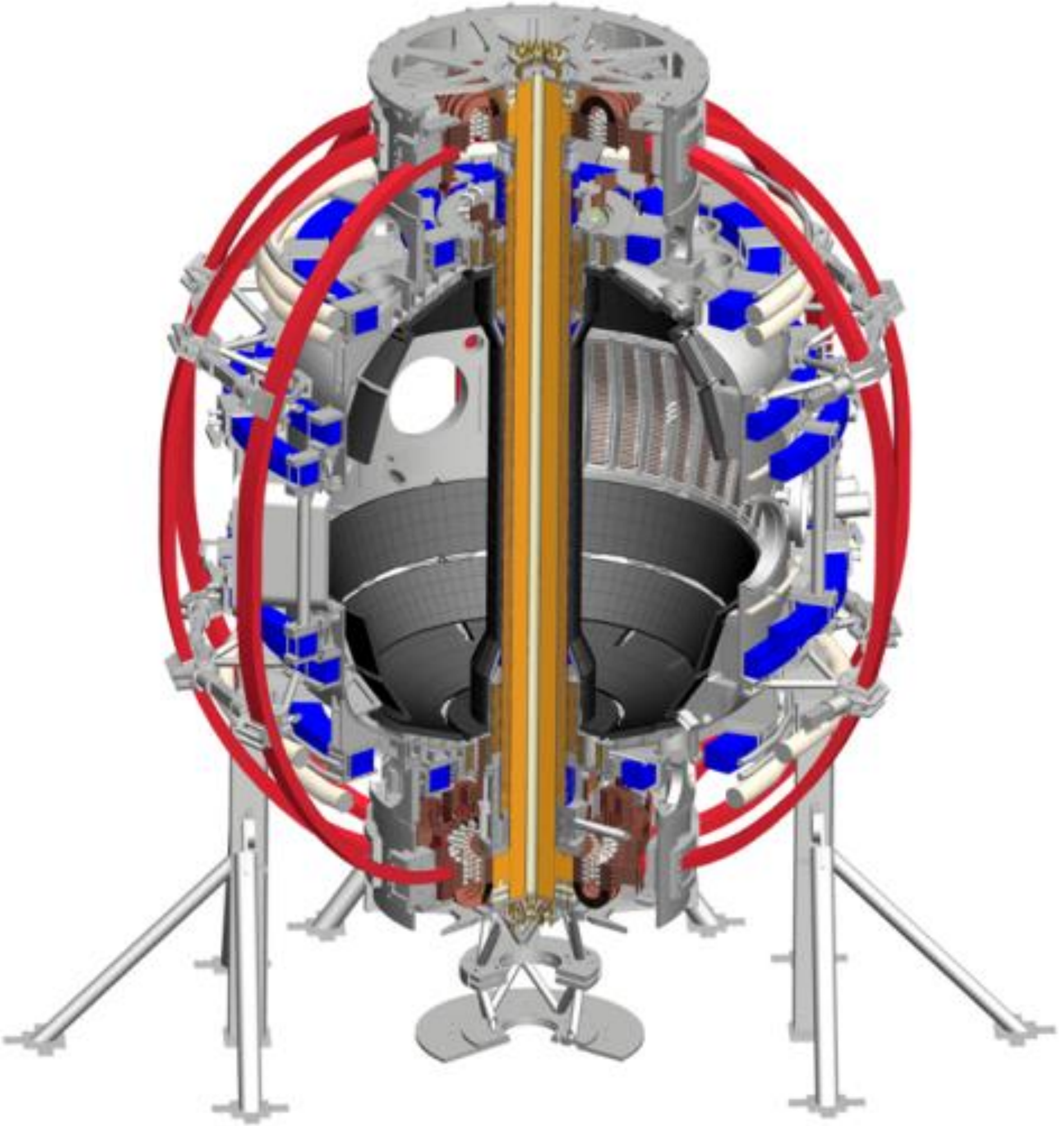

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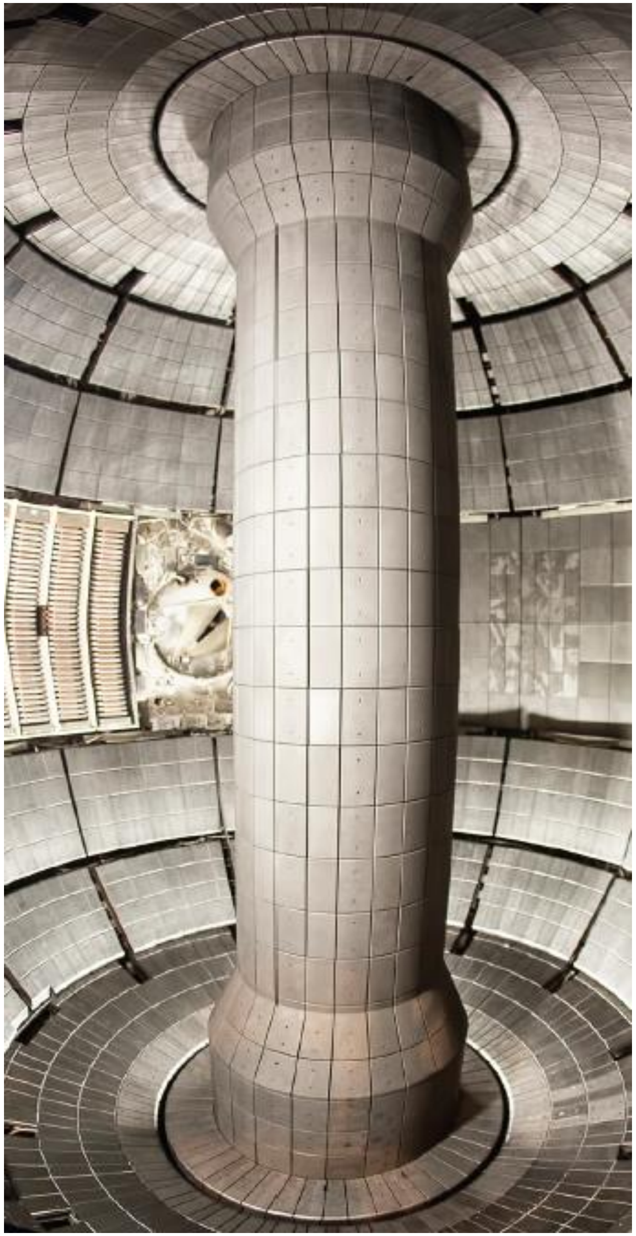
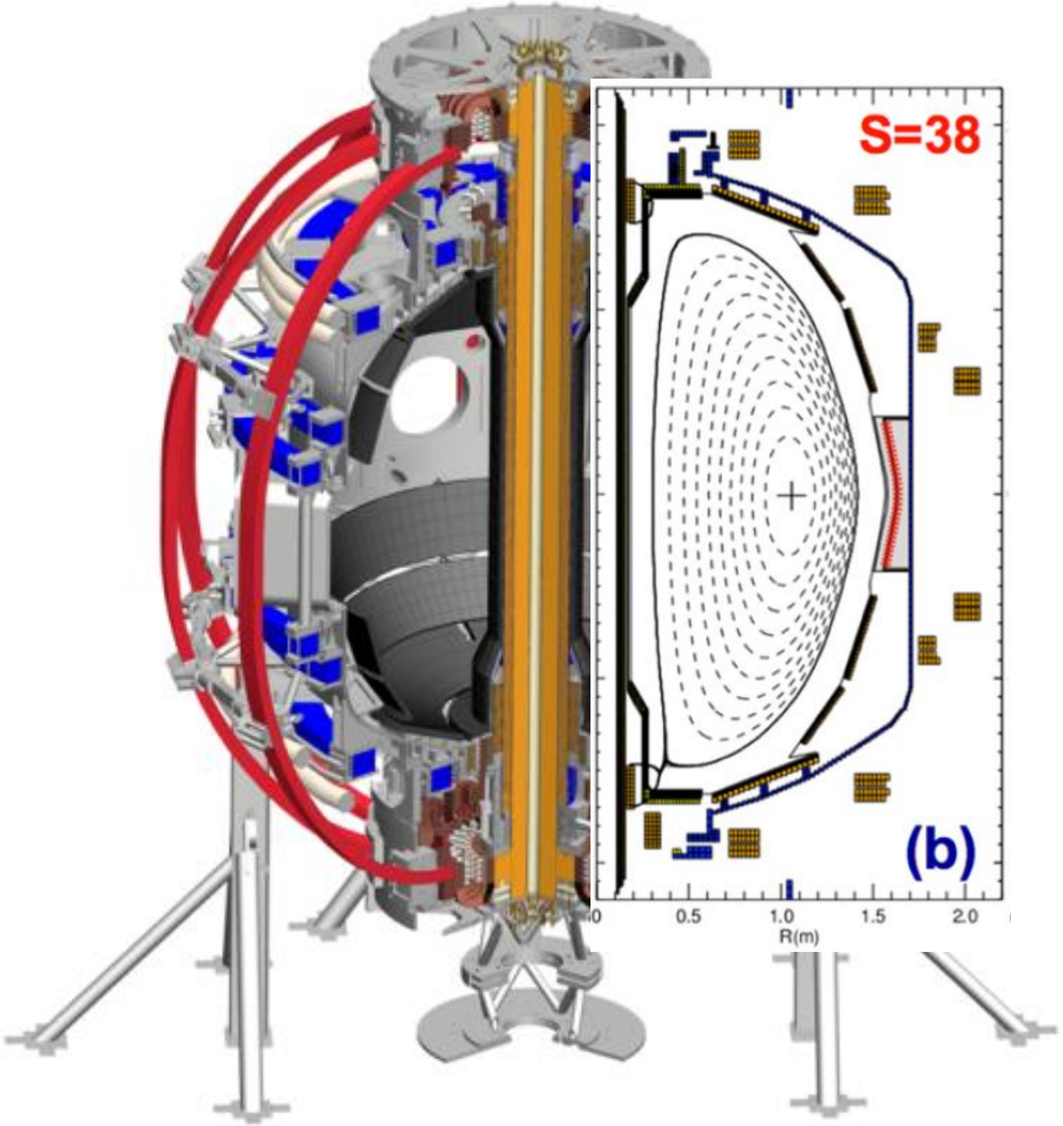
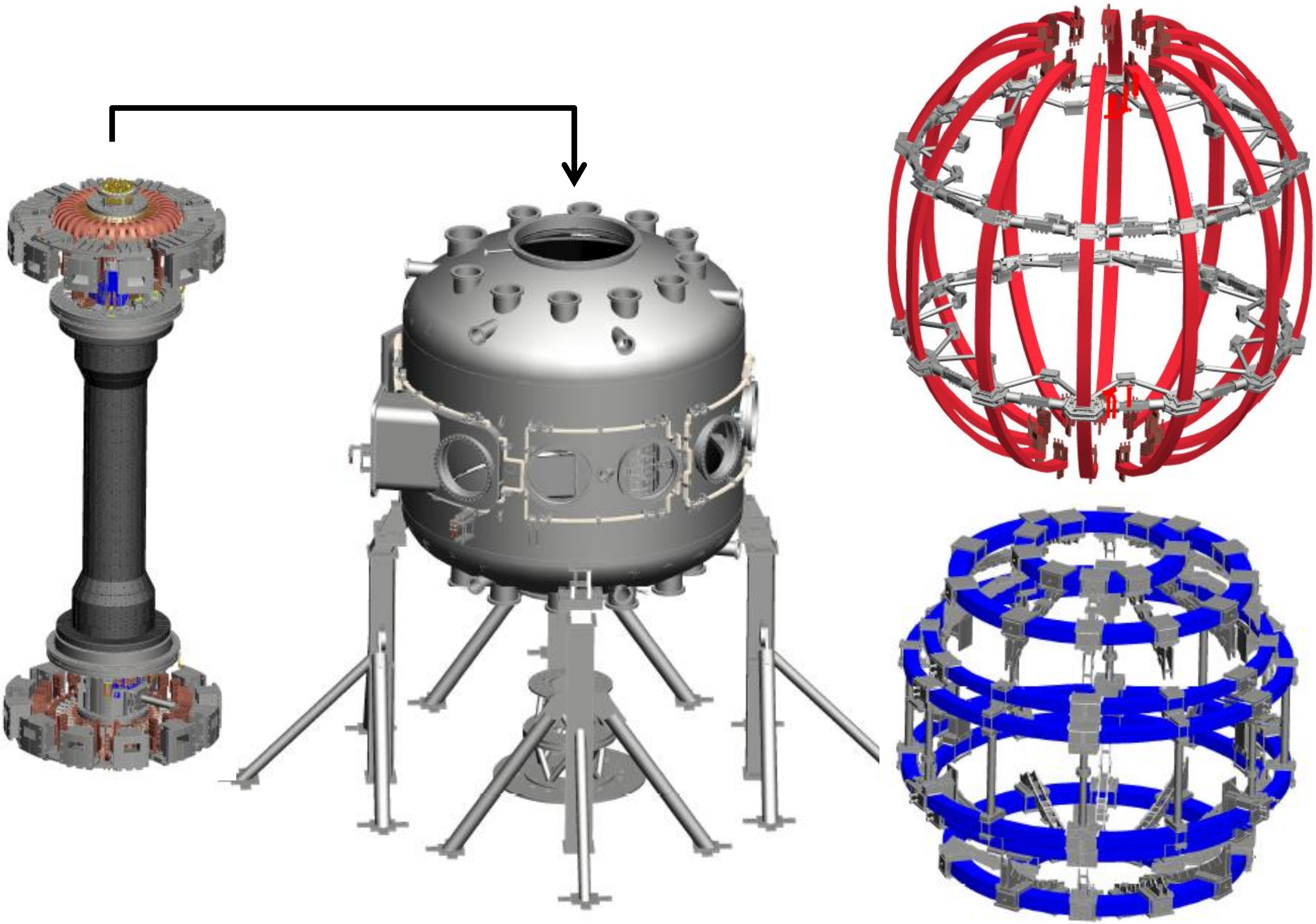
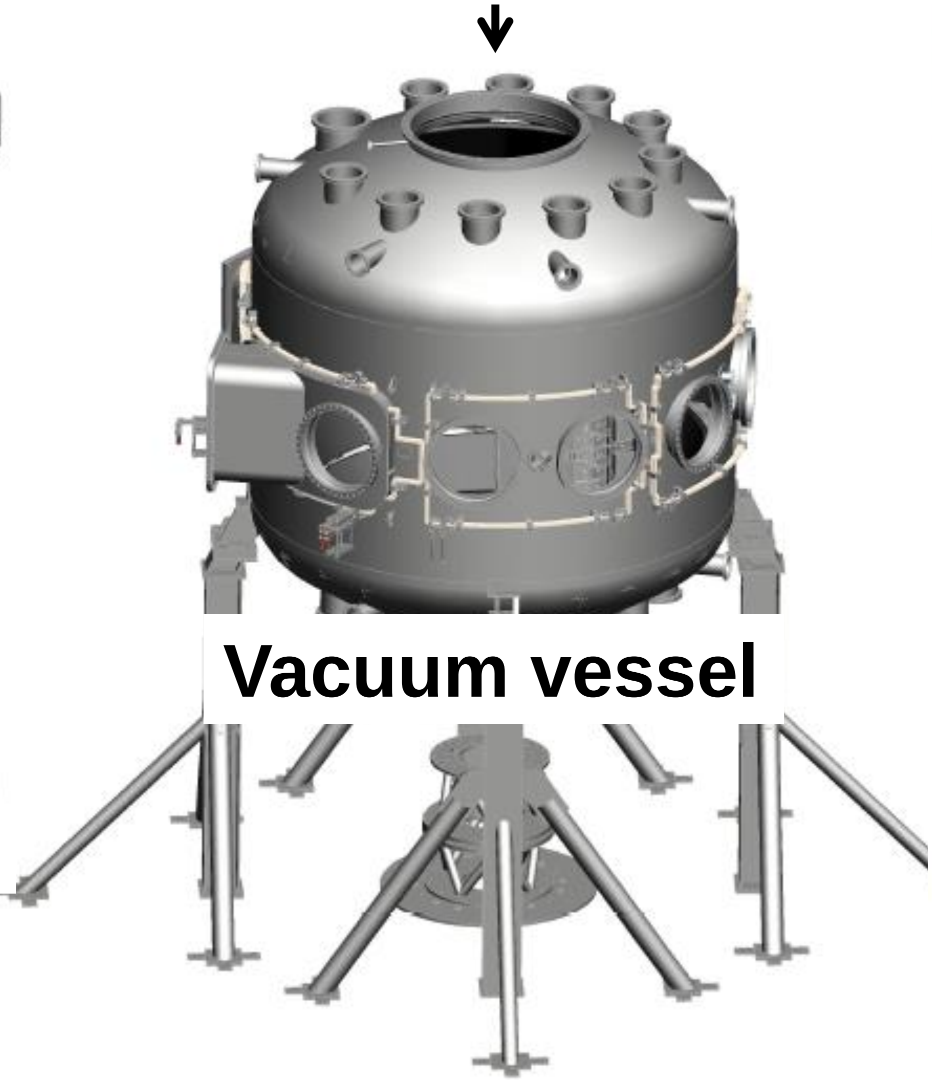




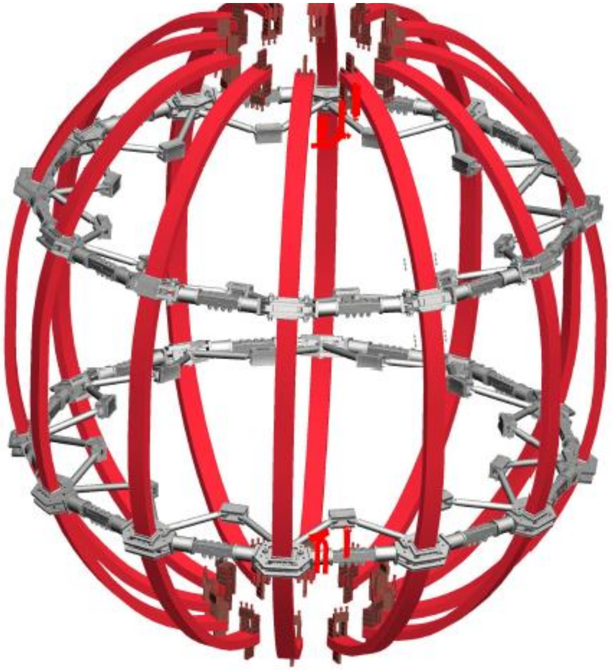


**Solenoid for inductive current drive**

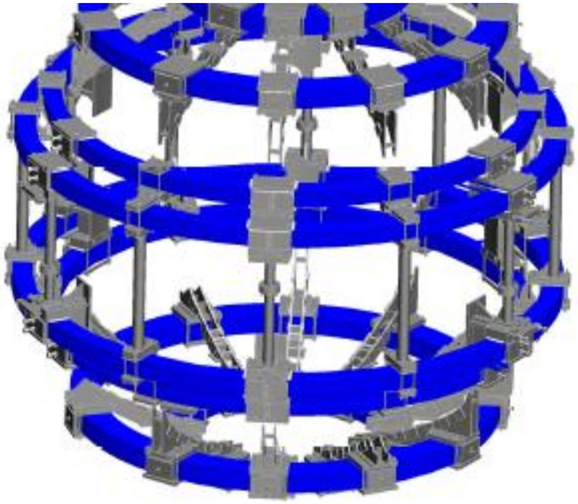


**Vacuum vessel**

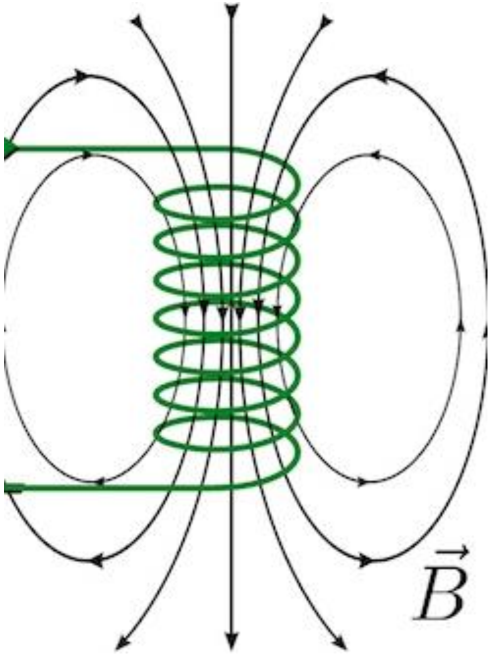
**Toroidal field coils**

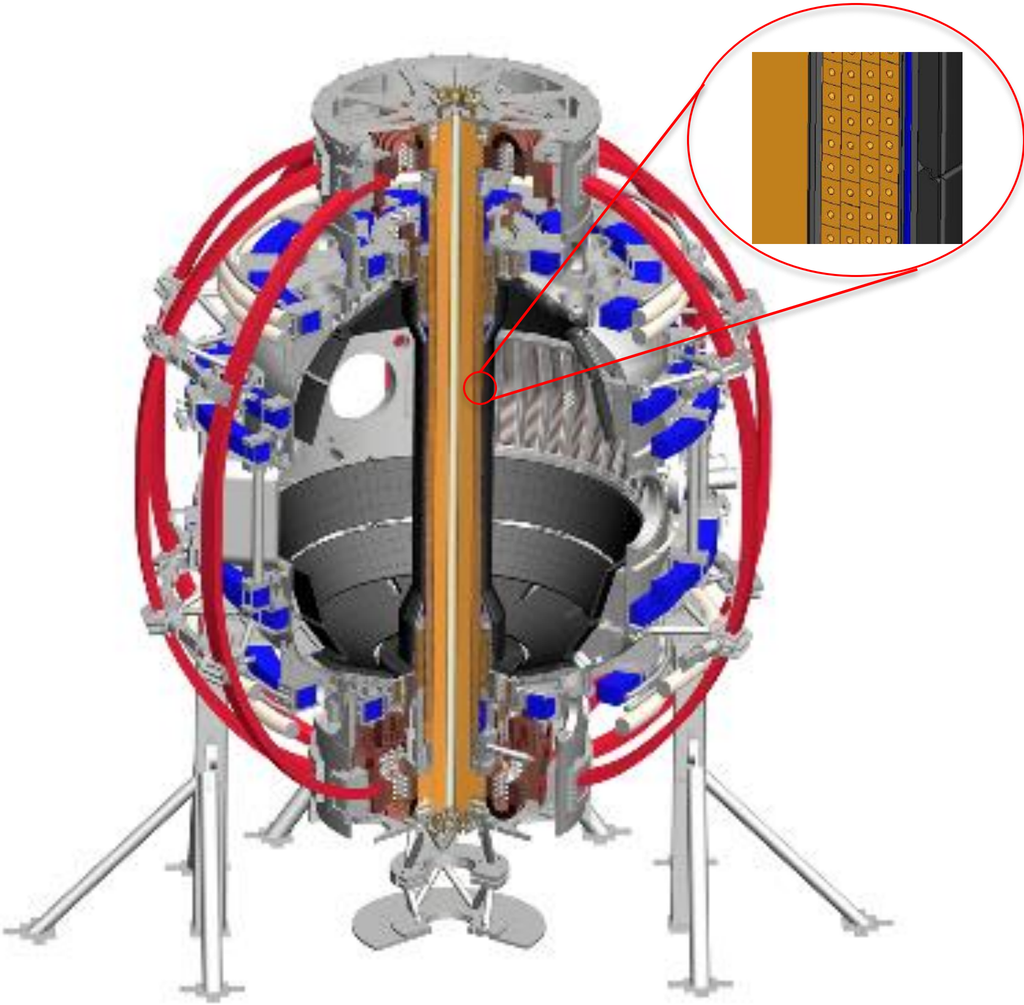


**Shaping coils**



# Plasma current induced through solenoid via transformer action (Faraday's law of induction)





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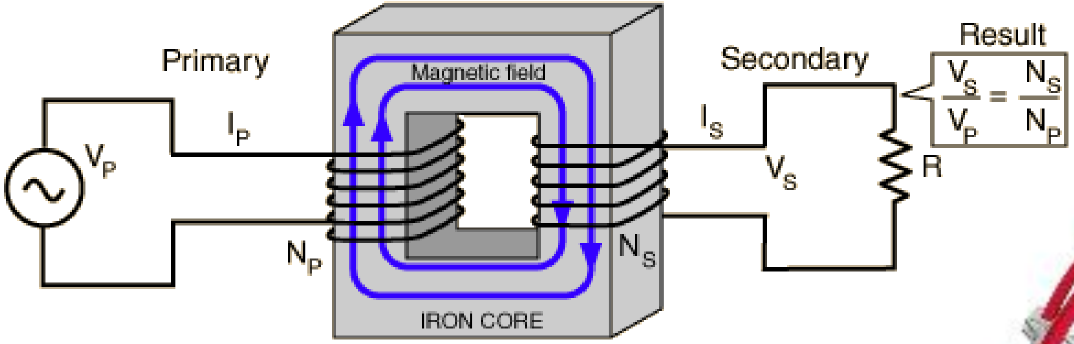
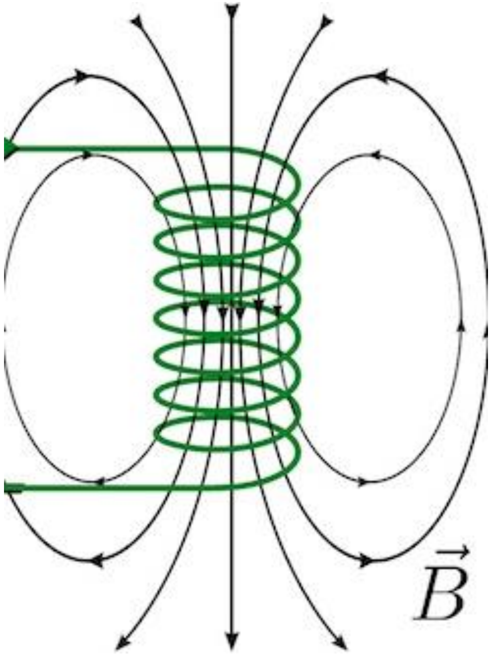
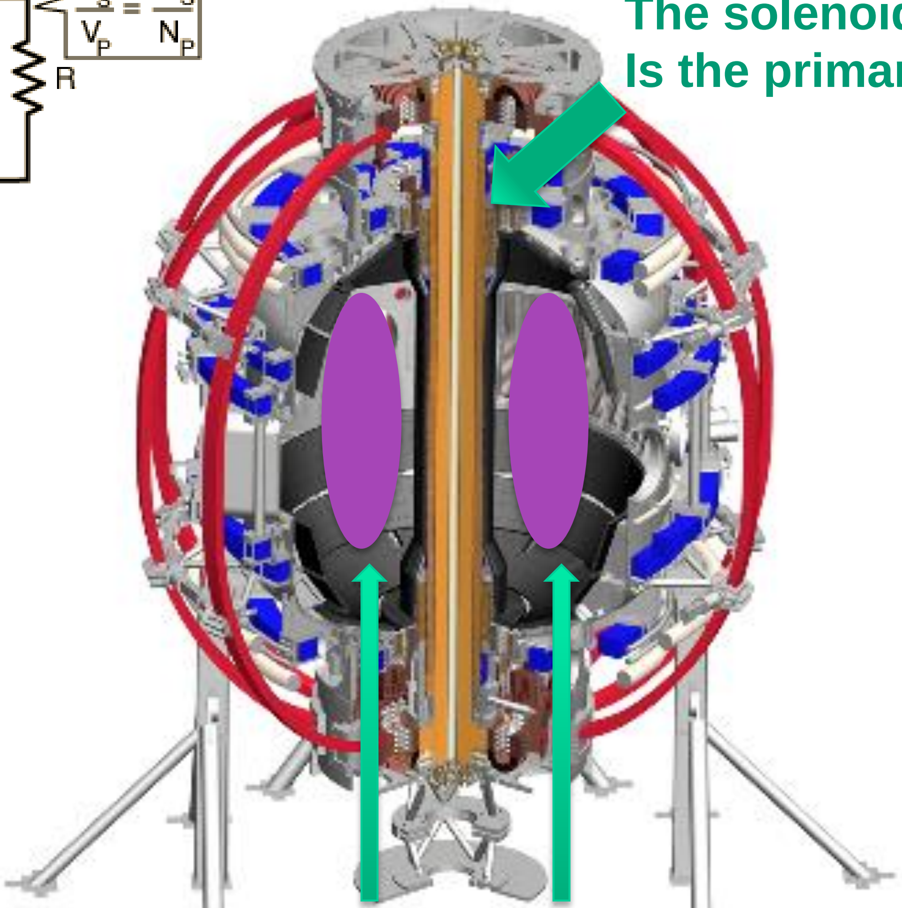


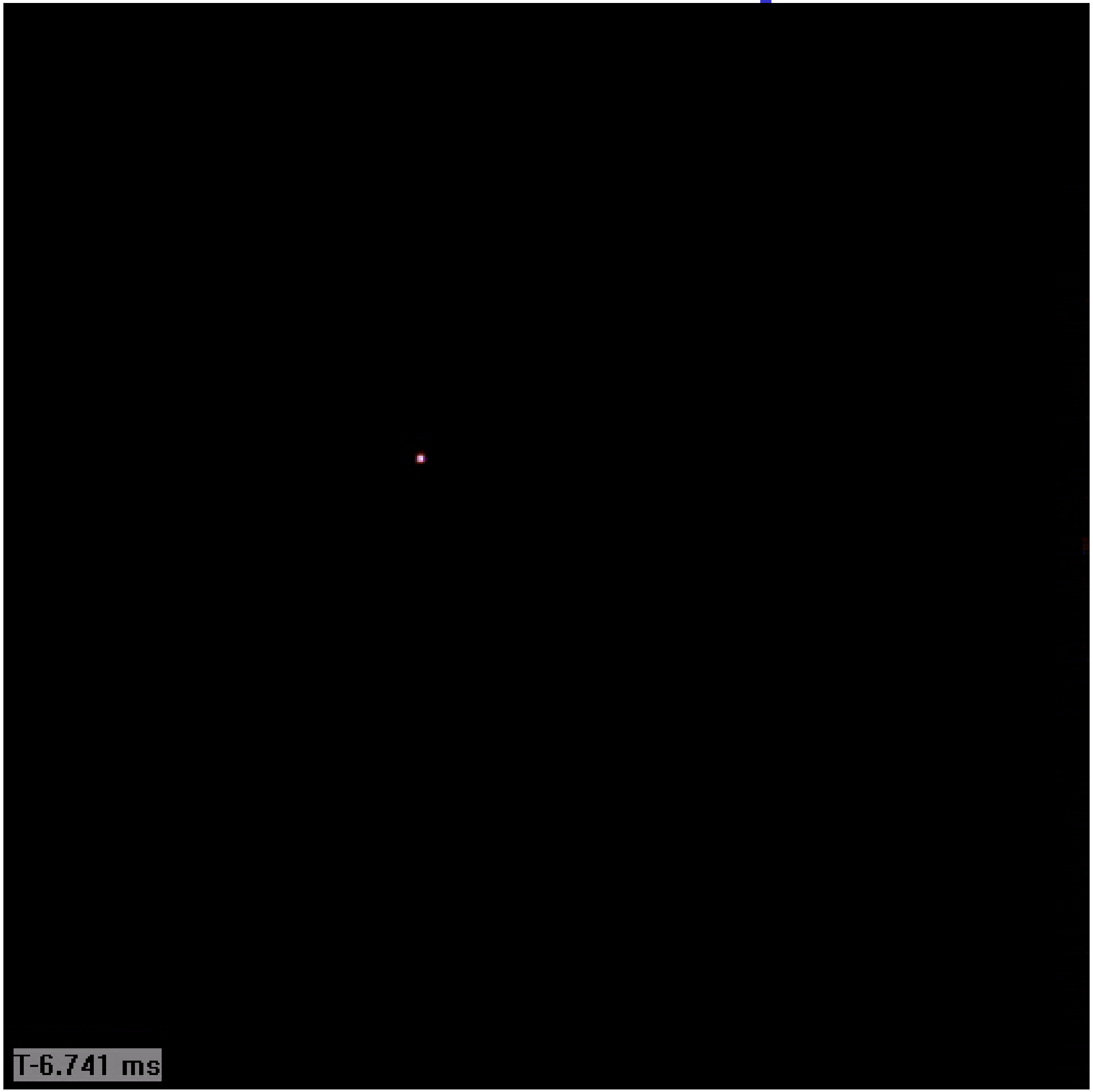




**The solenoid Is the primary**

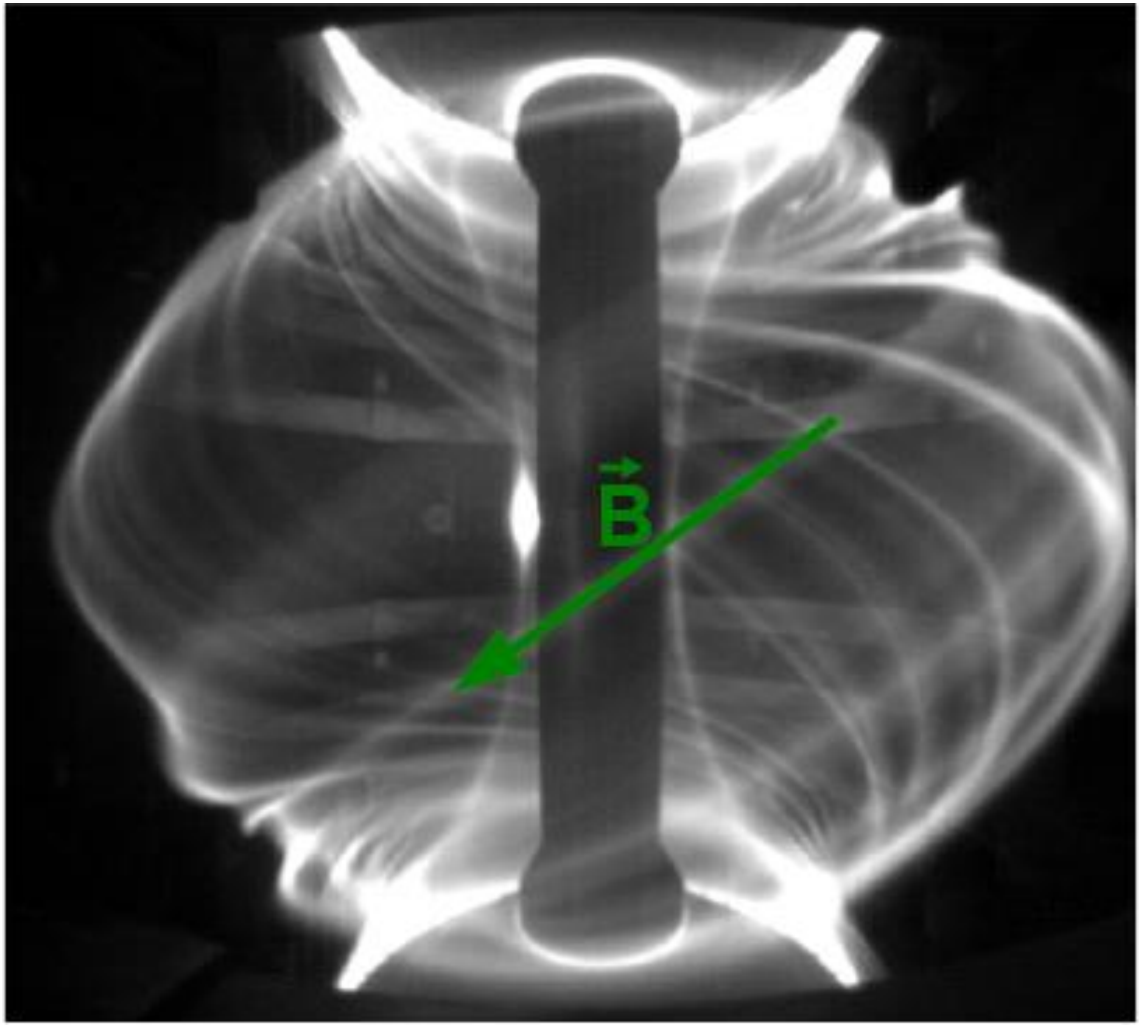
**The plasma is the secondary**

# Video of NSTX-U plasma



# Evidence of helical field seen in visible images of edge instabilities

MAST tokamak (UK)



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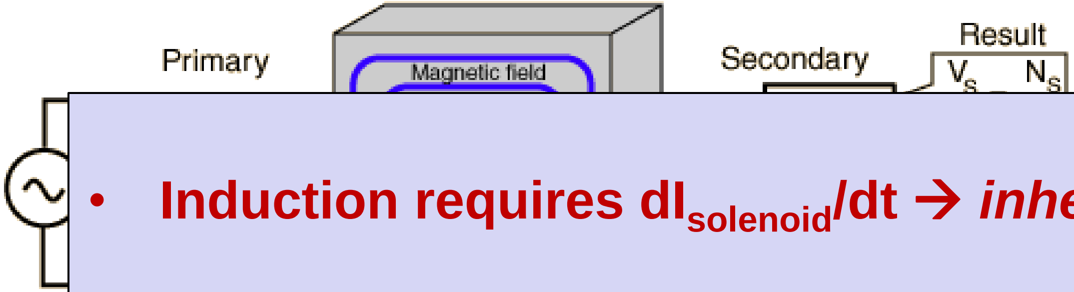
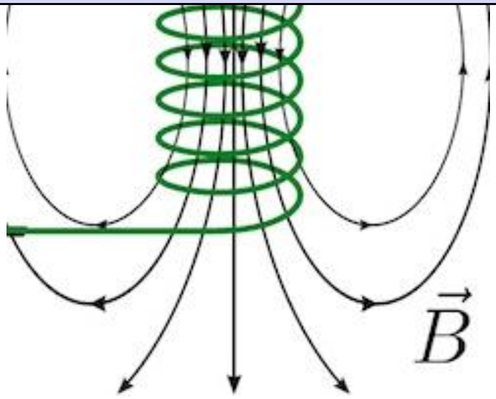
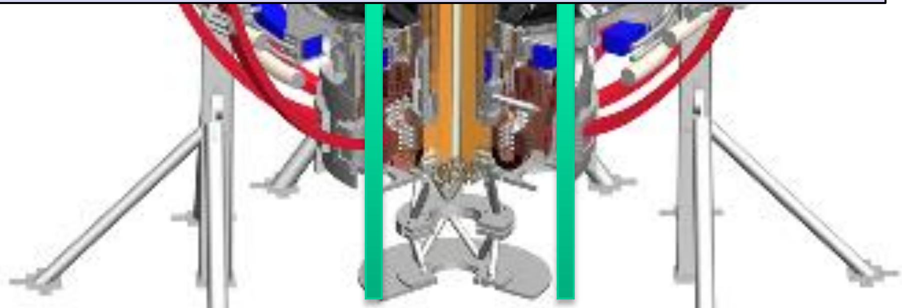


id
ary

- **Induction requires $dI_{solenoid}/dt$ → *inherently pulsed***
- **Steady-state tokamaks require 100% non-inductive current drive (external current drive + self-driven “bootstrap” current)**

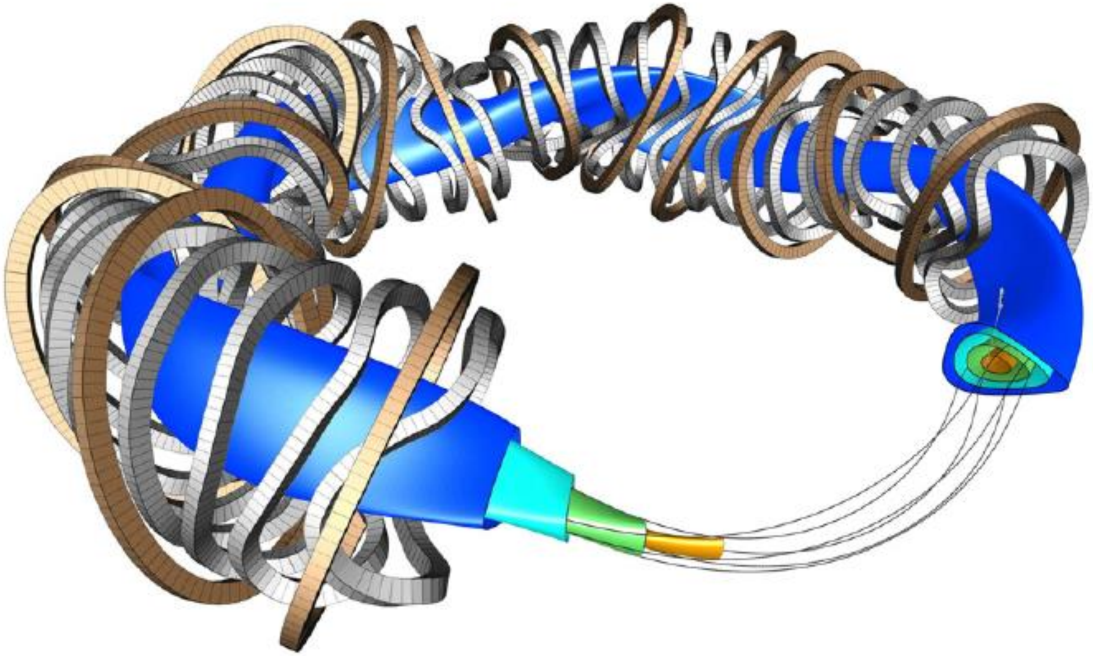




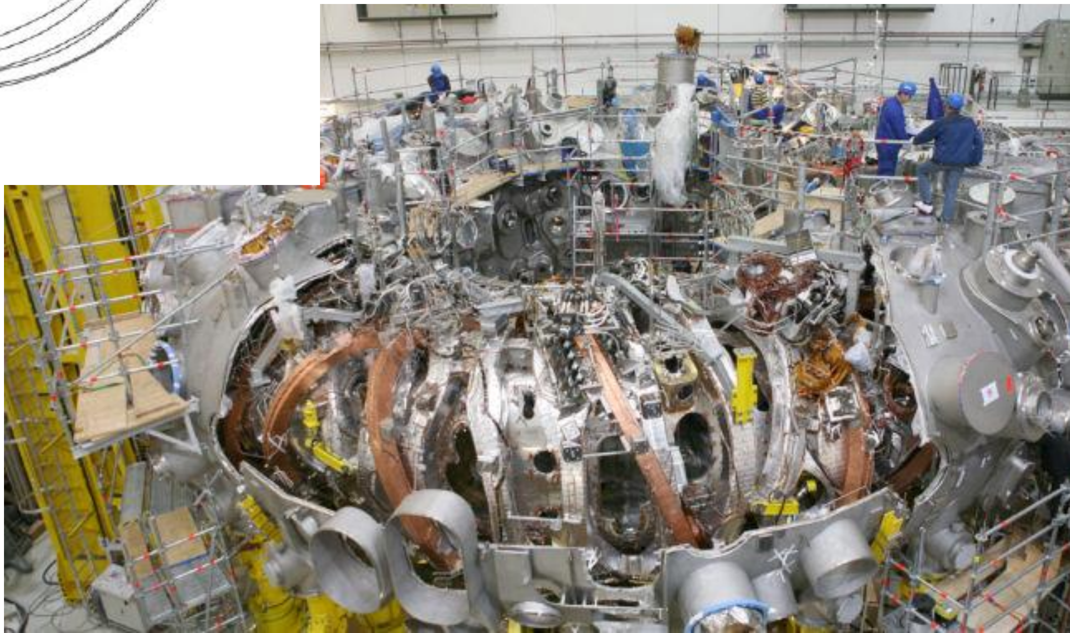
**The plasma is the secondary**

# Stellarator concept uses complex 3D coils to generate helical magnetic field without plasma current

**W7-X stellarator (Germany)**



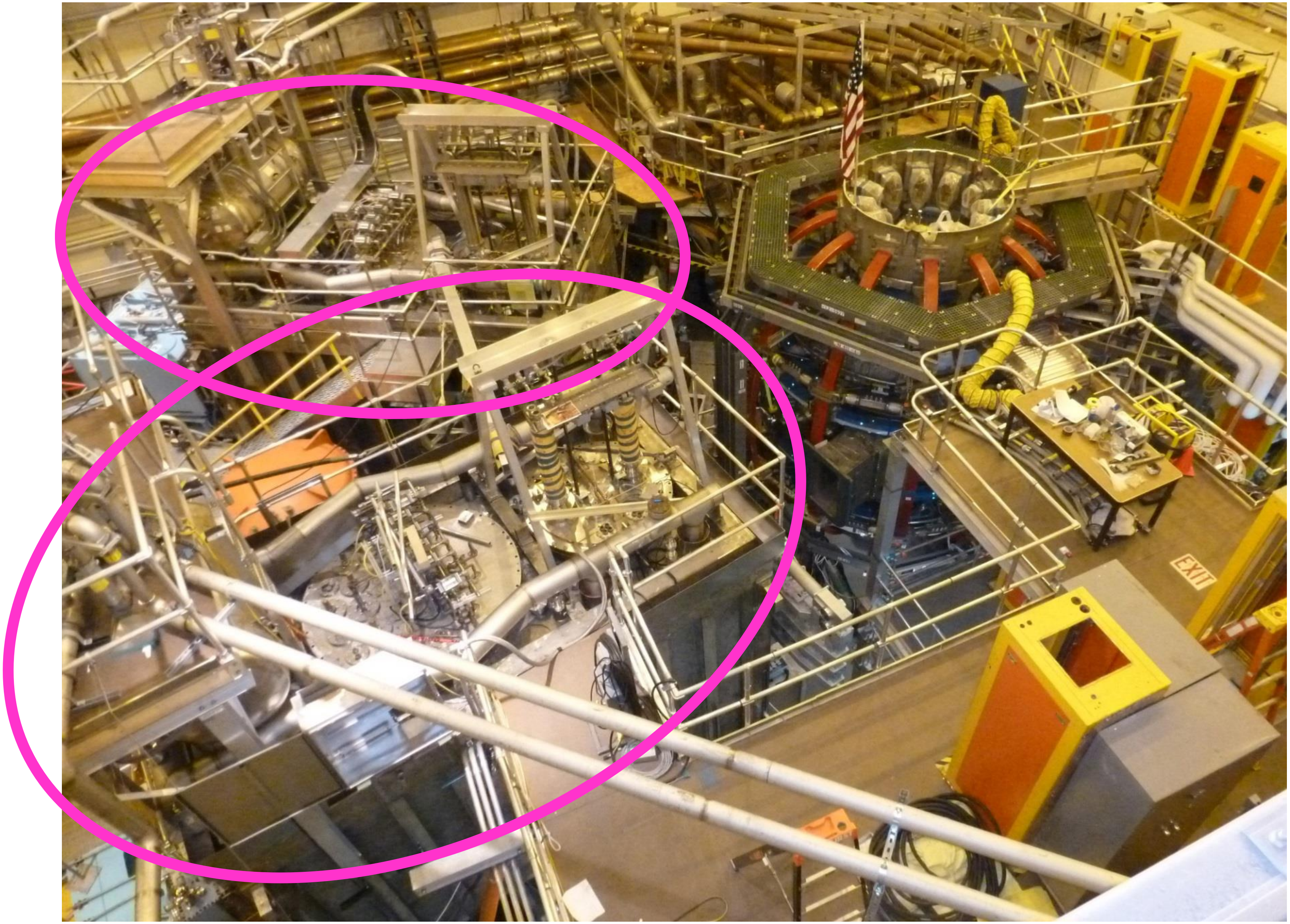
**Trading engineering complexity for inherent steady-state operation**



**More complicated BUT more degrees of freedom for performance optimization**

# We’ve created a magnetically confined plasma – how do we heat it?

# Mini particle accelerators (Neutral Beam Injectors) are used to heat the plasma



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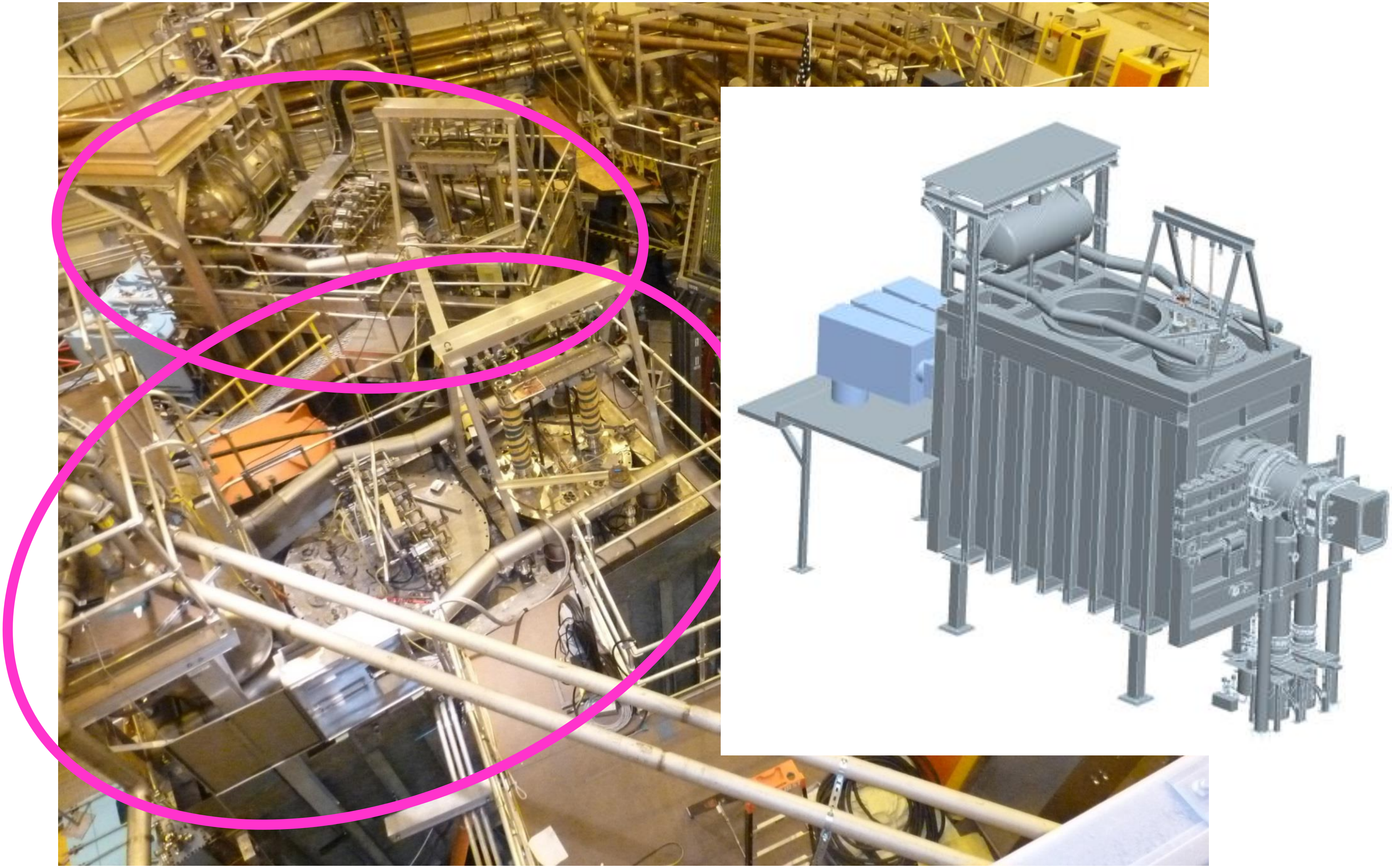
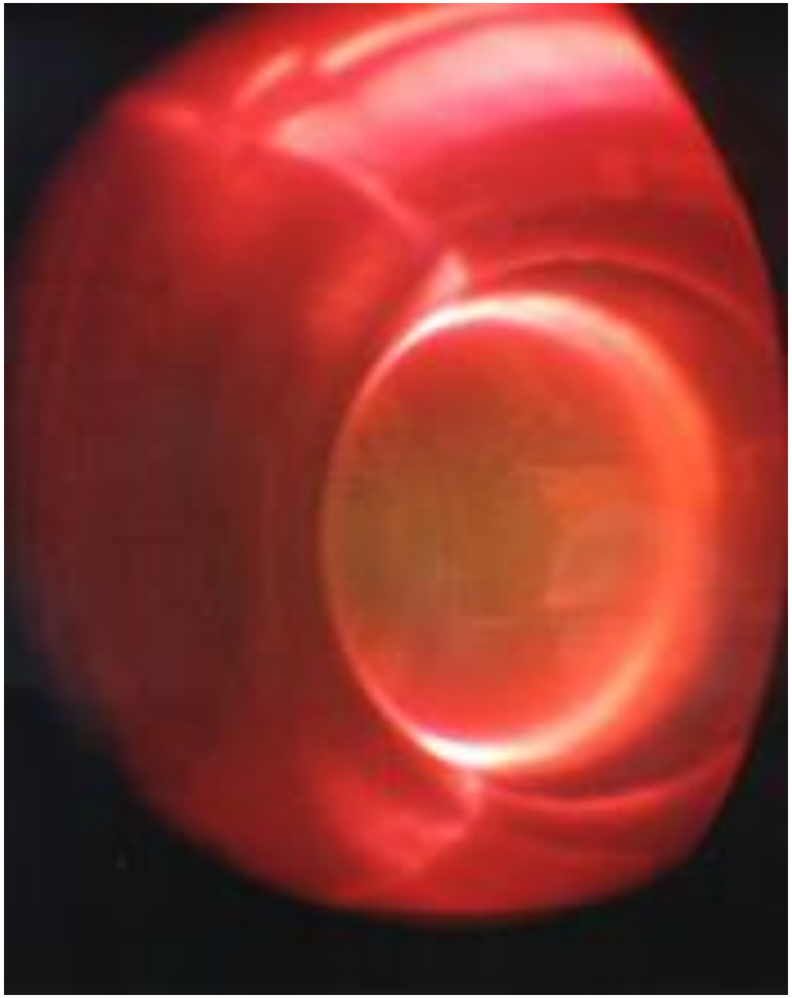


# Microwave heating is also used (works similar to microwave ovens)

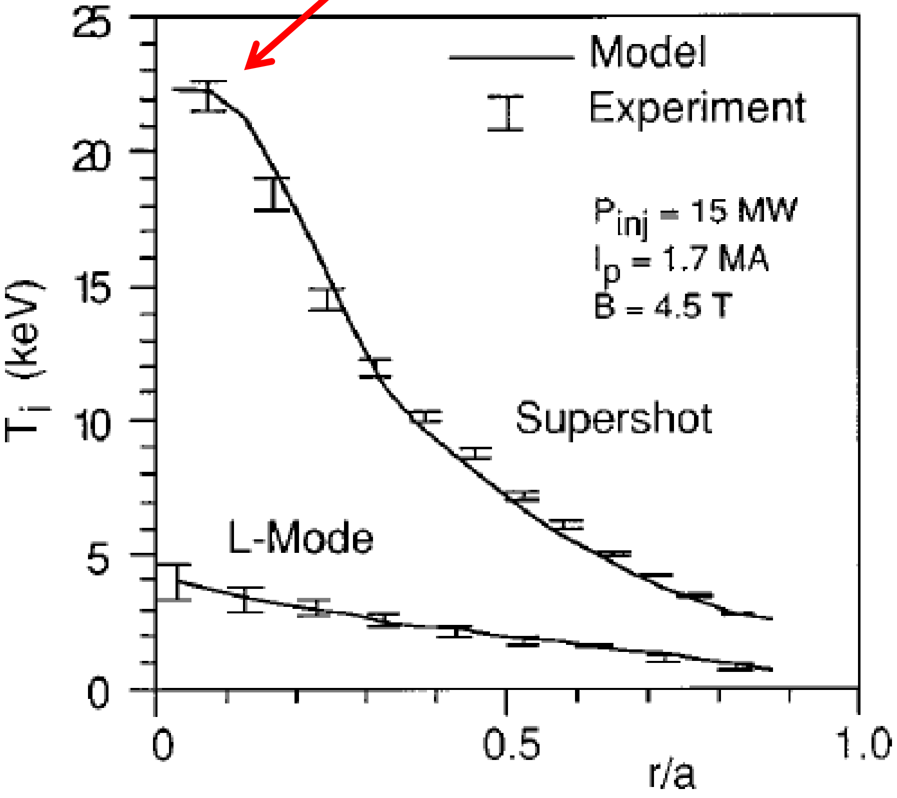
RF antenna

# Have achieved sufficient temperatures!

## Tokamak Fusion Test Reactor (PPPL, 1982-1997)



~250 million C

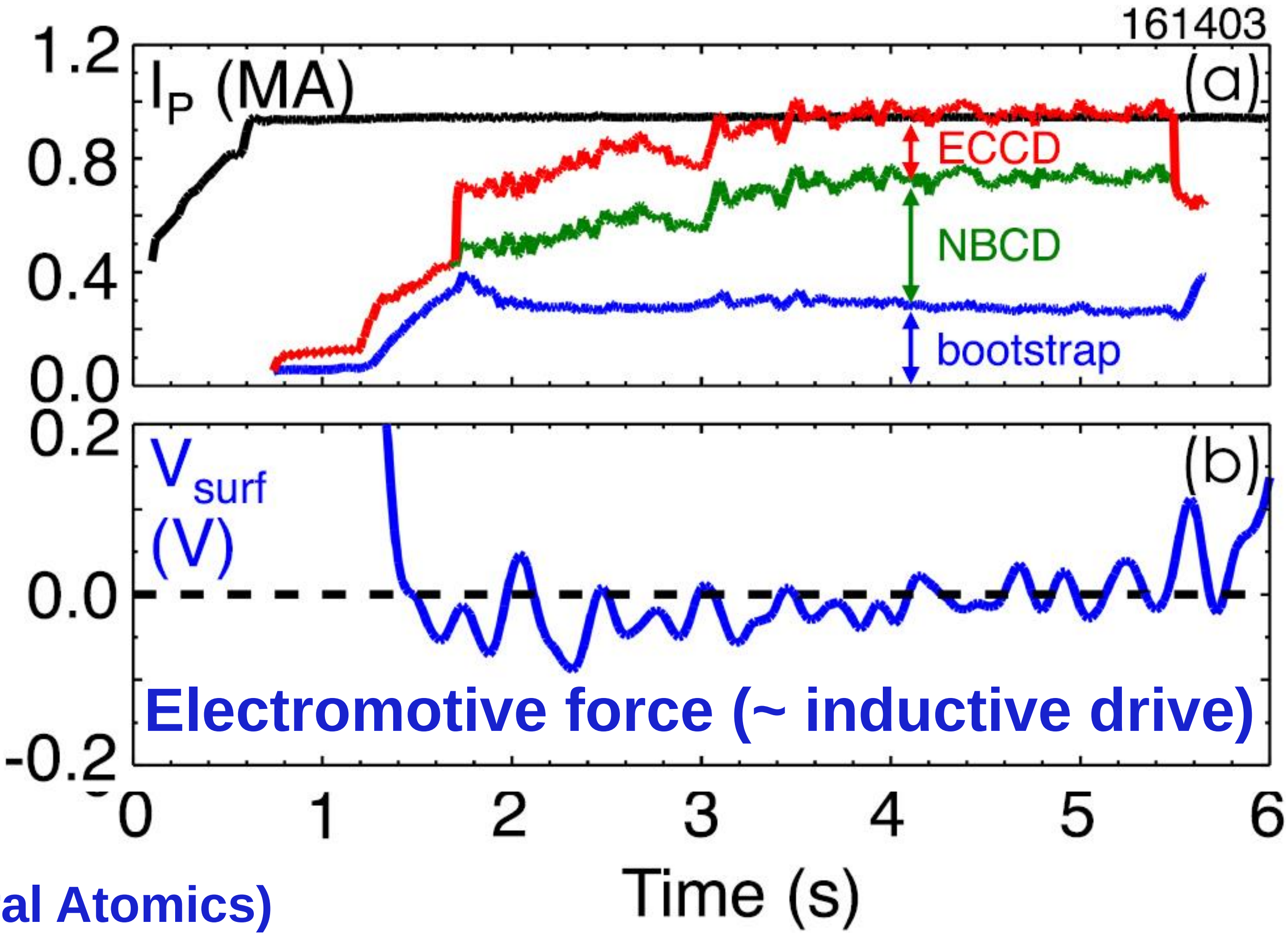


core

boundary

# NBI & RF also used to drive plasma current as part of 100% non-inductive scenarios

**Total plasma current = self-driven bootstrap current + NB current drive + RF current drive**



**Electromotive force (~ inductive drive)**

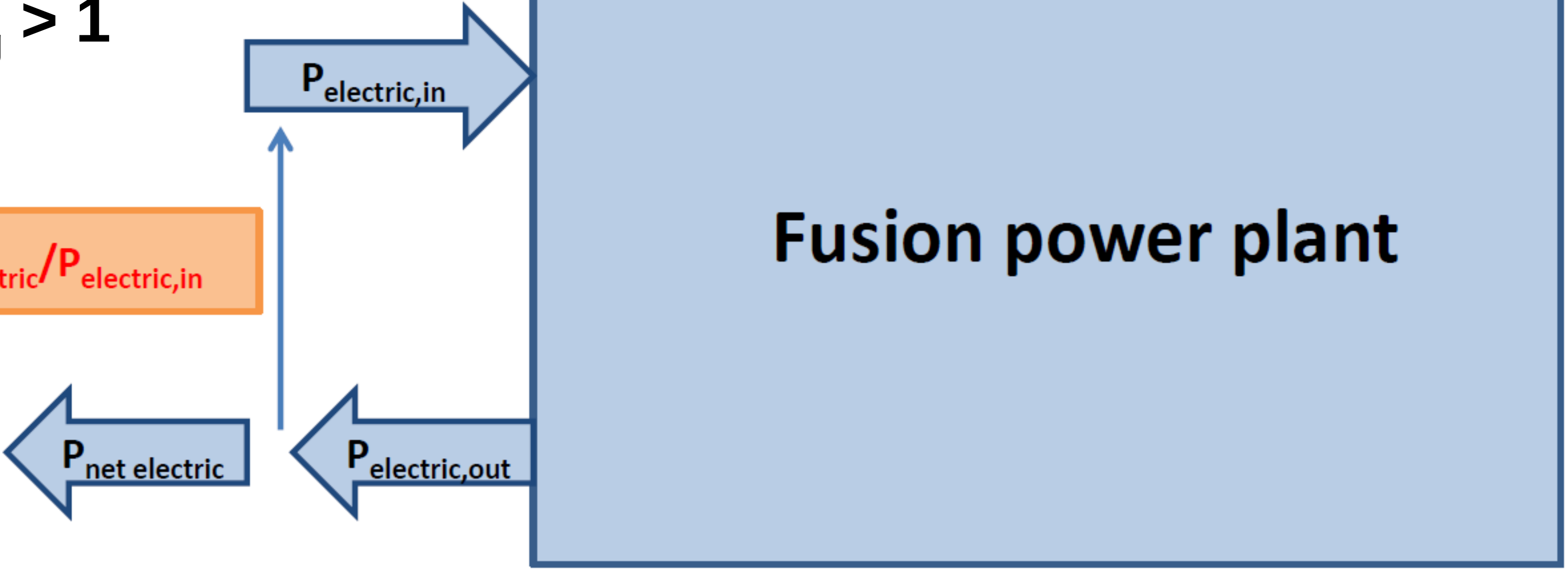
DIII-D (General Atomics)

# So what else do we need to make fusion <u>energy</u> a reality?

# Power balance in a fusion reactor

For net electricity, we need $Q_{eng} > 1$

$Q_{eng} = P_{net\ electric} / P_{electric,in}$



$P_{electric,in}$

Fusion power plant

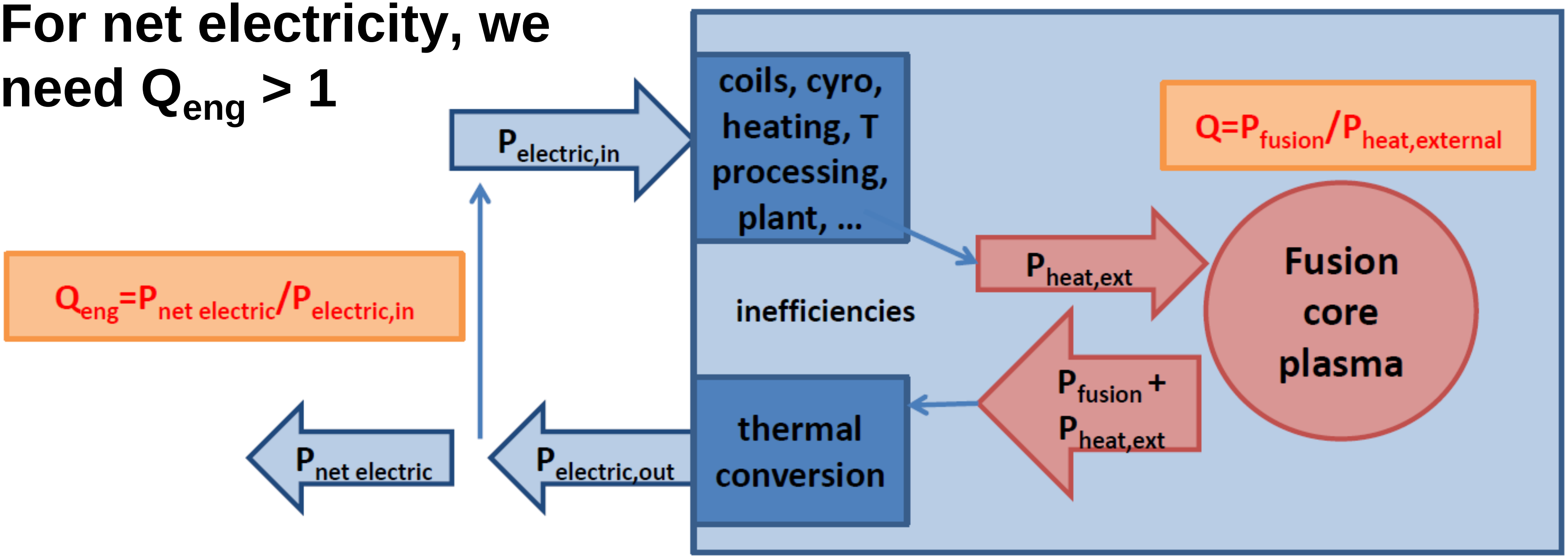
$P_{net\ electric}$

$P_{electric,out}$

# Power balance in a fusion reactor

**Typically requires a fusion gain Q >> 1 to account for thermal conversion, heating efficiency, cyro, plant, …**

**For net electricity, we need $Q_{eng} > 1$**



# Fusion gain depends on the “triple product” $nT\tau_E$

**Fusion plasma gain**

$$Q = \frac{P_{\mathrm{fusion}} \xrightarrow{\qquad} P_{\mathrm{fusion}} \sim (nT)^2 V}{P_{\mathrm{heat,external}}}$$

# Fusion gain depends on the “triple product” $nT\tau_E$

**Fusion plasma gain**

$$Q = \frac{P_{fusion}}{P_{heat,external}} \qquad P_{fusion} \longrightarrow P_{fusion} \sim (nT)^2 V$$

$$Q \sim (nT) \cdot \left( \frac{nTV}{P_{loss}} \right)$$

# Fusion gain depends on the “triple product” $nT\tau_E$

**Fusion plasma gain**

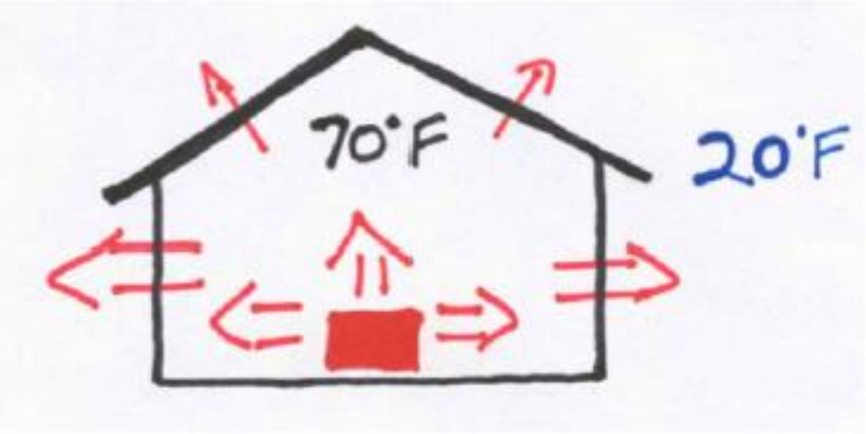
$$Q = \frac{P_{\text{fusion}}}{P_{\text{heat,external}}} \longrightarrow P_{\text{fusion}} \sim (nT)^2 V$$

$$Q \sim (nT) \cdot \left( \frac{nTV}{P_{\text{loss}}} \right)$$

$$\mathbf{Q \sim nT\boldsymbol{\tau}_E \sim p \cdot \boldsymbol{\tau}_E}$$

Energy confinement time: $\tau_E = \dfrac{\text{stored energy}}{\text{rate of energy loss}} \sim \dfrac{nTV}{P_{\text{loss}}}$

# Confinement time is a measure of how well insulated the plasma is from the surrounding boundary



$$\tau_E = \frac{\text{stored energy}}{\text{rate of energy loss}}$$

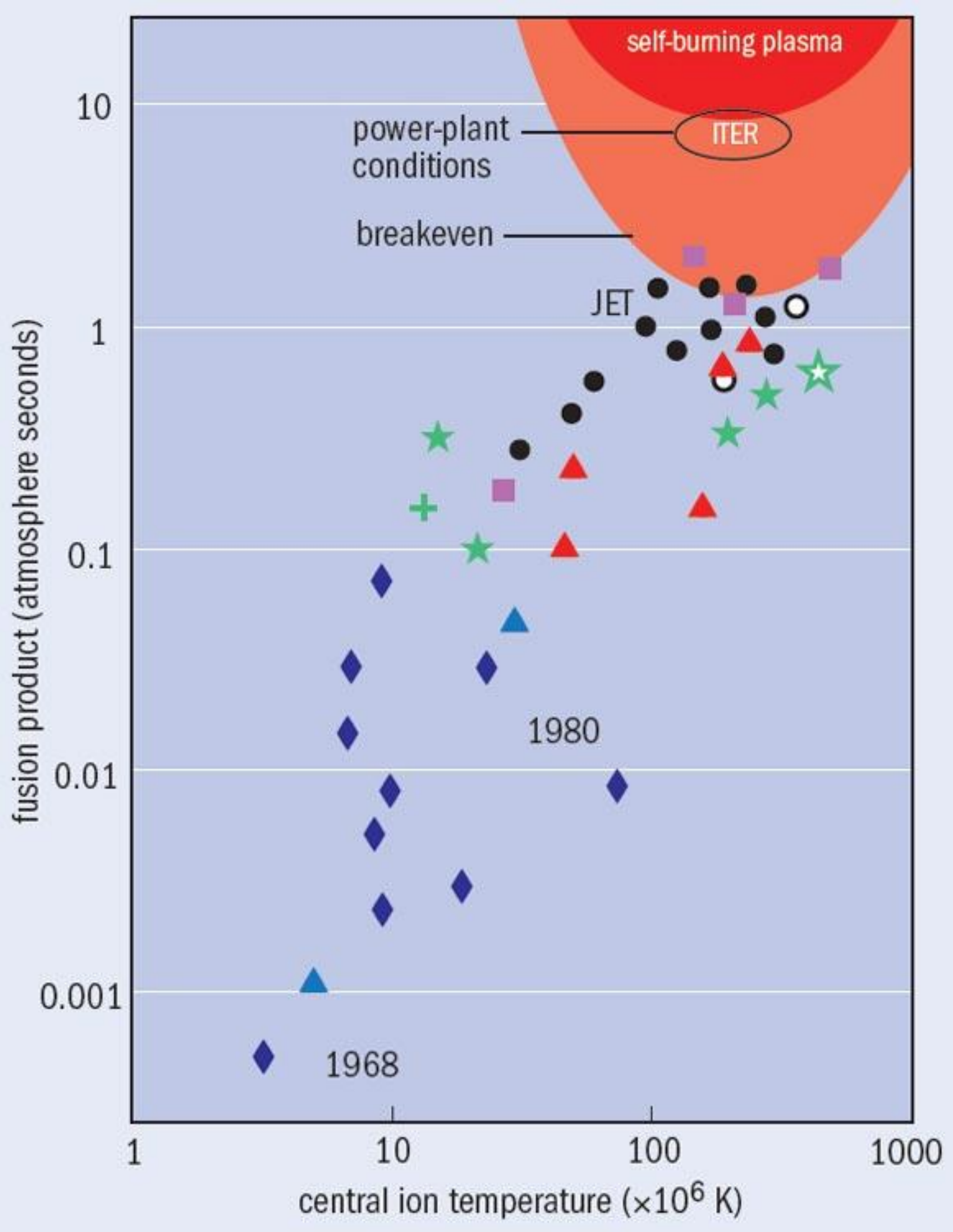
**For ignition (a self-sustaining, “burning plasma”)**

Q ~ $p \cdot \tau_E >$ 8 atm·s (at ~150 million C)

p ~ 2-4 × atmospheric pressure

$\tau_E$ ~ 2-4 seconds

# Have come very close to plasma "break-even" (Q=1)



<u>TFTR (PPPL, 1994)</u>

10.7 MW fusion power

46 MW heating power

**Q=0.23**

<u>JET (UK, 1997)</u>

16.1 MW fusion power

22 MW heating power

**Q=0.7**

# Next step: ITER is being built to study "burning plasmas"

- **Goal:** 500 MW fusion power using 50 MW heating power

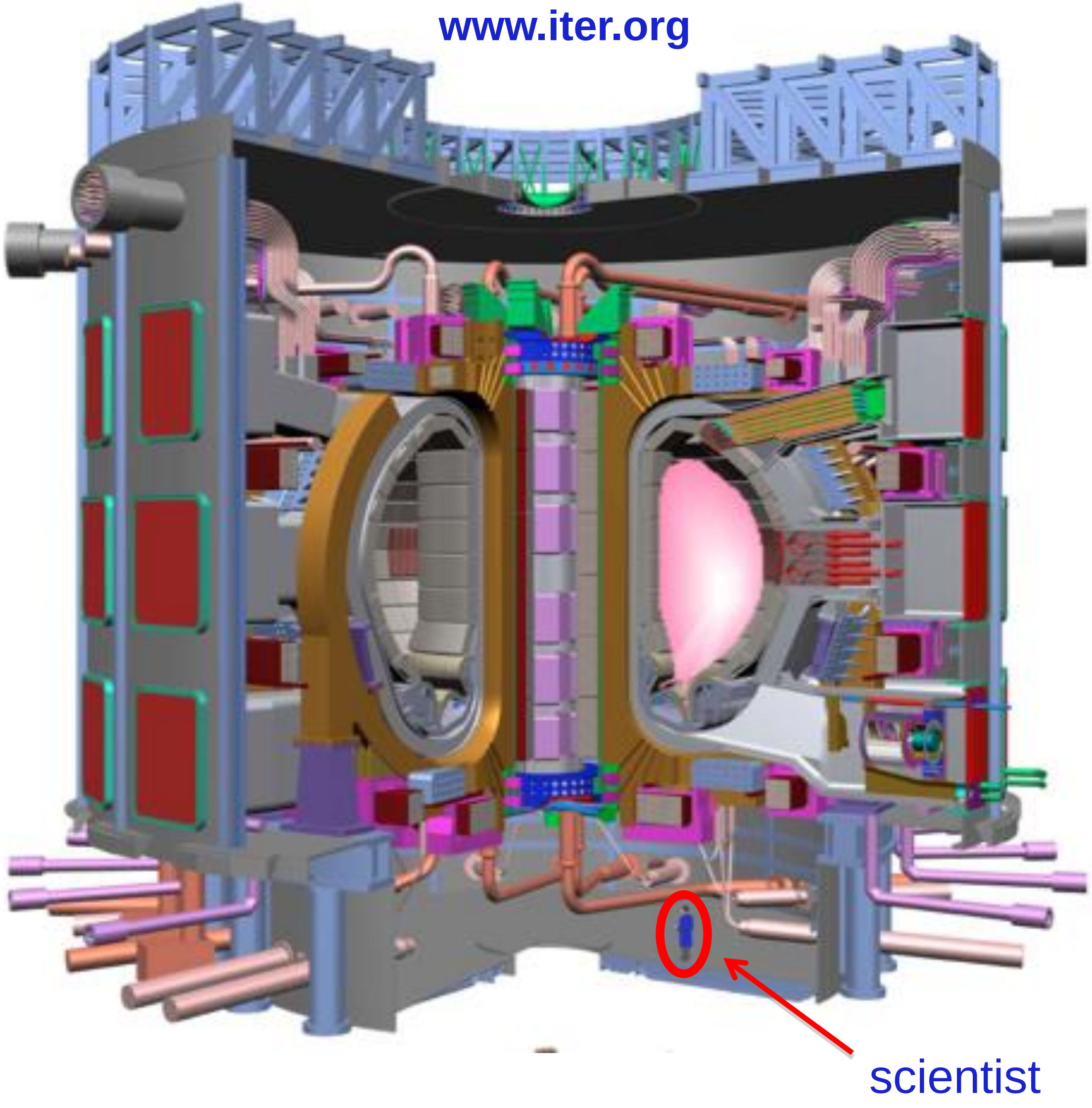
  **→large fusion gain Q = 10**

  Seven partners

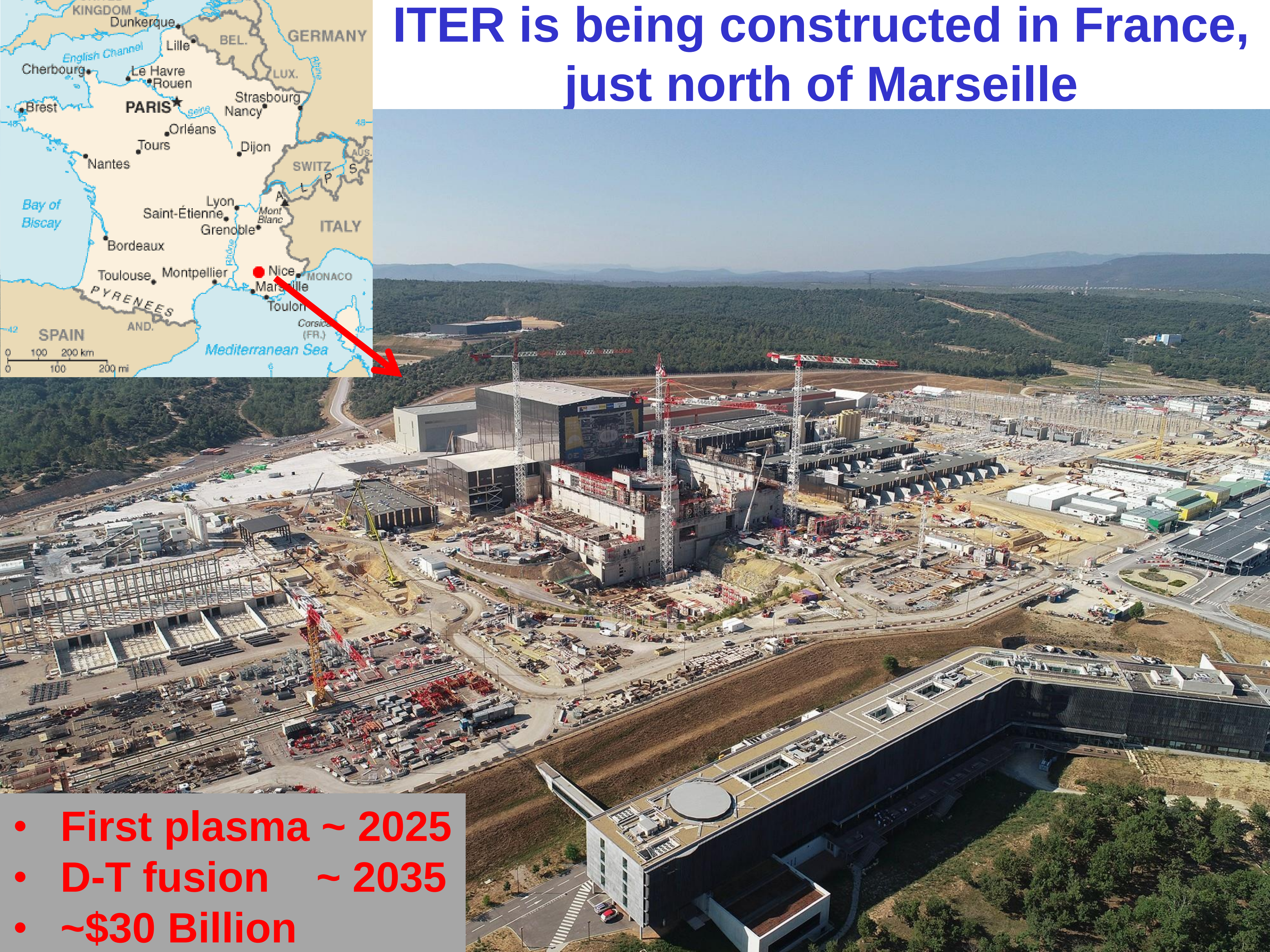
  China, EU, India, Japan, Korea, Russia, US

  R=6 m

  B=5.3 T, $I_p$=15 MA



# ITER is being constructed in France, just north of Marseille



- **First plasma ~ 2025**
- **D-T fusion ~ 2035**
- **~$30 Billion**

# Inside the tokamak pit (https://www.iter.org/album/construction)

# One toroidal field coil

# Not a bad place to visit!

***Lavender of Senanque***

***Les Beaux de Provence***

***Ocre cliffs of Rousillon***

***Wine is good and not too expensive***

# ITER will address a number of reactor relevant issues in an integrated fashion

- Demonstrate 500 MW fusion power for 400 sec, with large fusion power gain (Q=10)
- Study “burning plasma” regime ($P_\alpha > P_{heat,ext}$) with self-heating via energetic particles (3.5 MeV $\alpha$’s)
- Test tritium breeding
- Demonstrate safety characteristics of fusion device (has already obtained nuclear licensing)
- … *(and more)*

ITER & next-step power plant projections are big ($$)

What can we do to improve on this?

# Triple product (fusion gain) depends on stability, engineering and energy confinement

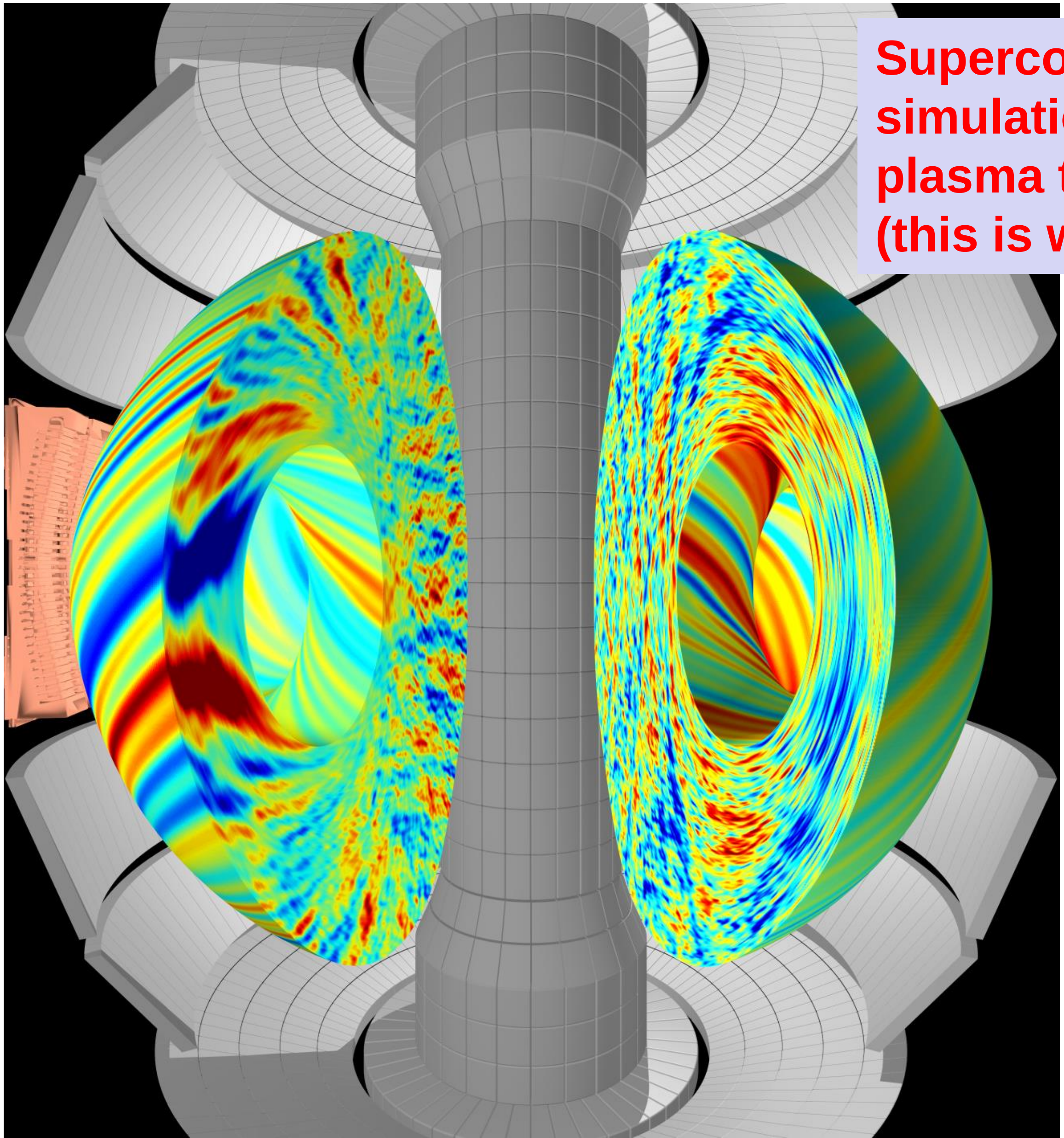
$$\boxed{\mathbf{Q \sim nT\tau_E \sim \beta \cdot B^2 \cdot \tau_E}}$$

- Plasma beta $\beta = nT/(B^2/2\mu_0)$ = plasma / magnetic pressure → limited to $\beta$~5-10% by macroscopic (MHD) stability constraints (e.g. need to avoid “disruptions”)

- Magnetic field strength B limited by superconductor technology ($B_{crit}$, $J_{crit}$) & mechanical stress limits

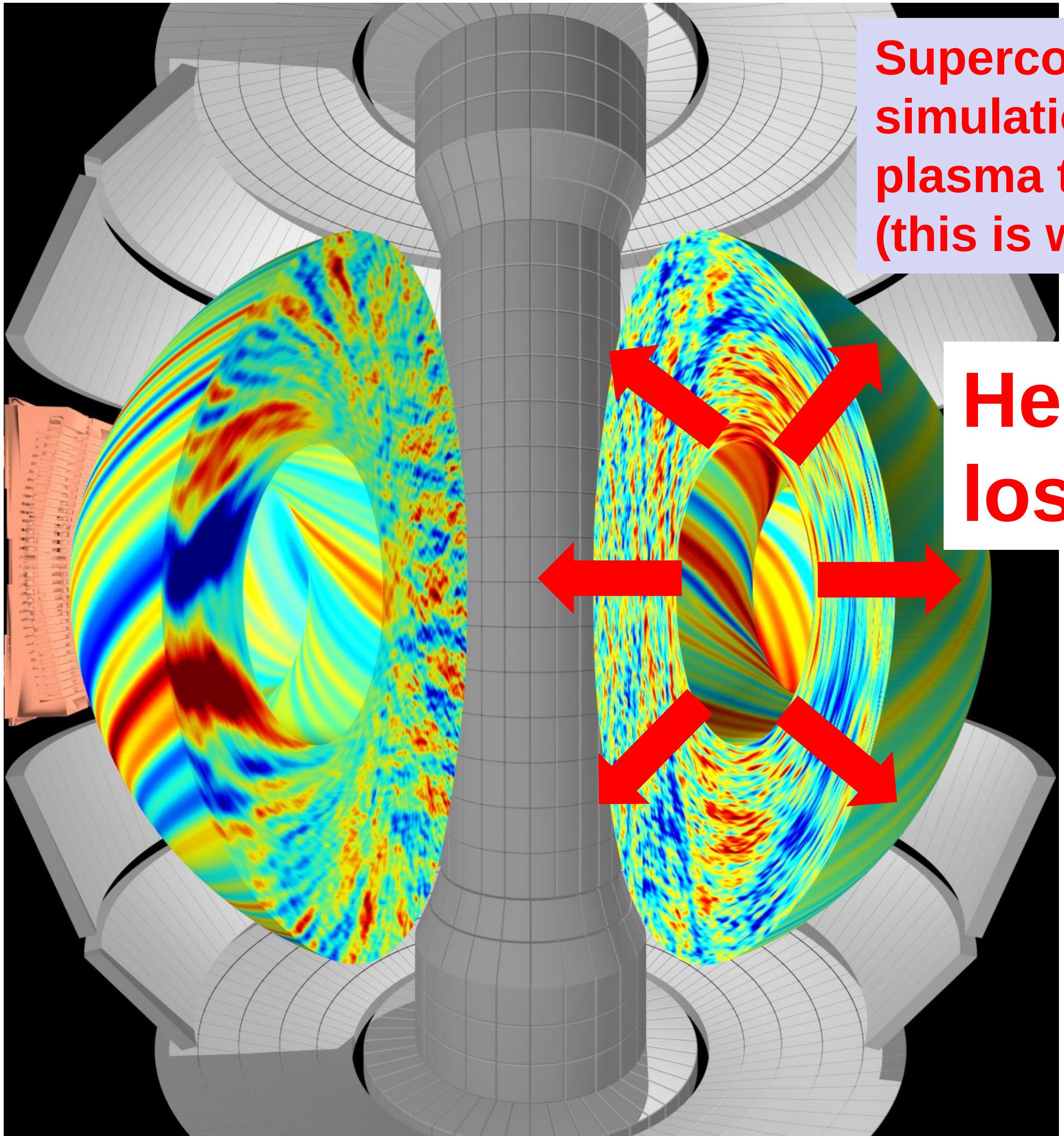
- $\tau_E$ limited by energy loss → dominated by turbulence

# Turbulence in the plasma can (unfortunately) be very efficient at flushing out energy



**Supercomputer simulation of plasma turbulence (this is what I do 🙂 )**

# Turbulence in the plasma can (unfortunately) be very efficient at flushing out energy



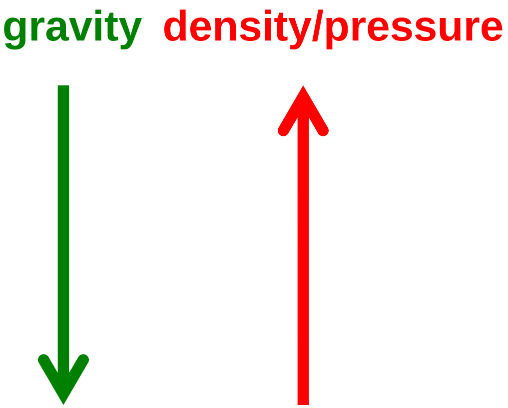
Supercomputer simulation of plasma turbulence (this is what I do 🙂 )

Heat loss

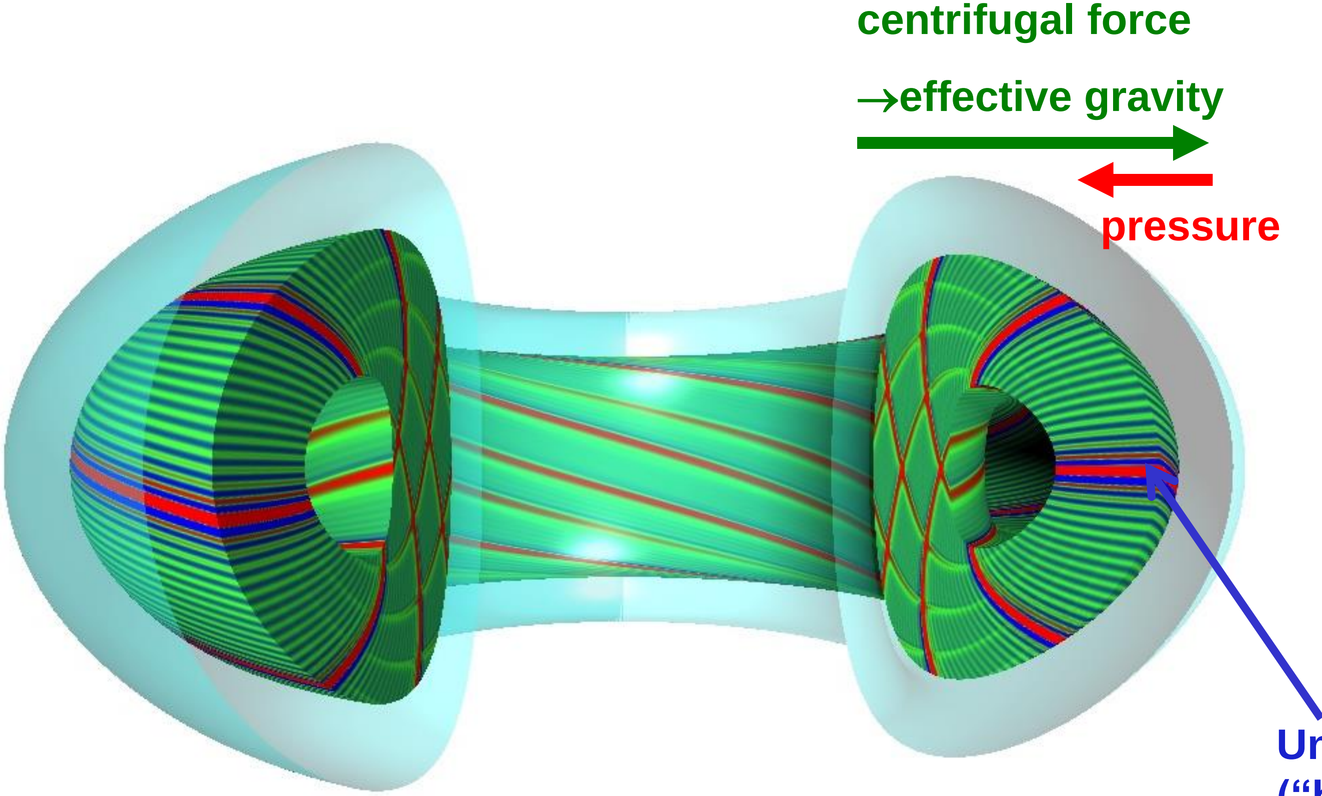
# Why does turbulence develop in tokamaks?

# Analogy for turbulence in tokamaks - density gradient in the presence of gravity

- Higher density on top of lower density, with gravity acting downwards (**Rayleigh-Taylor instability**)
- Any small perturbation becomes unstable
- Convection mixes regions of different density



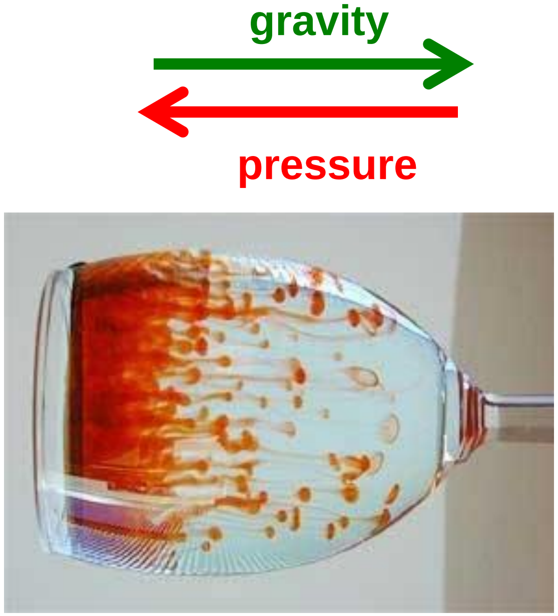
# Inertial (centrifugal) force in toroidal field acts like an effective gravity



centrifugal force

→effective gravity

pressure

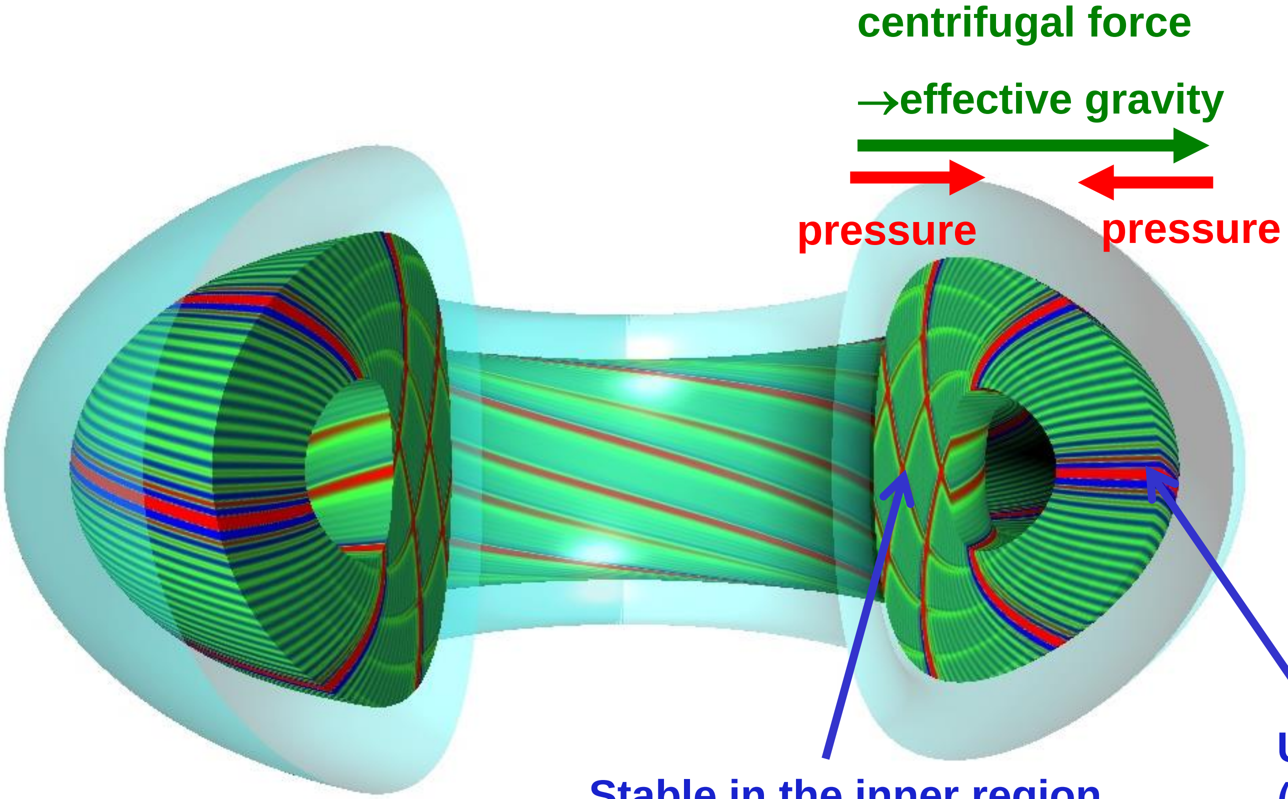


gravity

pressure

Unstable in the outer region
(“bad curvature”)

# Inertial (centrifugal) force in toroidal field acts like an effective gravity



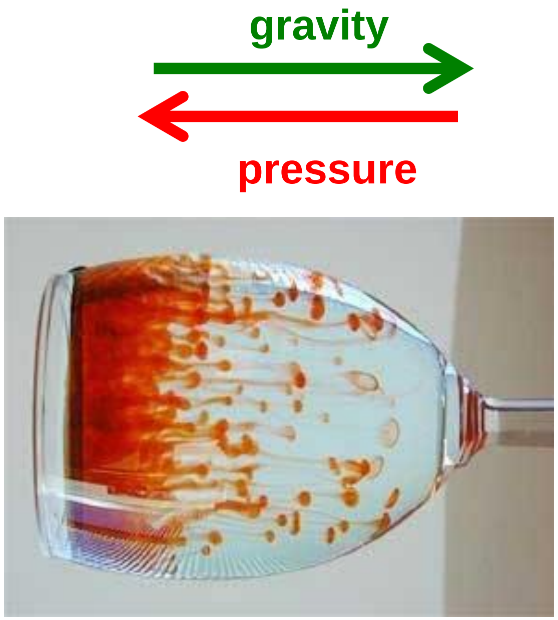
centrifugal force

→effective gravity

pressure

pressure

Stable in the inner region
("good curvature")



gravity

pressure

Unstable in the outer region
("bad curvature")

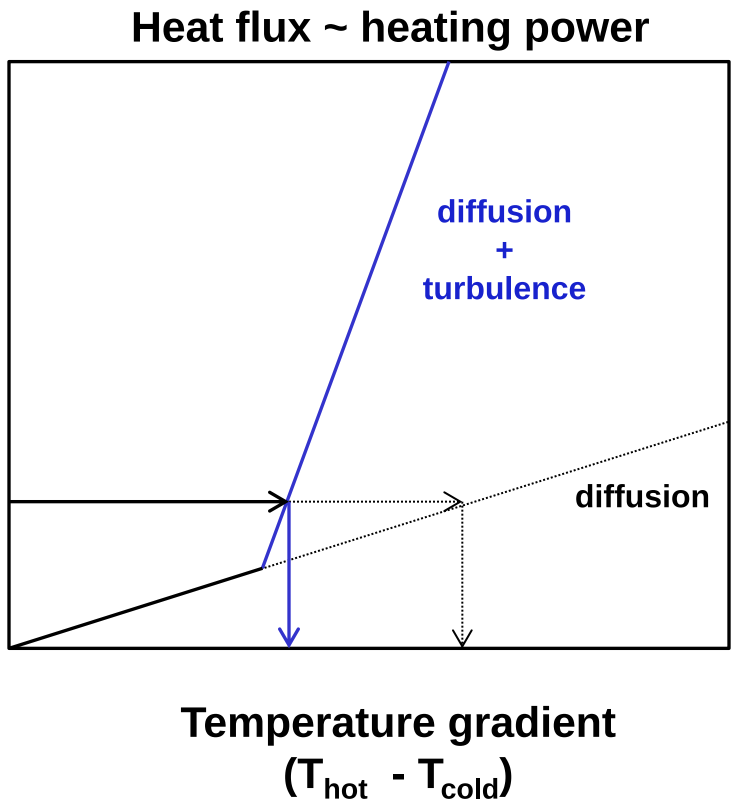
Fast parallel dynamics + helical field lines provides stability → gradient must surpass a threshold for instability

# DIII-D Shot 121717

GYRO Simulation

Cray X1E, 256 MSPs

# Onset of turbulence reduces the achieved temperature that would have been present due only to diffusion



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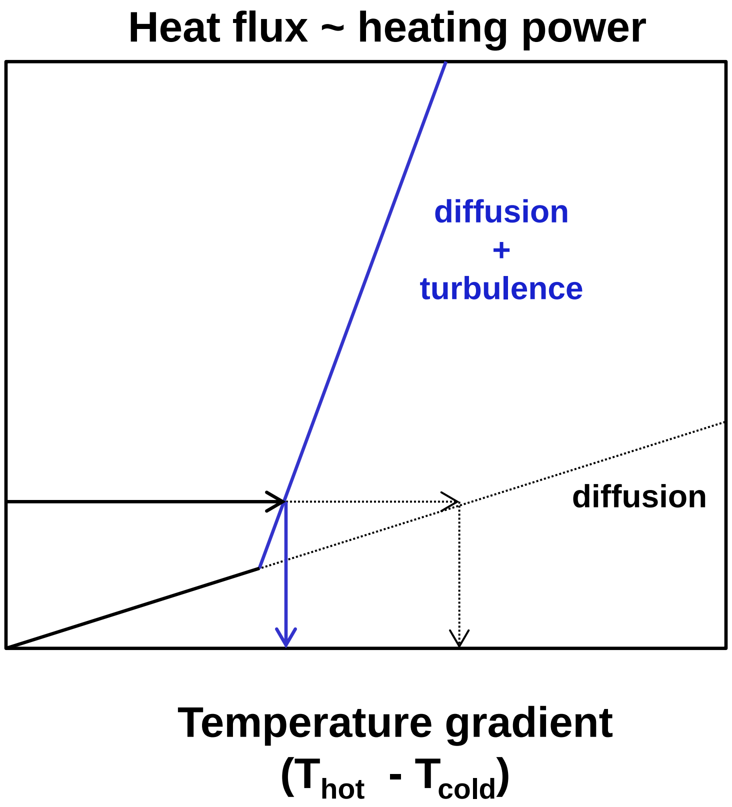


Analogous to convective transport when heating a fluid from below …
boiling water (before the boiling)

**Rayleigh, Benard instability**
**(early 1900's)**

# Numerous elements of US MFE research are actively addressing optimizing performance

$$\boxed{Q \sim nT\tau_E \sim \beta \cdot B^2 \cdot \tau_E}$$

- Refining operational scenarios to optimize beta, tau & steady-state (100% non-inductive) *simultaneously*
  - DIII-D (General Atomics, San Diego)

- Pursuing very high beta (~30-40%) at low aspect ratio
  - NSTX-U (PPPL) → low-A potentially useful as a compact volume neutron source for nuclear material qualification

- Pursing stronger magnetic fields: high temperature superconductors (HTS) enable larger $B_{crit}$, $J_{crit}$, $T_{crit}$
  - MIT & Commonwealth Fusion Systems (CFS – one of many privately funded fusion ventures)

# Challenges (& career opportunities) to help enable a future with fusion energy

- Steady state operation with good confinement → **plasma physics**

- Handling intense heat fluxes at plasma-material boundary → **plasma, chemistry & materials science**

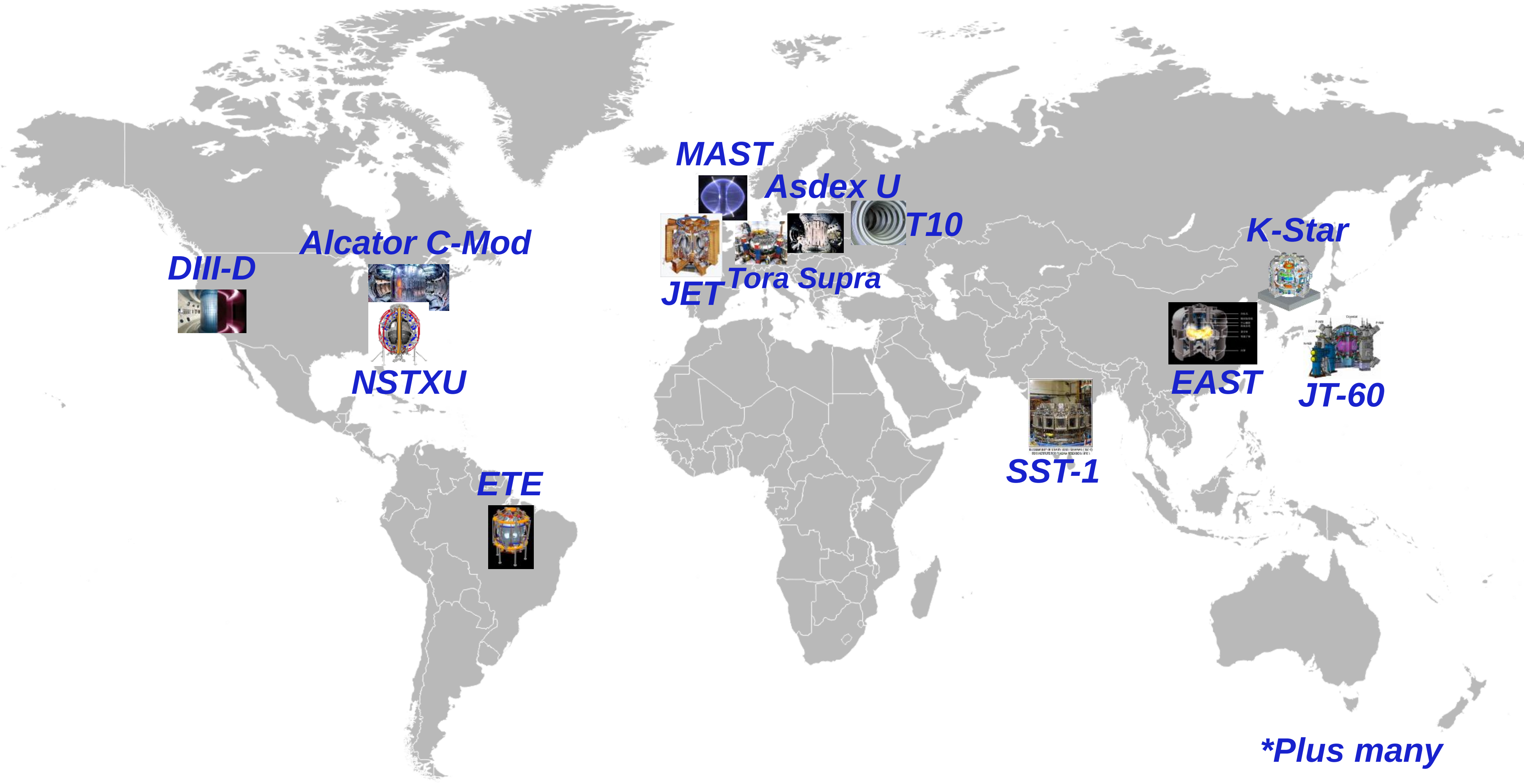
- Managing materials in a neutron environment & tritium breeding → **nuclear engineering**

- Better electromagnets → **superconductor R&D**

- Never-ending need for diagnostic development (**spectroscopy**, …), data analysis (**big data analysis, machine learning**, …), and just all around **good scientists & engineers**!

# Numerous tokamak, stellarator & other experiments are globally attacking these research topics

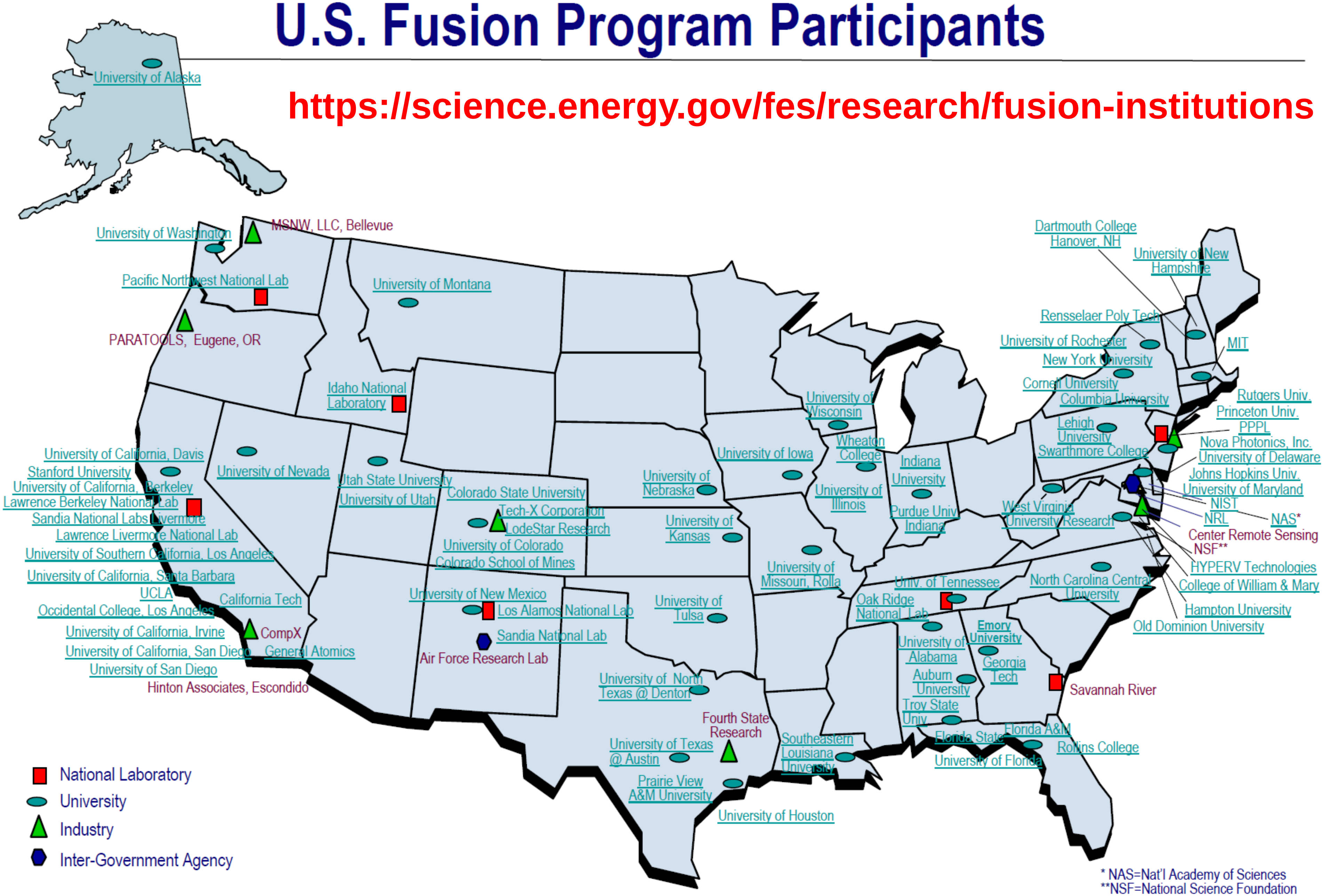
- **Lot's of fun places to visit / work** 😉



**Plus many more*

# U.S. Fusion Program Participants

https://science.energy.gov/fes/research/fusion-institutions



🟥 National Laboratory

⬭ University

▲ Industry

⬢ Inter-Government Agency

* NAS=Nat'l Academy of Sciences

**NSF=National Science Foundation

# U.S. Fusion Program Participants

https://science.energy.gov/fes/research/fusion-institutions

## DOE-funded undergraduate internships

- **Summer Undergraduate Laboratory Internship (SULI):** https://science.energy.gov/wdts/suli/
- **Community College Internship (CCI)**: https://science.energy.gov/wdts/cci/

- **Graduate Summer School** at PPPL for grad students from non-fusion programs (gss.pppl.gov)

# Summary

- Nuclear fusion offers a promising solution for clean energy, especially for growing global energy demands
- The progress in magnetic fusion energy research has been immense – ITER is the next evolution on-the-horizon!
- Numerous US and international institutions are focused on solving remaining challenges to bring fusion energy to the market – always looking for new, young talent!

# Thank you!

www.iter.org

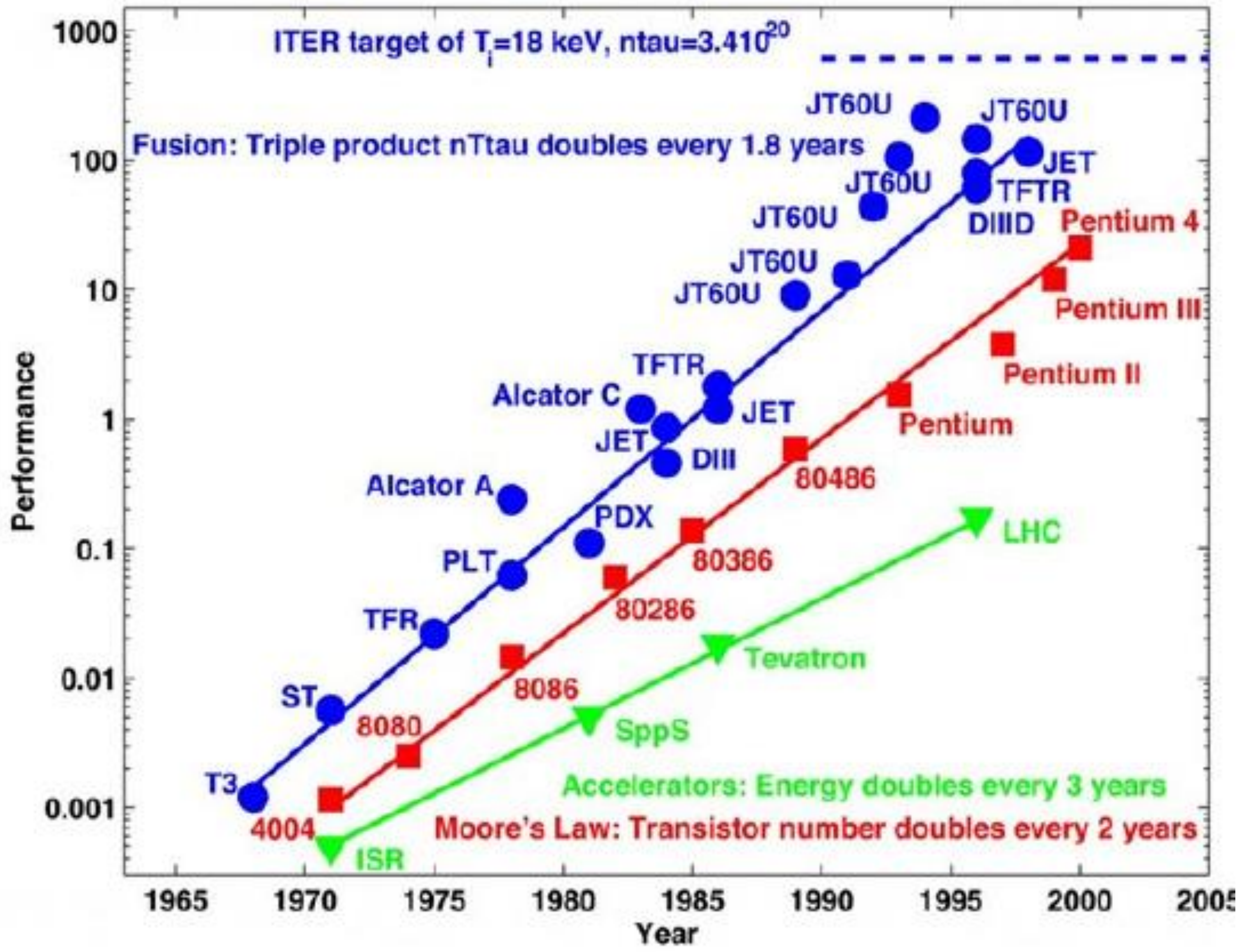
www.pppl.gov

science.energy.gov/wdts/suli/

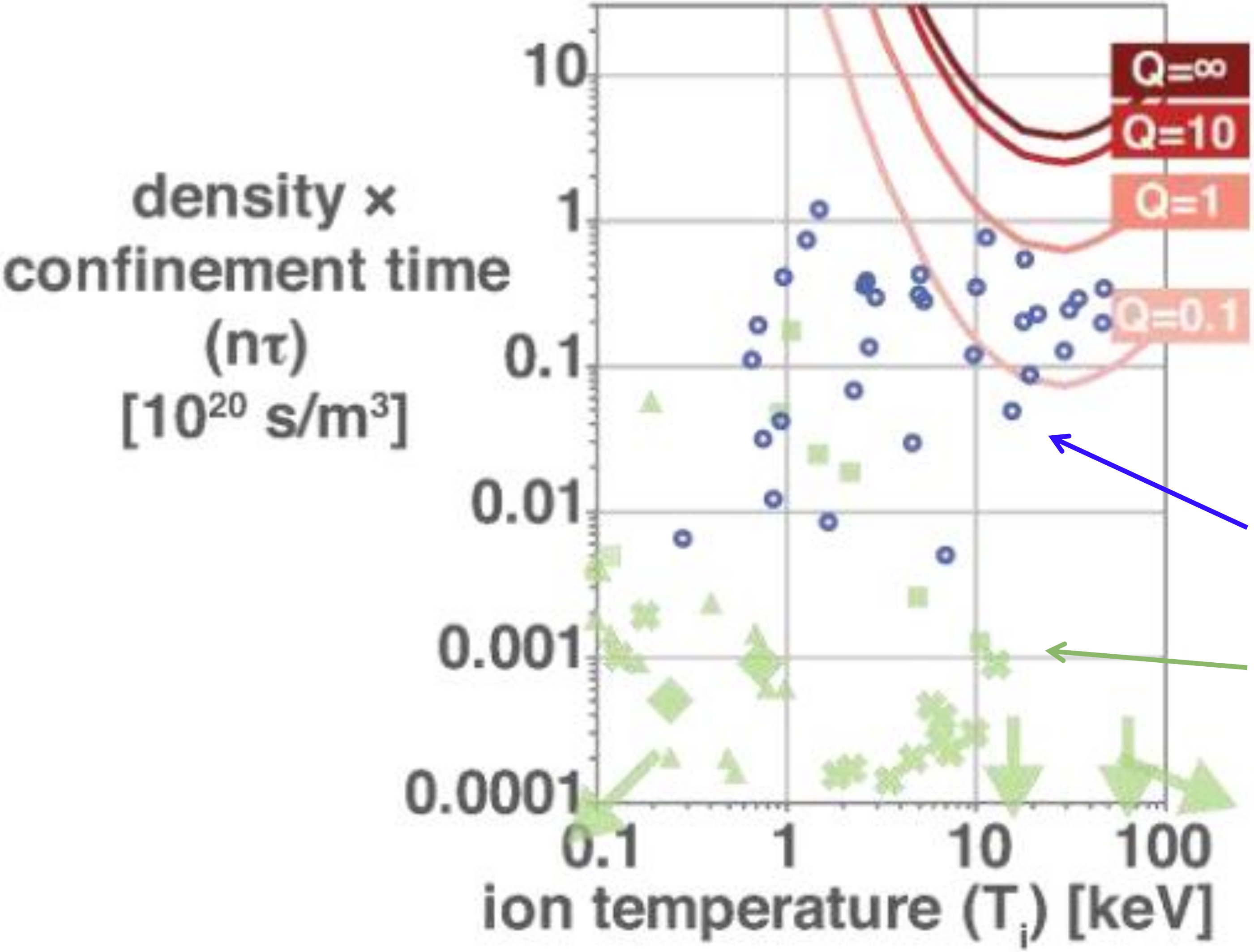
science.energy.gov/wdts/cci/

# BACKUP SLIDES

# Progress in achieved fusion performance outpaces (outpaced) Moore's Law



# Comparing fusion-relevant performance among different magnetic energy confinement configurations



**tokamaks**

**others**

Z. Hartwig (MIT)

# Princeton Plasma Physics Laboratory (PPPL) Plainsboro, New Jersey

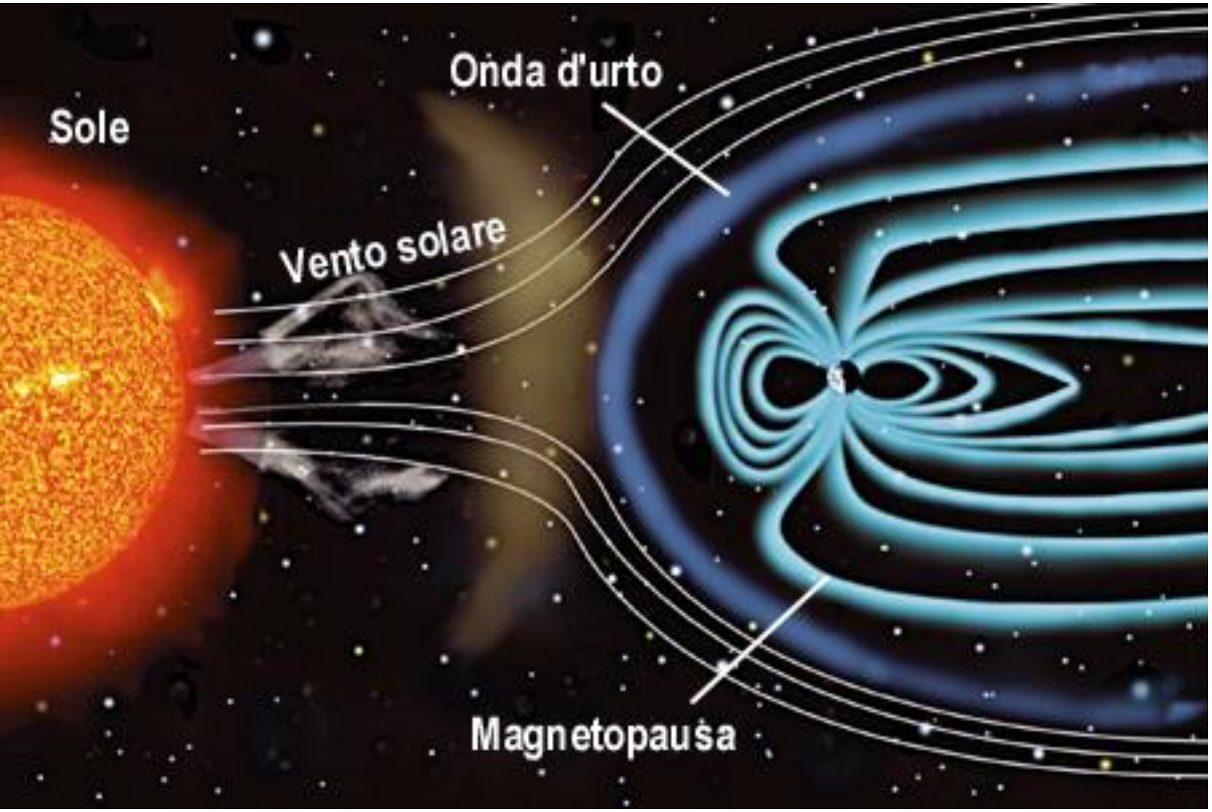
90 acres, ~450 employees
Originally called “Project Matterhorn” (1951)

At PPPL, we try to understand many aspects of plasmas

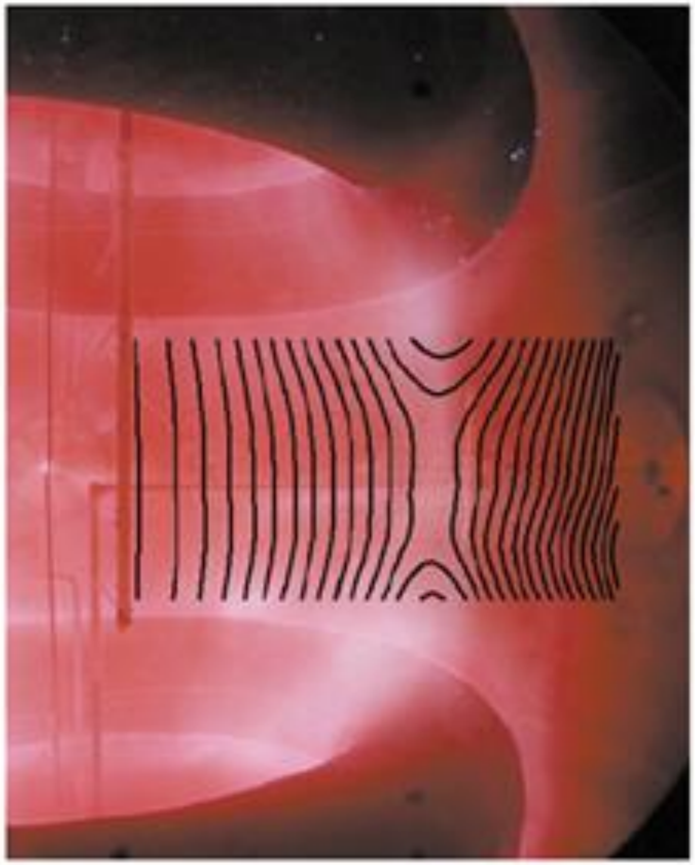
For example…

# Experiments to study astrophysical "reconnection" (solar flares)

- Laboratory experiment to mimic interaction of solar flare impinging on earths magnetic field (relevant to telecommunications)

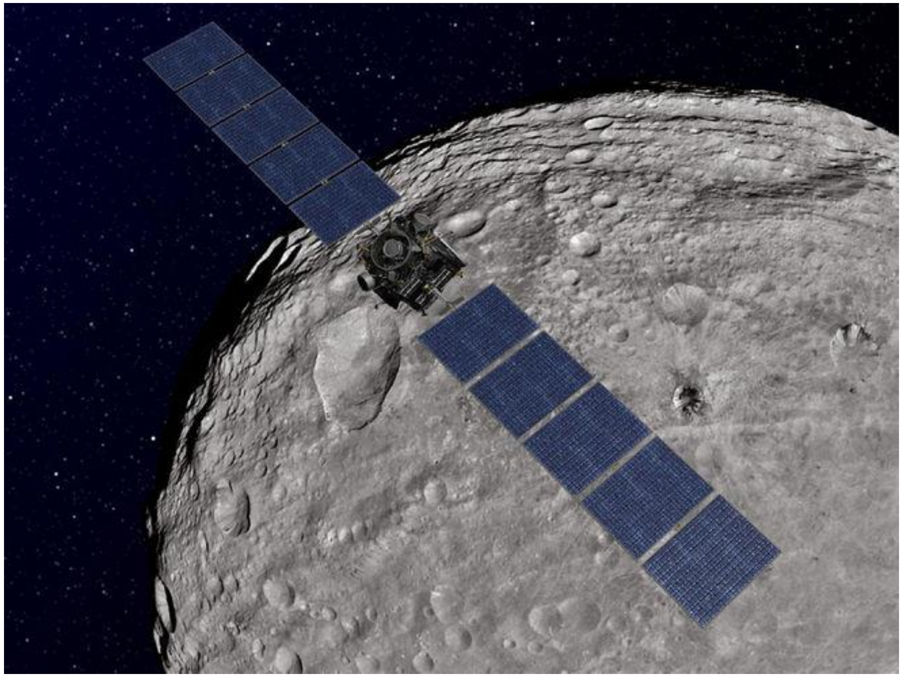


**MRX**
**Magnetic Reconnection Experiment**

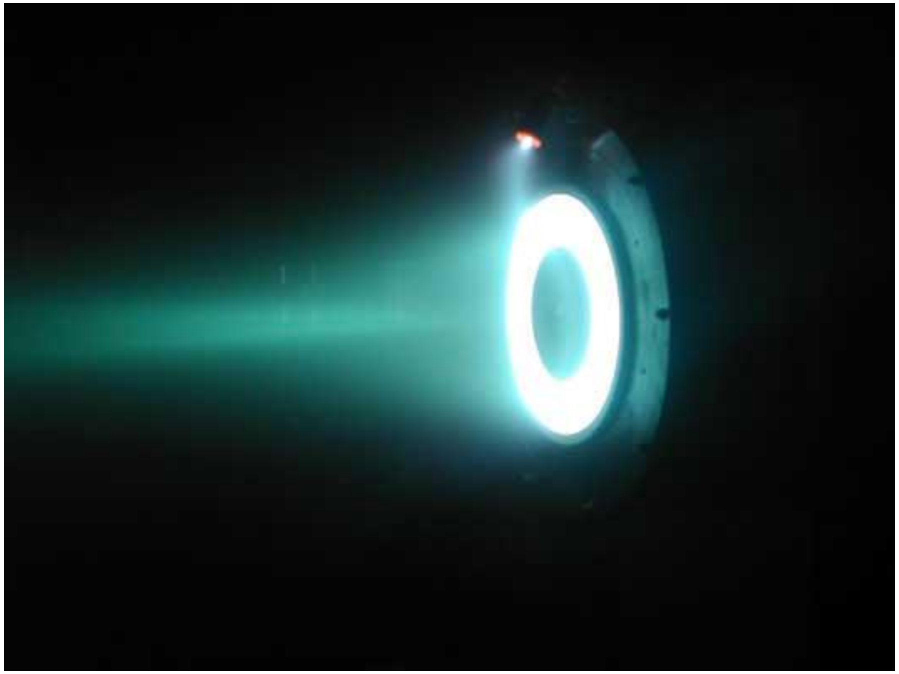


# Experiments to study plasma thrusters for satellites and deep space exploration

**The success of NASA's Dawn mission to orbit two asteroids depended on plasma thrusters**



**HTX**
**Hall Thruster Experiment**



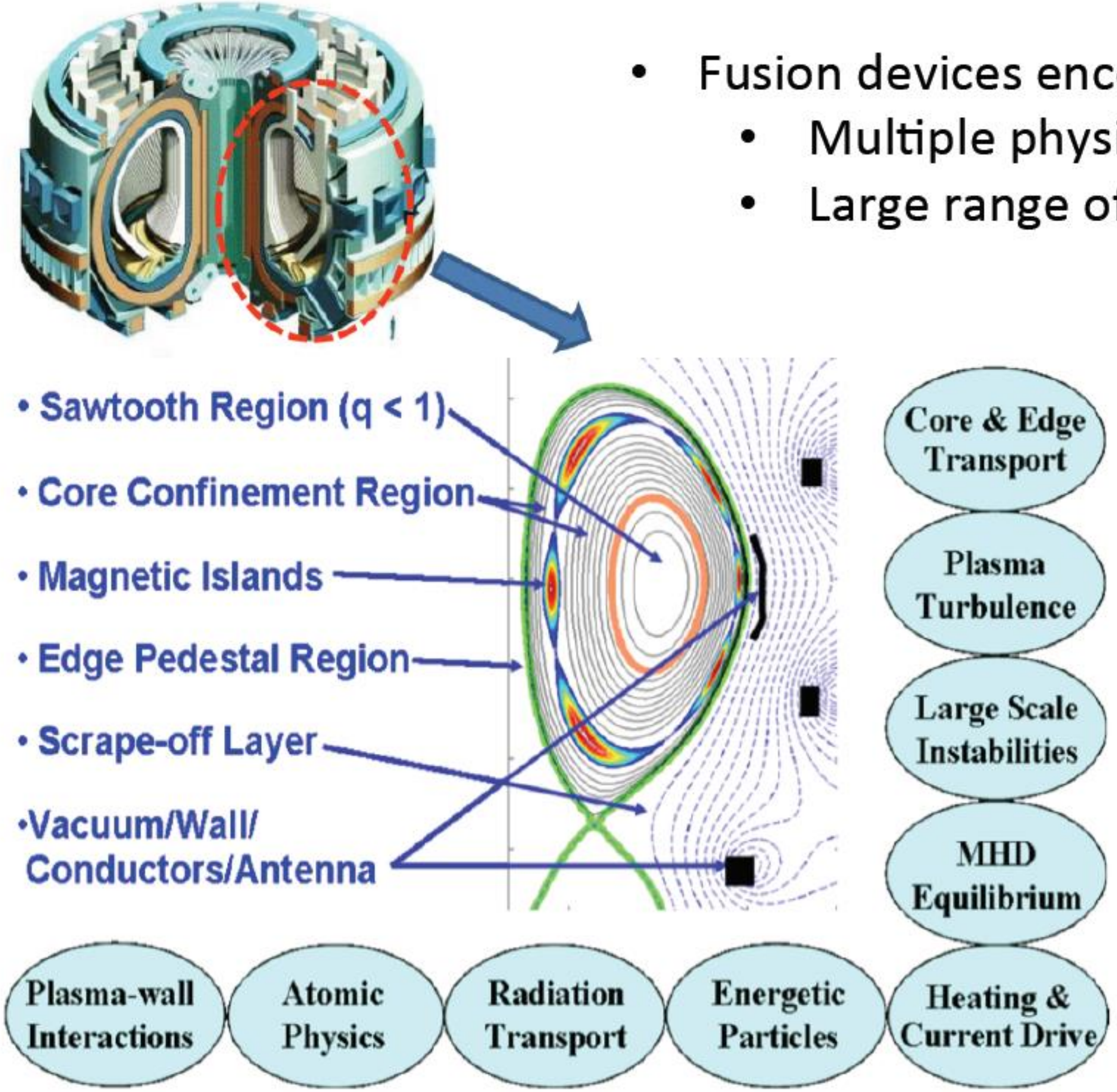
# Additional plasma research at PPPL

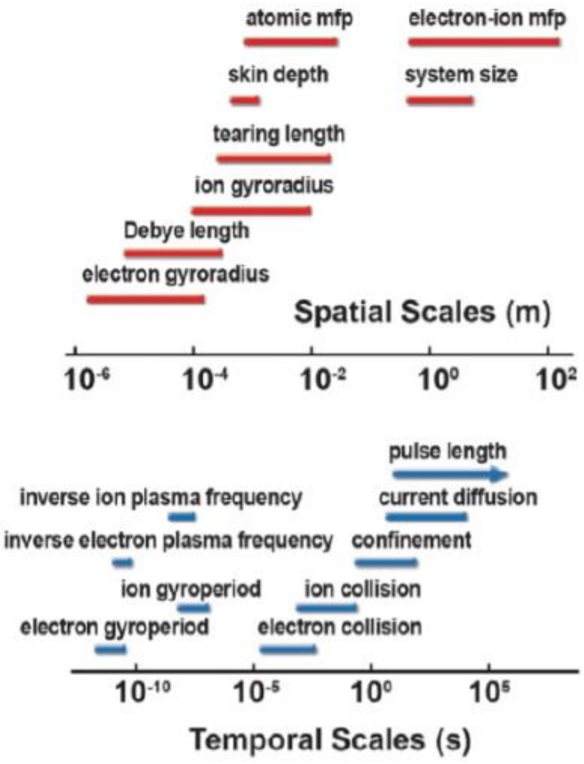
- Astrophysics
- Plasma thrusters
- Basic plasma physics
- Nanotechnology
- Plasma-surface chemistry interaction
- Developing medical isotopes
- Plasma theory and simulation

➢ **Plasmas for nuclear fusion energy research**

# Characteristics length & time scales that govern instabilities span orders of magnitude

- Fusion devices encompass:
  - Multiple physical processes
  - Large range of scales in time and space





Report of the Workshop on Integrated Simulations for Magnetic Fusion Energy Sciences