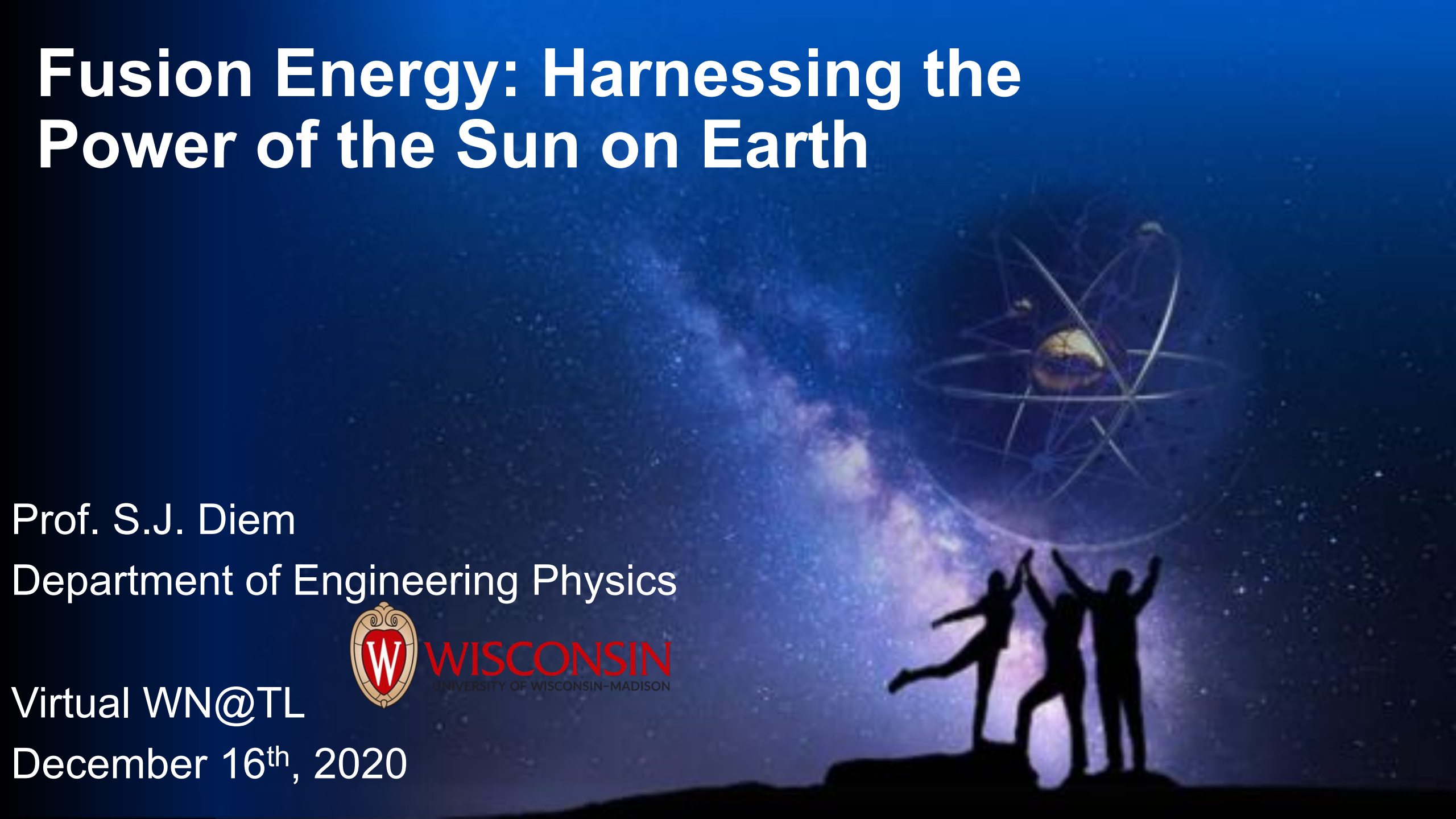
Fusion Energy: Harnessing the Power of the Sun on Earth

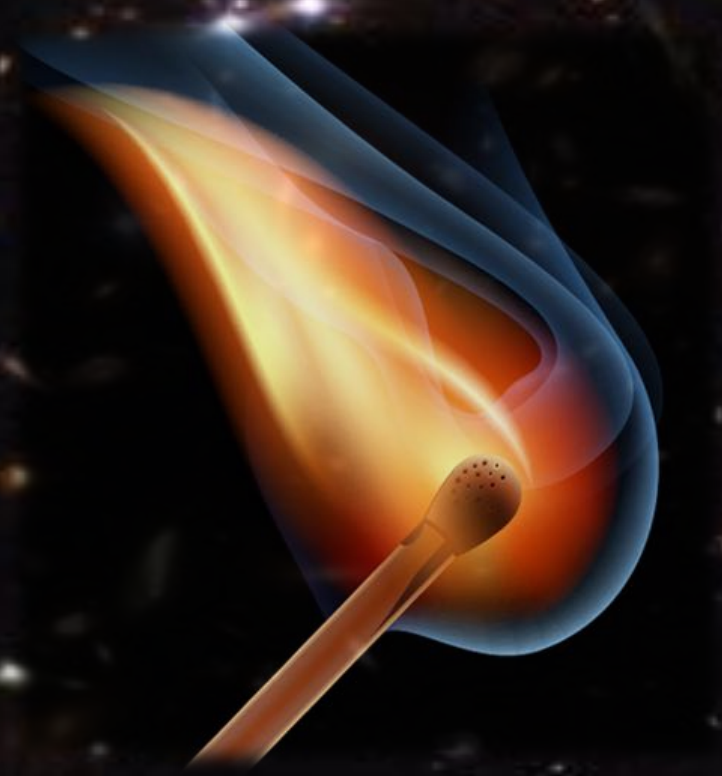


Prof. S.J. Diem
Department of Engineering Physics
WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Virtual WN@TL
December 16th, 2020

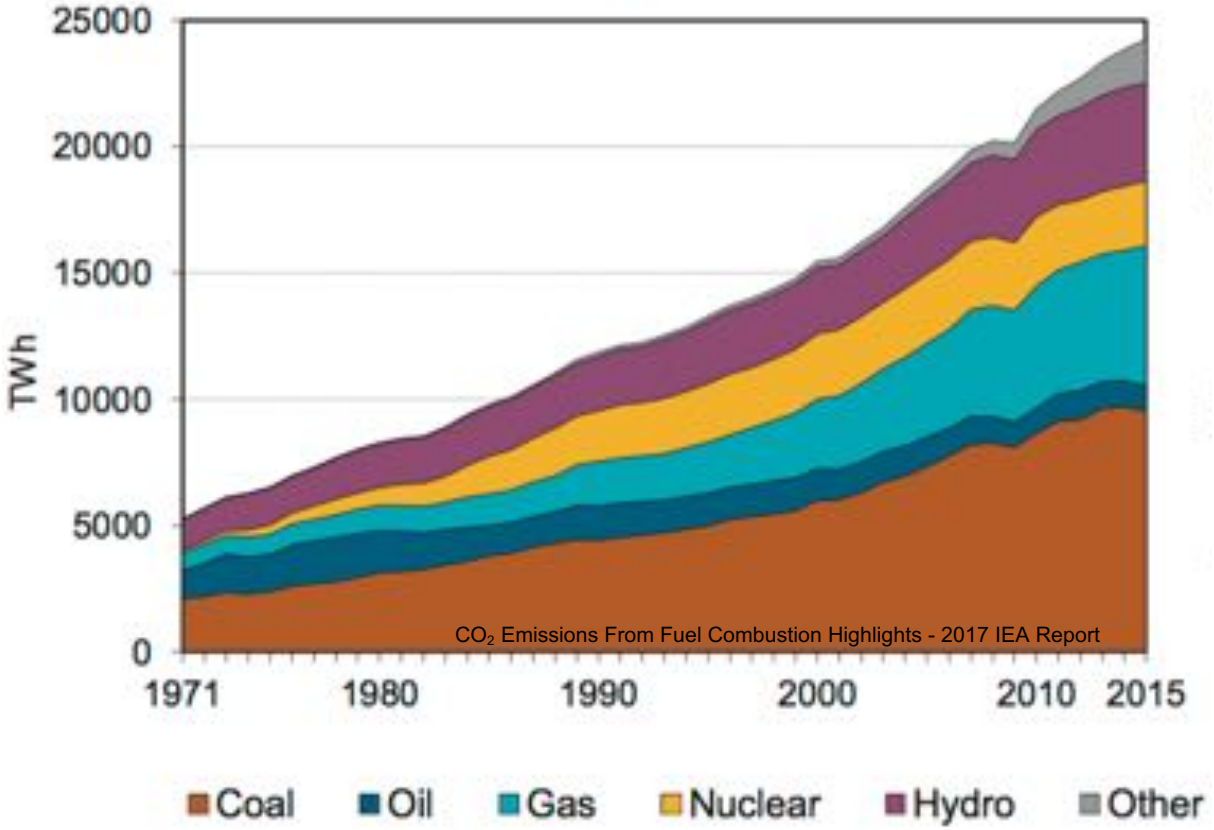
For more than a century, most of our energy generated by burning fossil fuels

Fire: Self-sustaining chemical reaction at 2000^{o} F

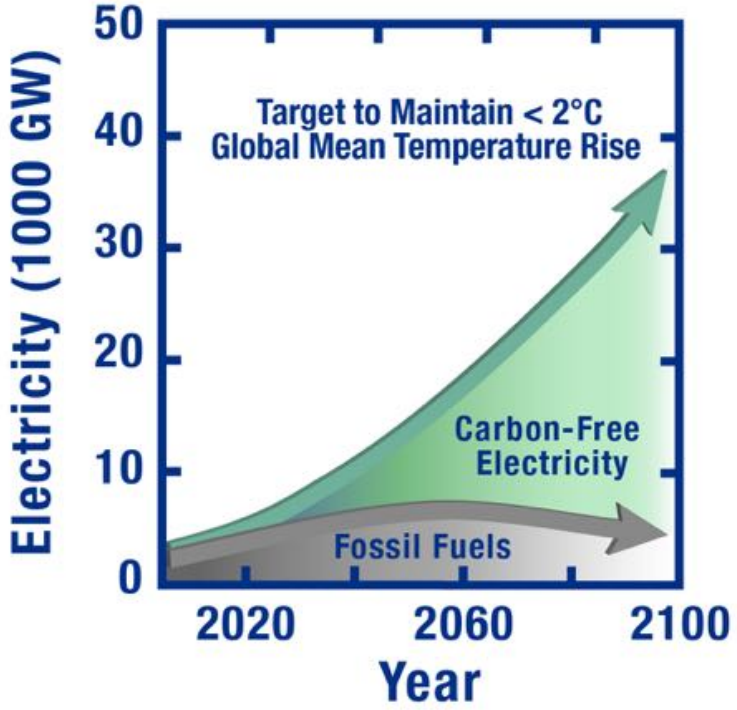


As our demand for energy grows, need for clean, alternative energy sources grows

Electricity generation by fuel



Alternative sources required to meet demands



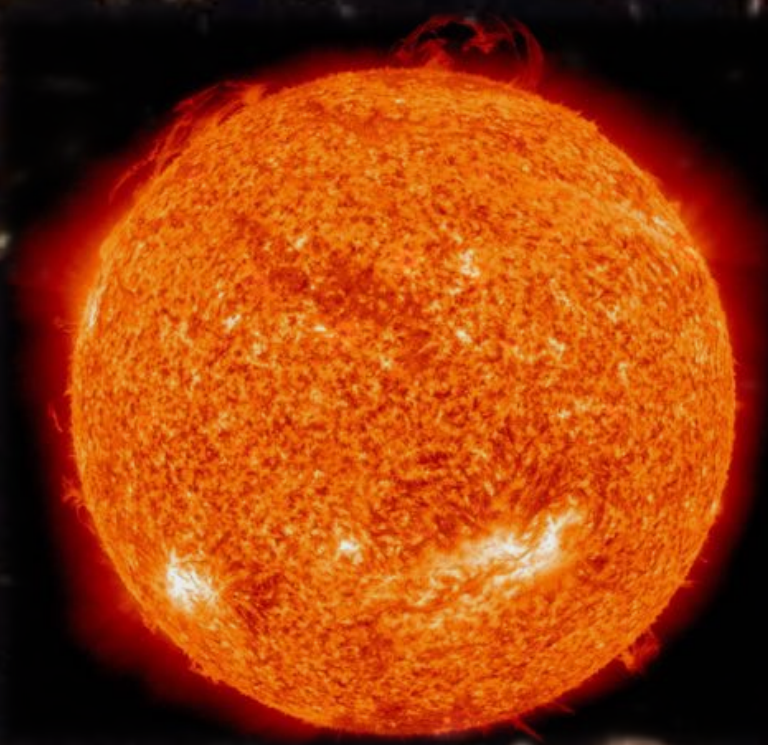
Source: IPCC AMPERE Project, AMPERE-450-FullTech-OPT Scenario

Fusion — Fundamental energy source that helped create the universe we live In

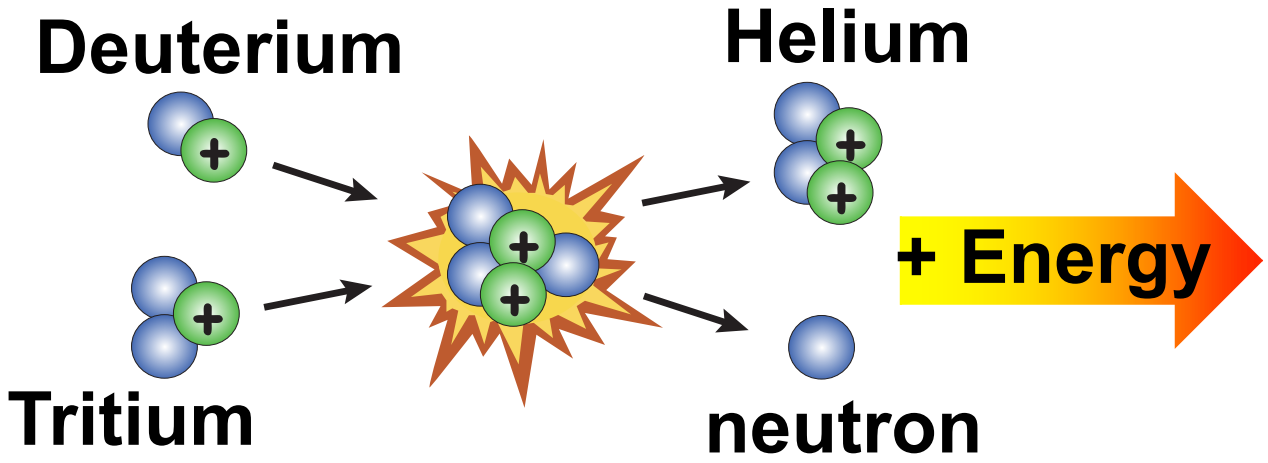
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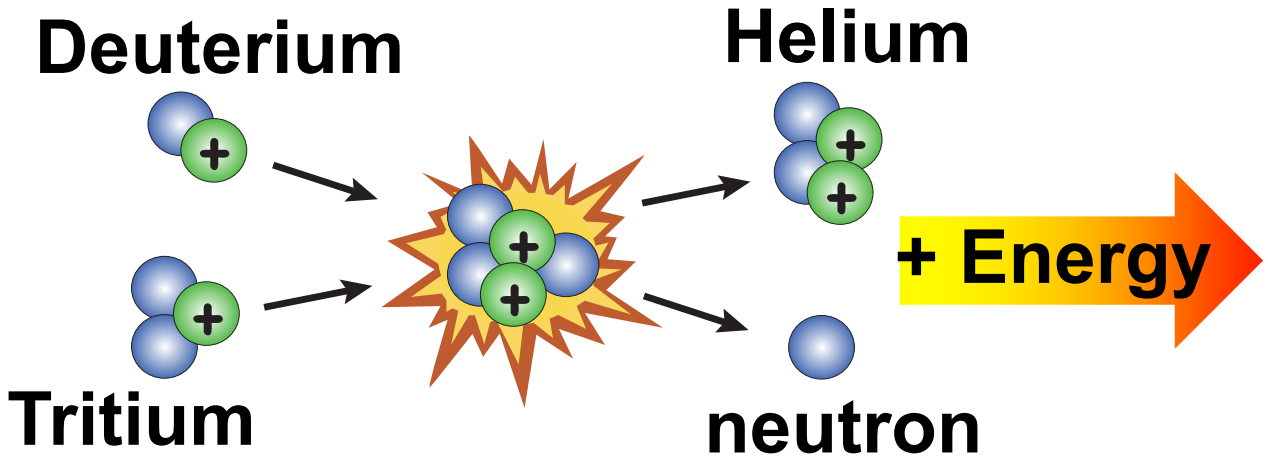
Fusion: Self-sustaining nuclear reaction at > 20,000,000° F



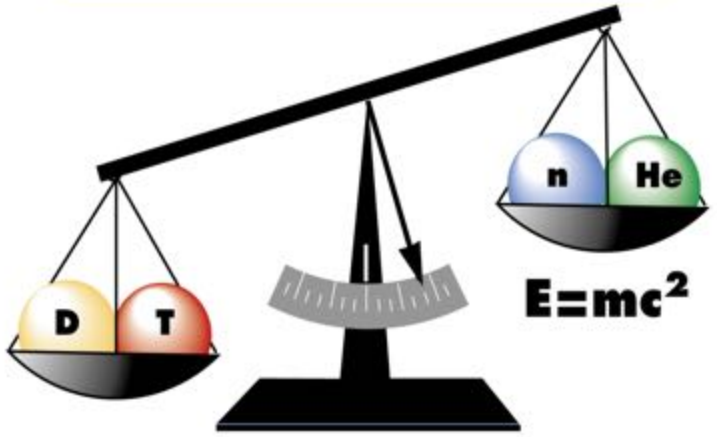
Fusion is the energy source of the stars



Fusion is the energy source of the stars



Difference in mass is converted to energy:



Energy = (mass) * (speed of light)^2
or more simply, **$E = mc^2$**

High fuel efficiency of fusion makes it an attractive energy sources



Deuterium from 1 bath

+



Tritium from Lithium in 2 laptop batteries

=



Energy for 1 lifetime!

+ **Helium**

High fuel efficiency of fusion makes it an attractive energy sources



Deuterium from 1 bath

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230 tons of coal

=

Same amount of energy
+380 tons of **pollution**

High fuel efficiency of fusion makes it an attractive energy sources



Deuterium from 1 bath

+

Triti

Takes a forest of 51,000+ trees to absorb this much pollution!



Energy for 1 lifetime!
+ **Helium**

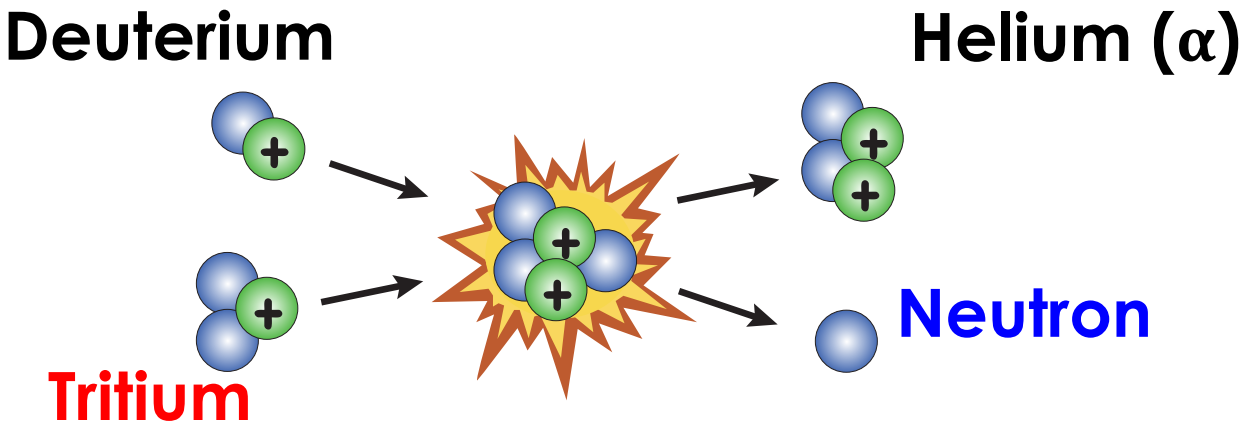




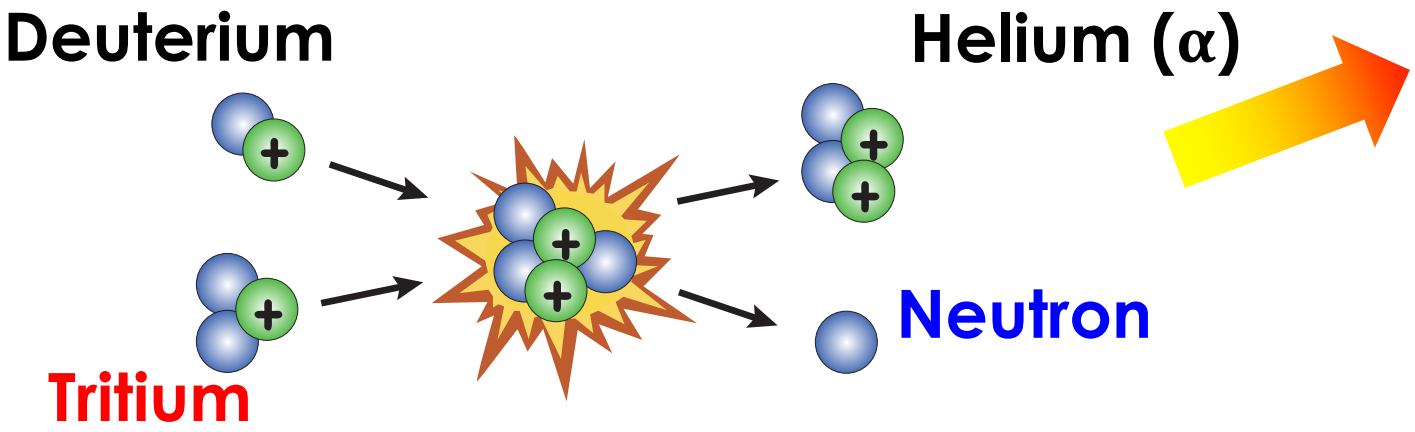
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Fusion has a virtually unlimited supply of fuel



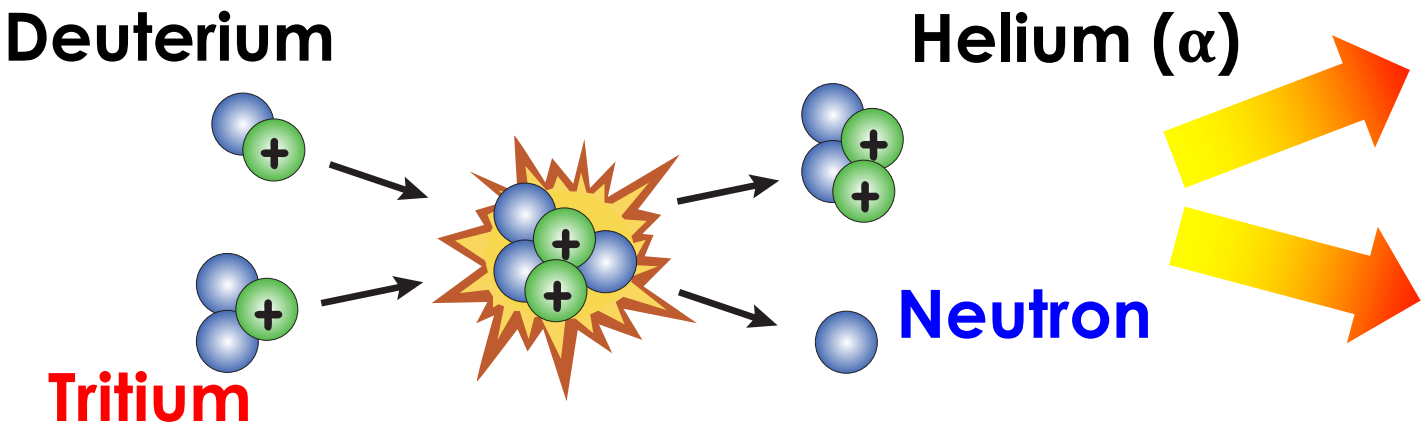
Fusion has a virtually unlimited supply of fuel



GOAL:

Use 20% to sustain reaction

Fusion has a virtually unlimited supply of fuel

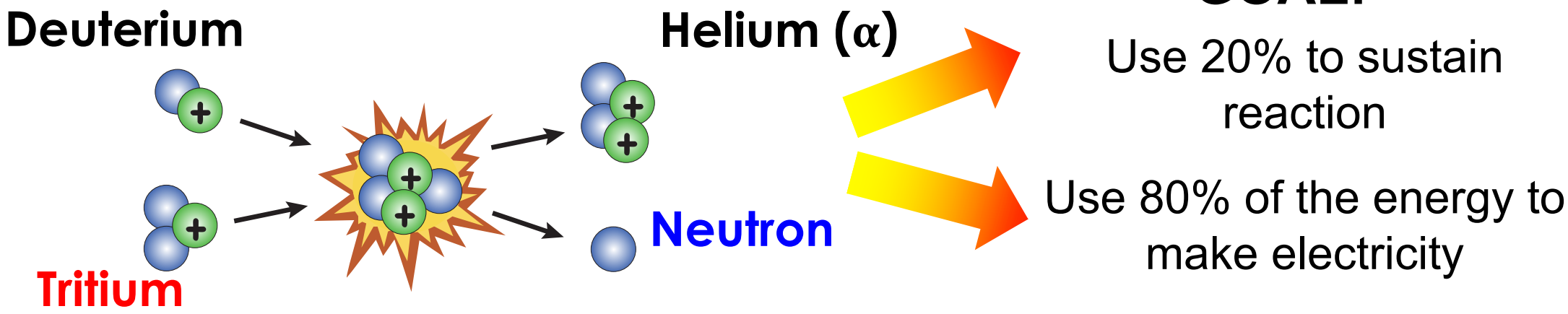


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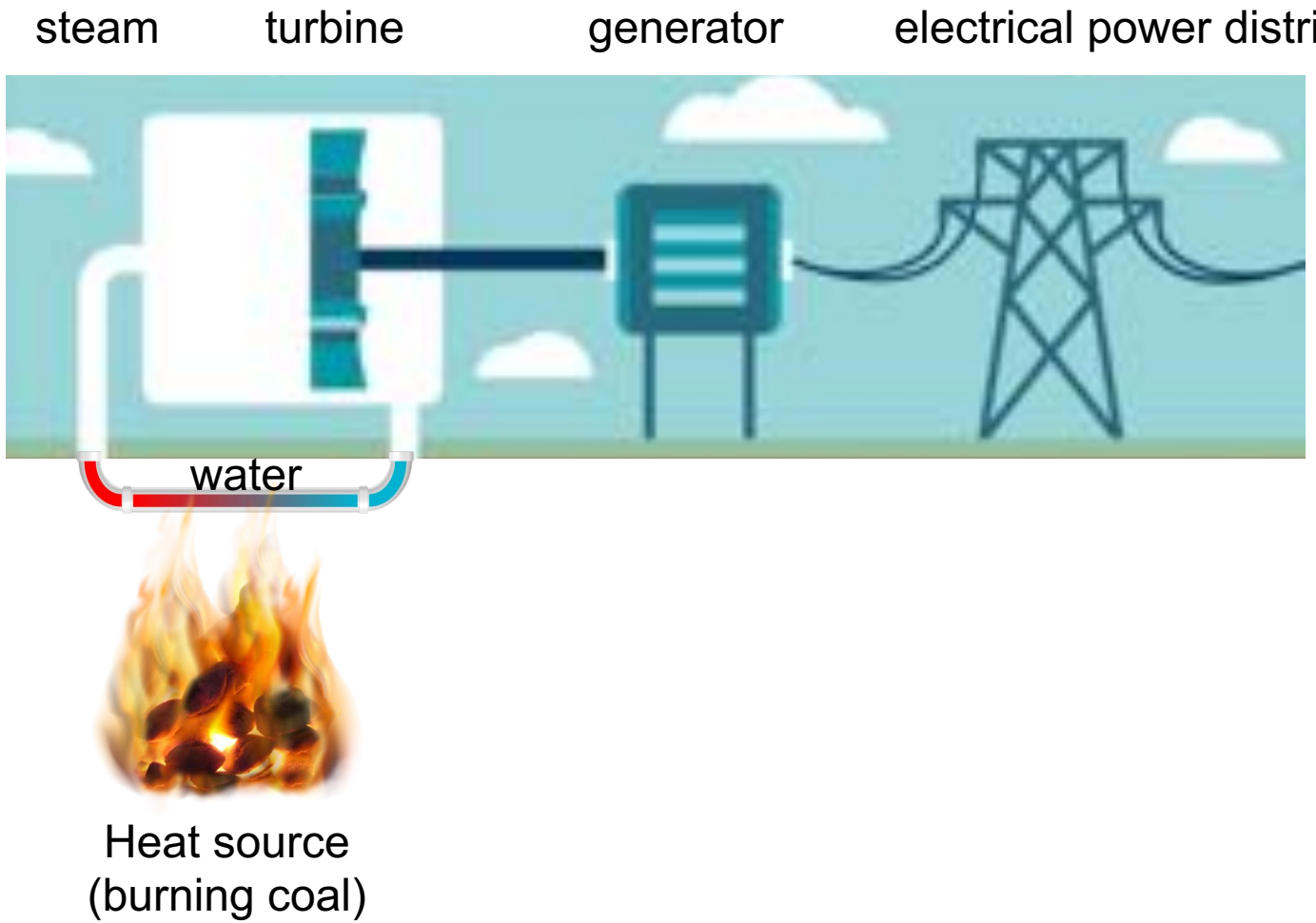
Use 80% of the energy to make electricity

Fusion has a virtually unlimited supply of fuel

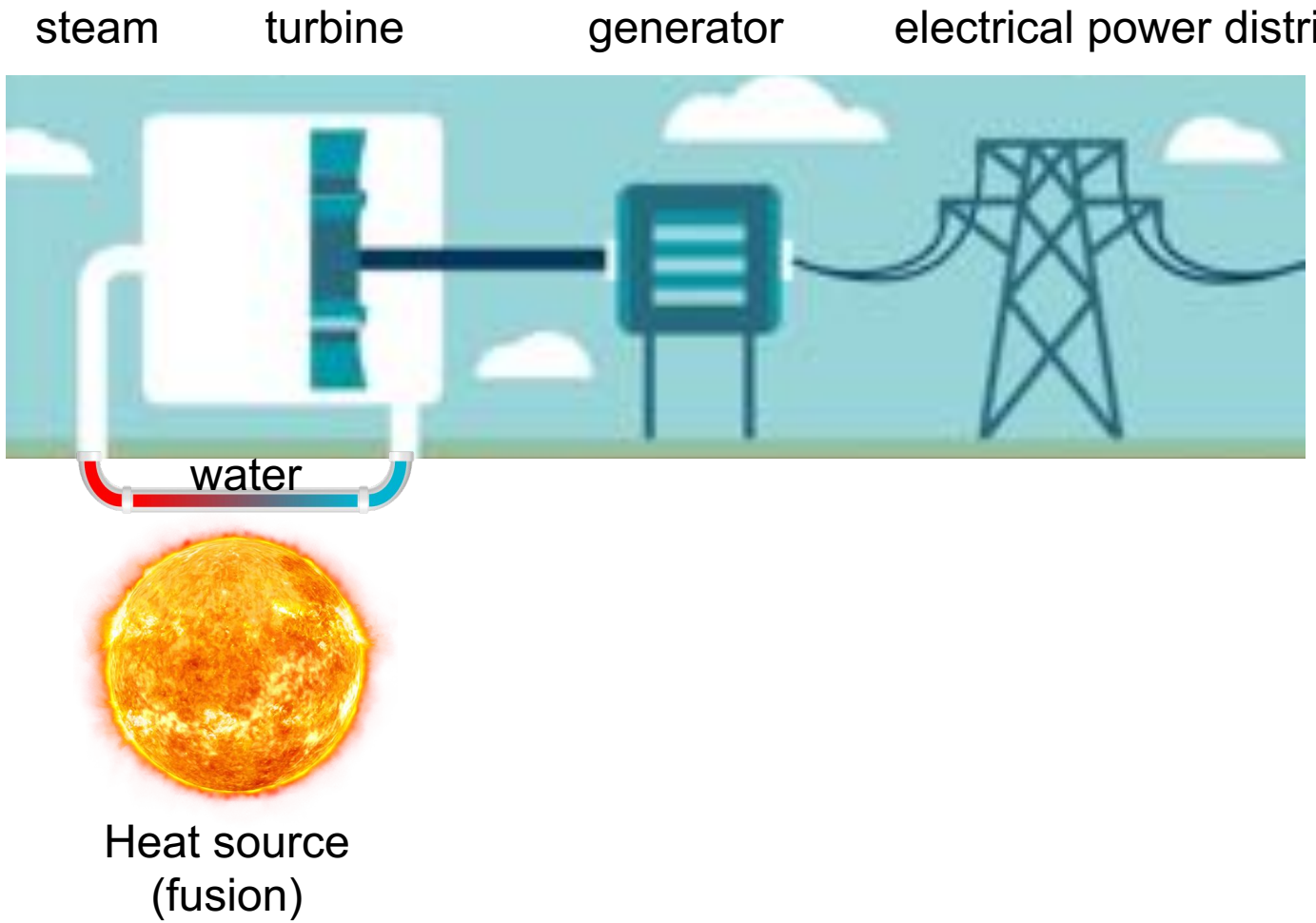


- Enough lithium in land to supply 6k-10k years
  - At least 12x more energy than all uranium, thorium, coal, oil, and natural gas supplies
- Enough lithium in ocean to supply ~ 6 million years

In a power plant, fusion energy would heat water to generate electricity

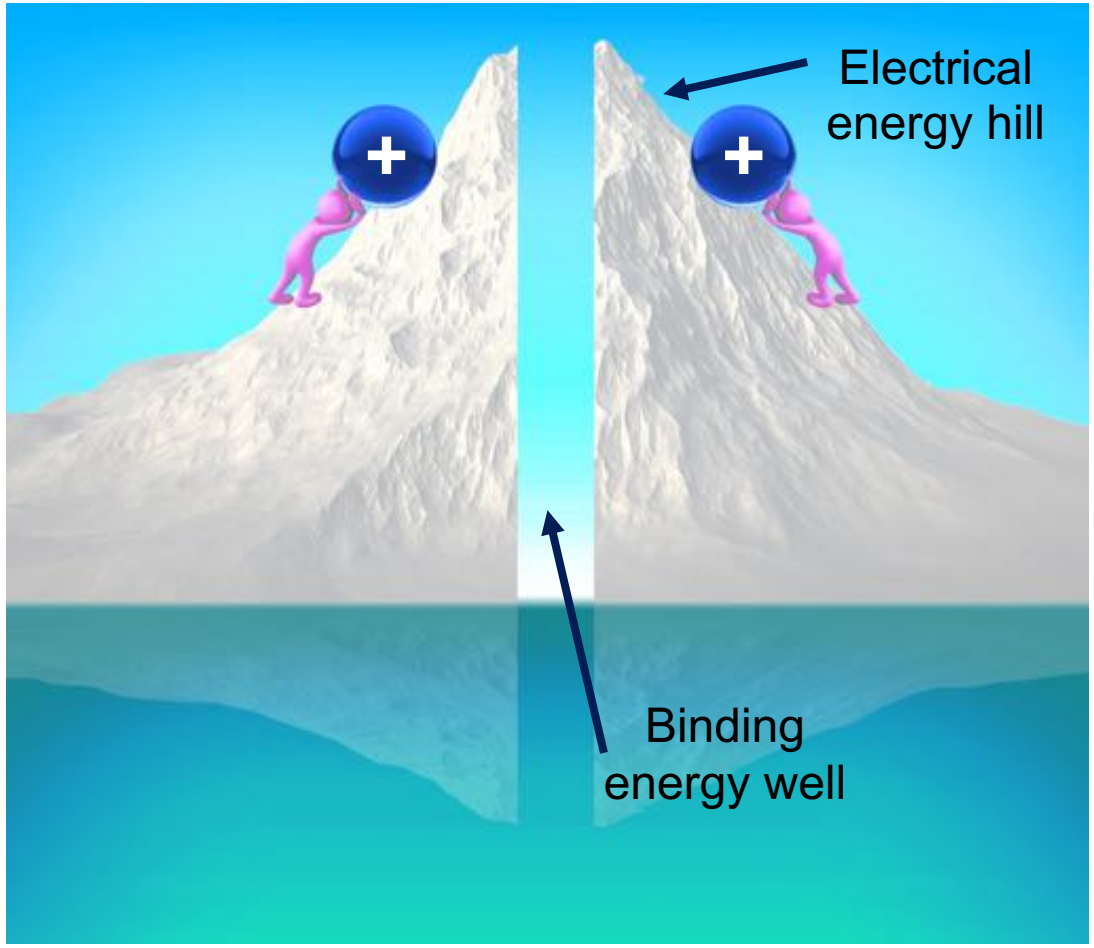


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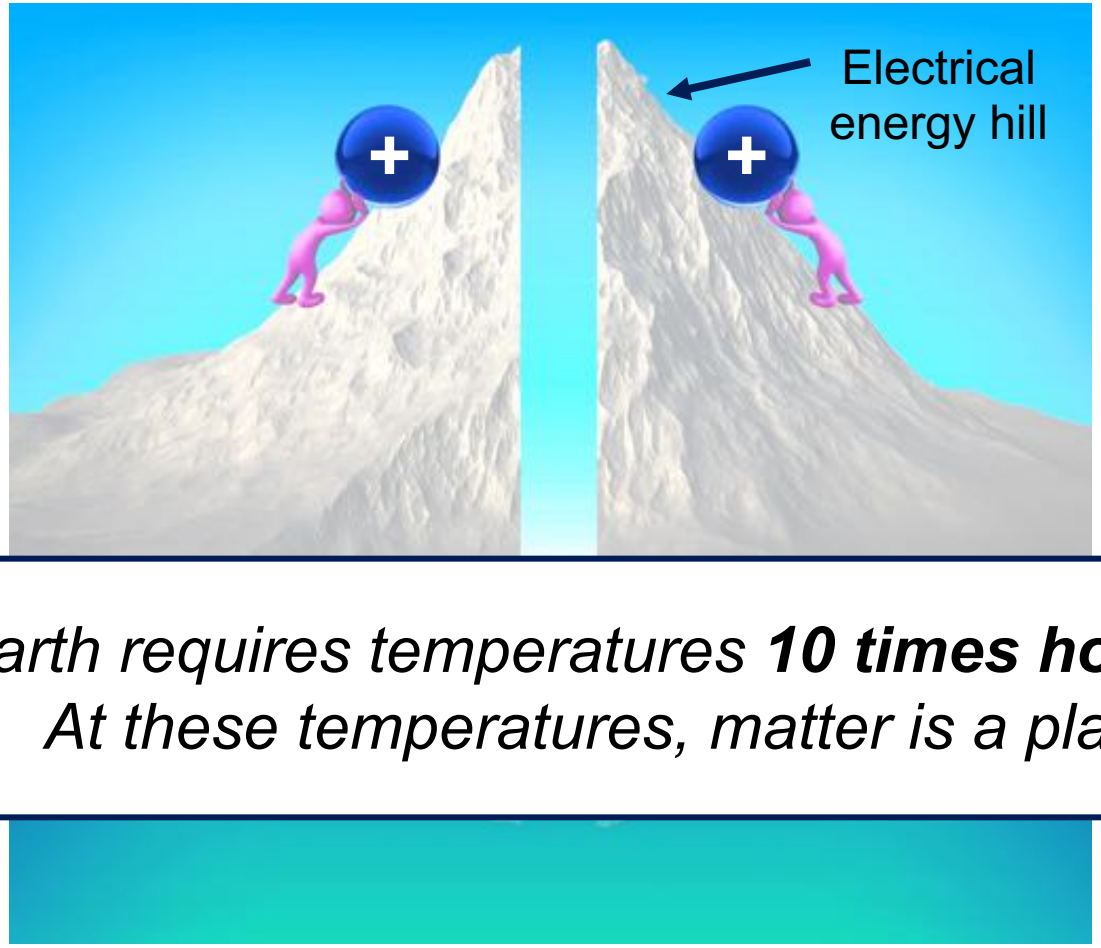
Creating the right conditions for fusion isn't easy

To fuse together, two positive charges must have enough energy to overcome electric repulsion



Creating the right conditions for fusion isn't easy

To fuse together, two positive charges must have enough energy to overcome electric repulsion



*Fusion on Earth requires temperatures **10 times hotter than the Sun!***
At these temperatures, matter is a plasma.

At fusion temperatures, matter is a plasma

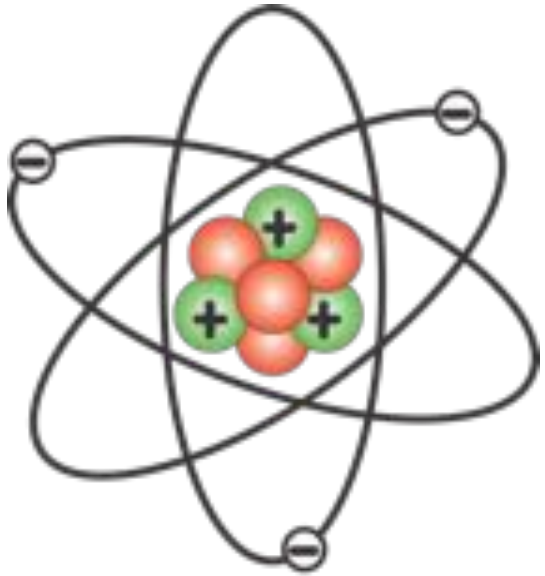
A plasma:

- Contains charged particles
- Conducts electricity, responds to magnetic fields

Gas







Plasma





Add heat

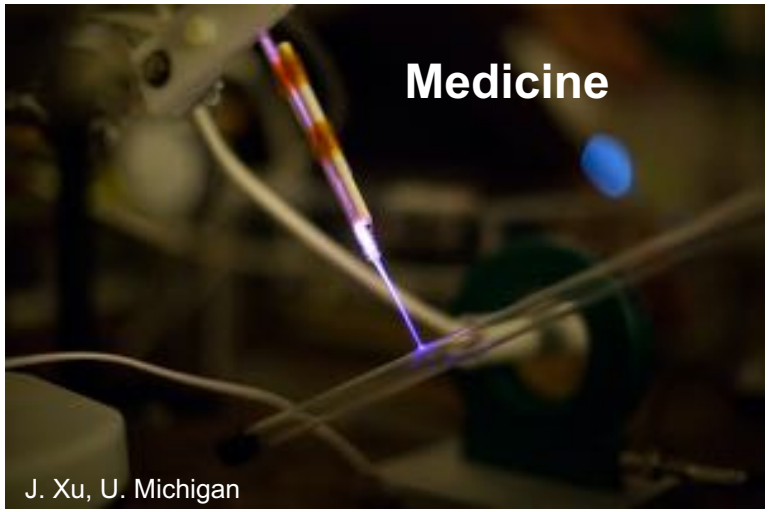
Places you can find plasma





Lighting





Plasma processing



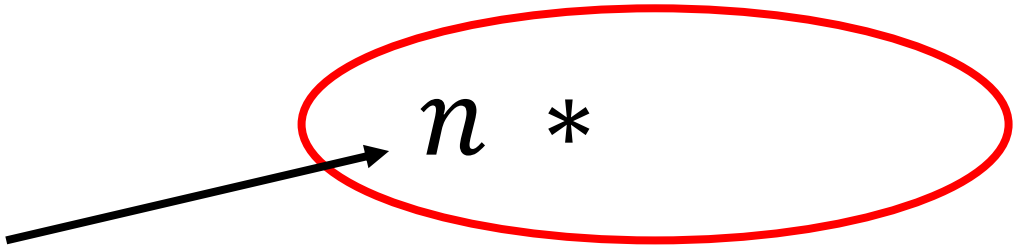




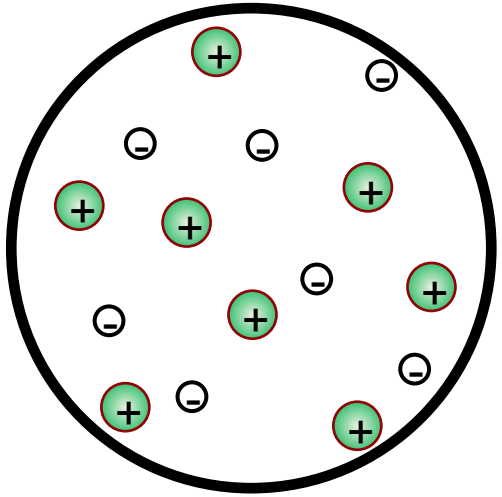


What conditions are needed for fusion?

- Sustained fusion reactions require:



Density



Enough particles…

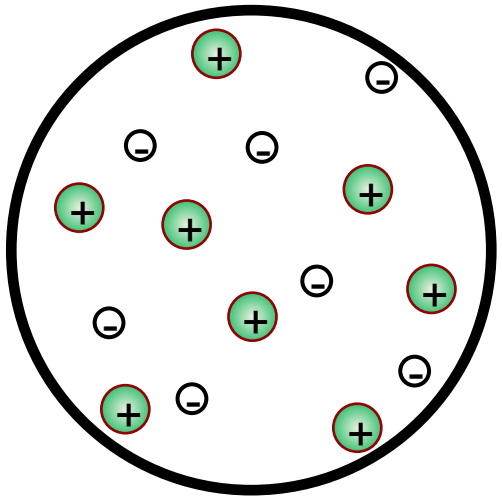
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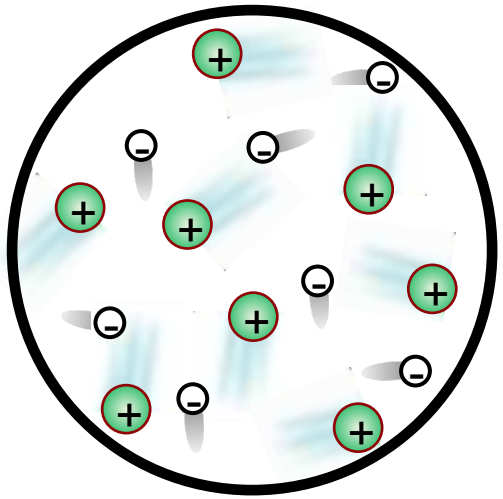
- Sustained fusion reactions require:

$$n * T *$$

Density

Temperature





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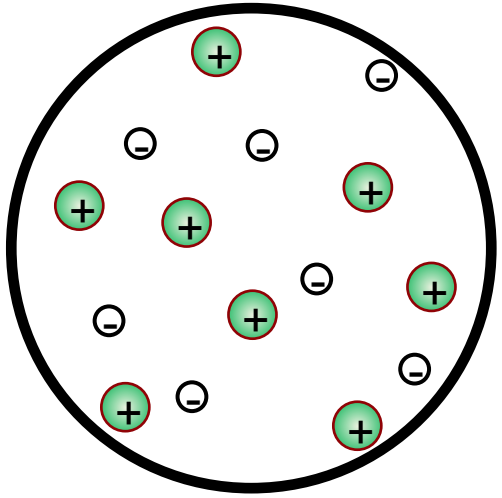
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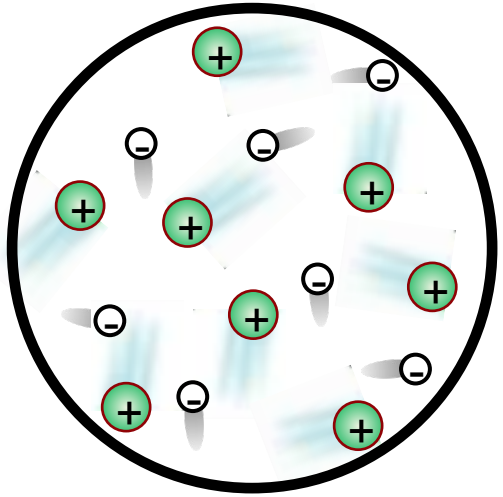
$$n * T * \tau$$

Density



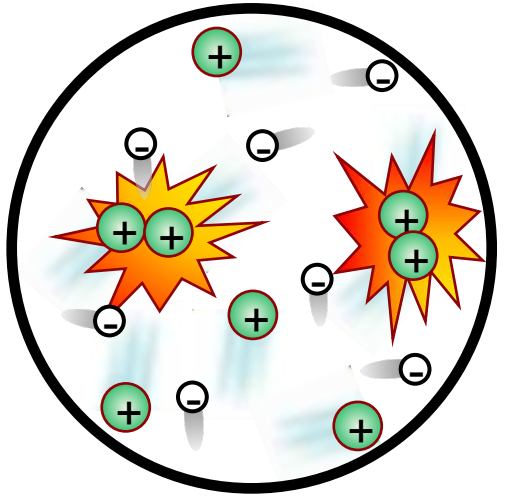
Enough particles…

Temperature



that are energetic enough…

Confinement Time



and collide often enough…

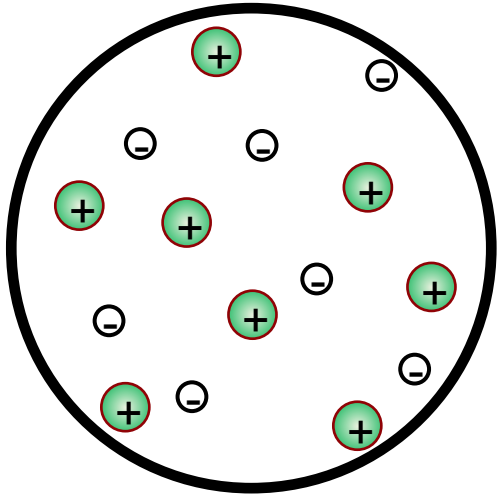
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Triple product is fusion figure of merit

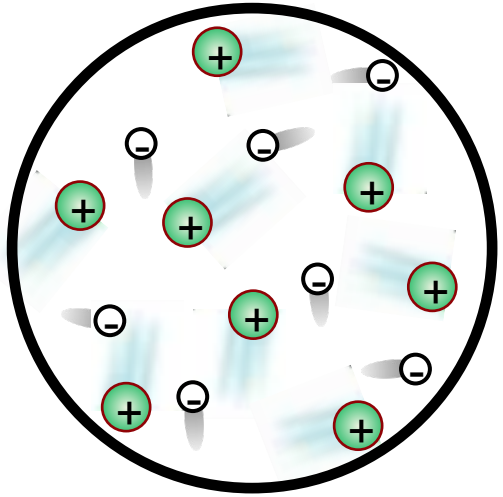
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Density



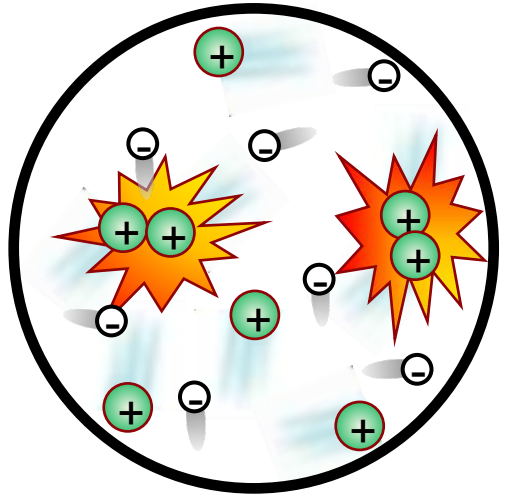
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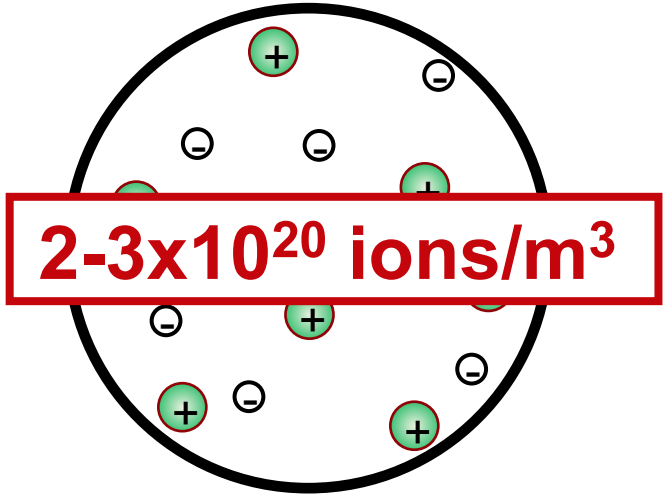
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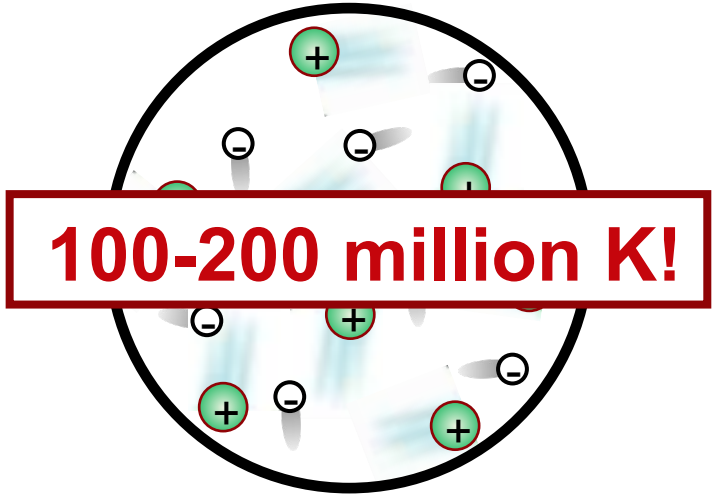
Plasma must be cleverly confined!

Density



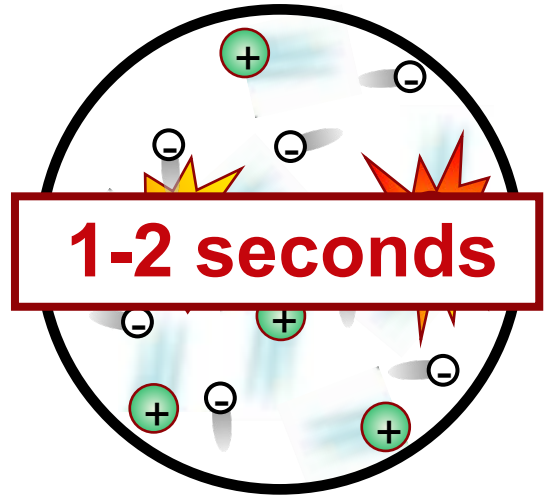
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Temperature



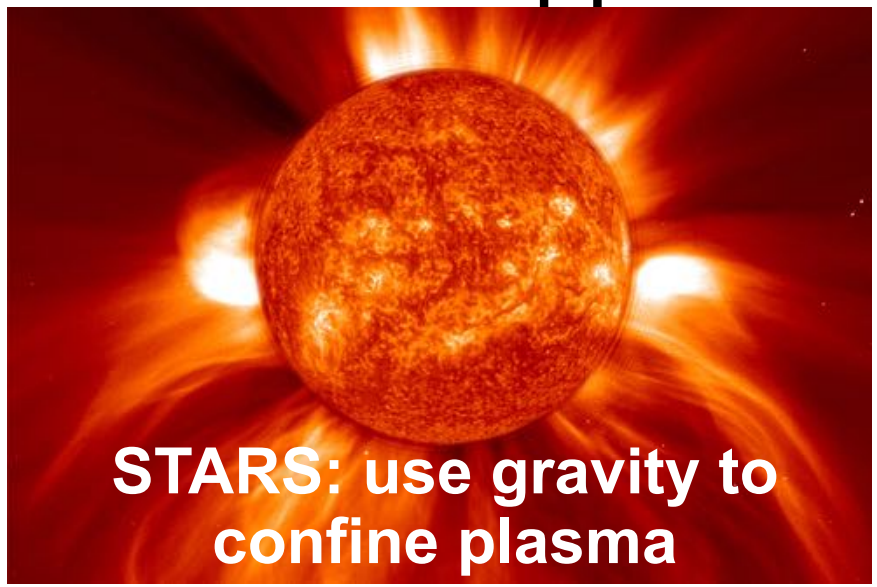
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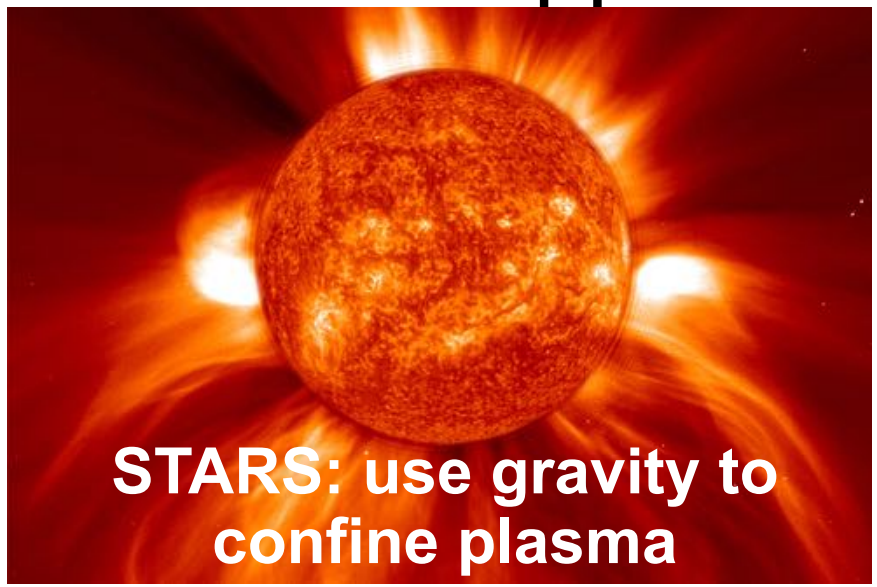


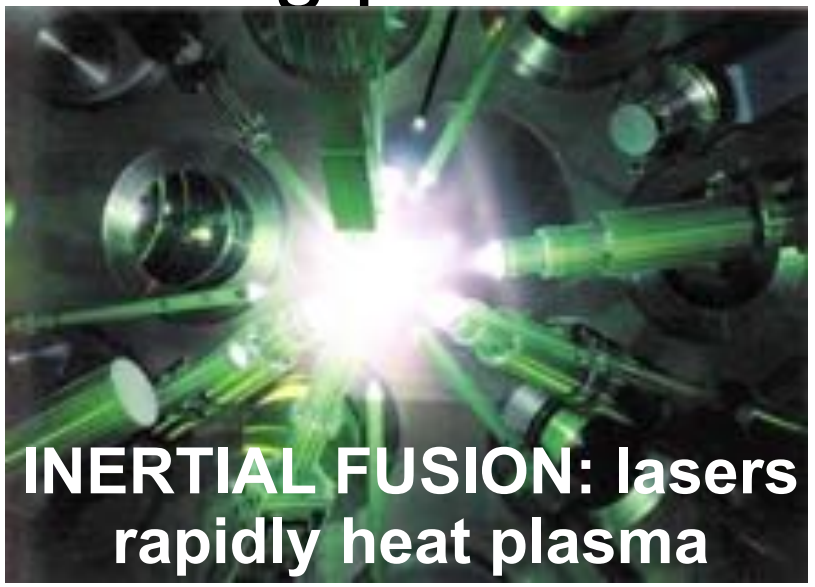
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Three main approaches to confining plasma for fusion



Three main approaches to confining plasma for fusion





Three main approaches to confining plasma for fusion

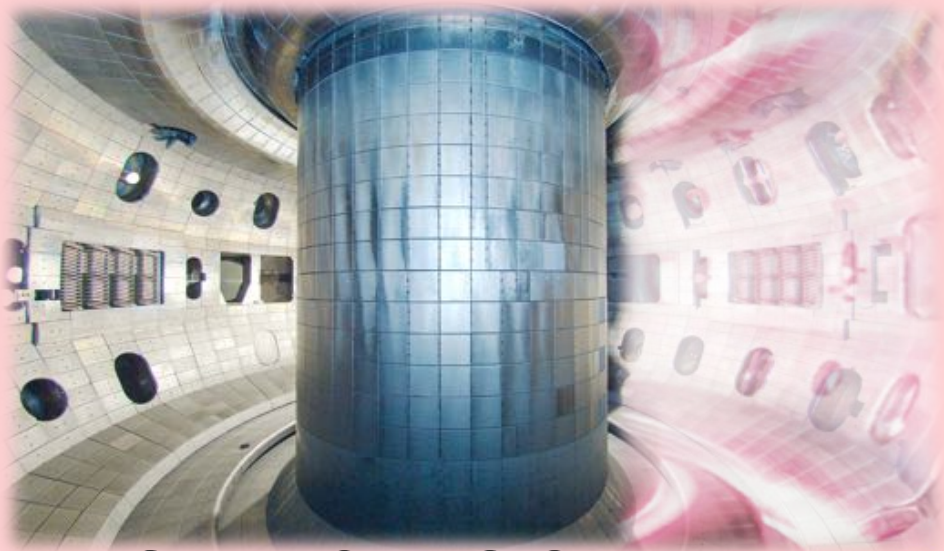


STARS: u
confi



l: lasers
asma

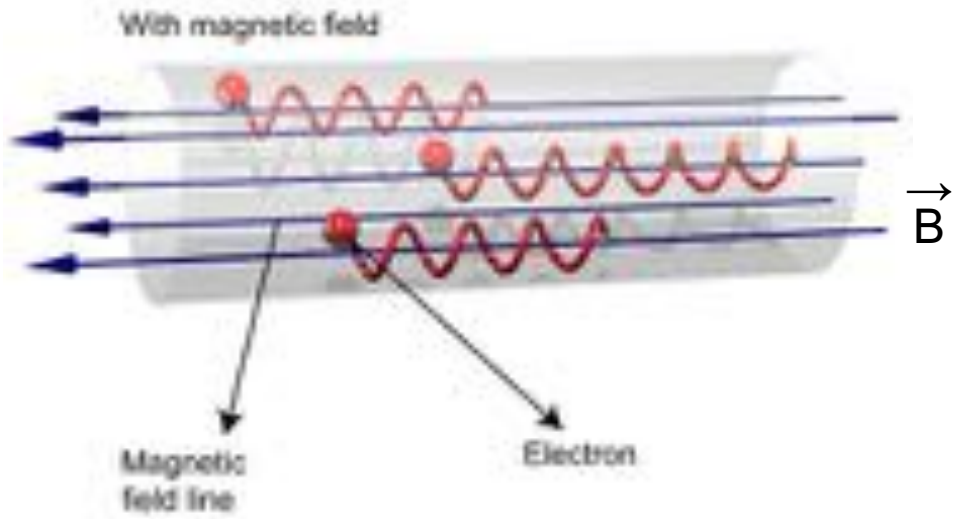
Focus of this talk



MAGNETIC FUSION: magnetic fields used to confine plasma

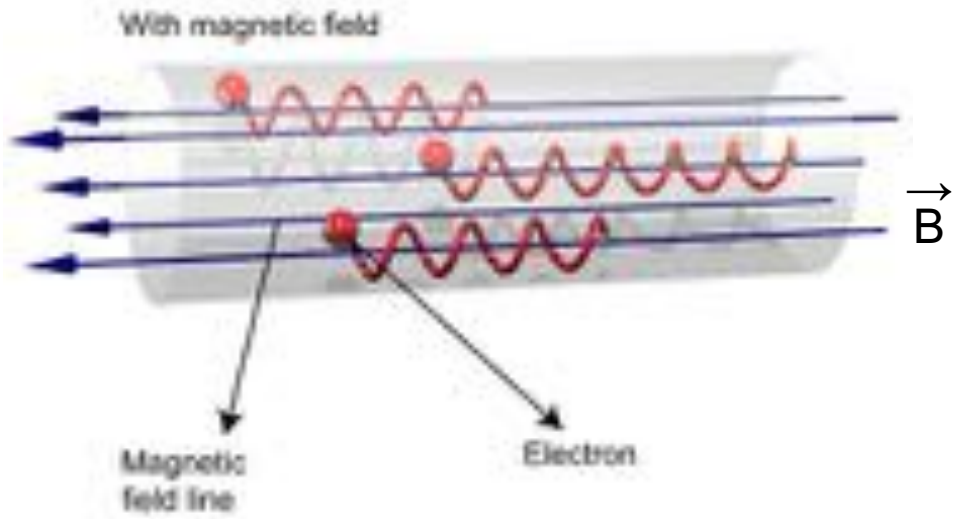
Plasmas can be confined with magnetic fields

Magnetically confined plasma



Plasmas can be confined with magnetic fields

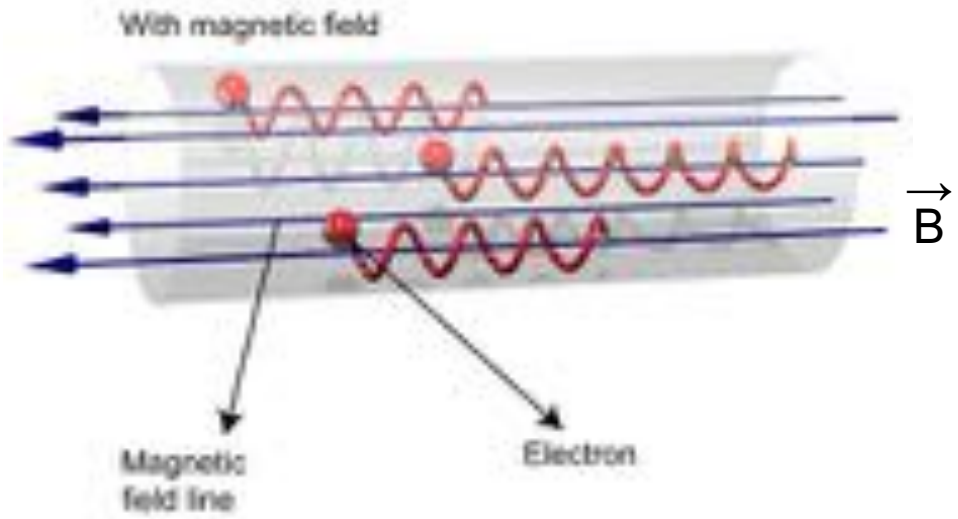
Magnetically confined plasma



But particles are easily lost from the ends

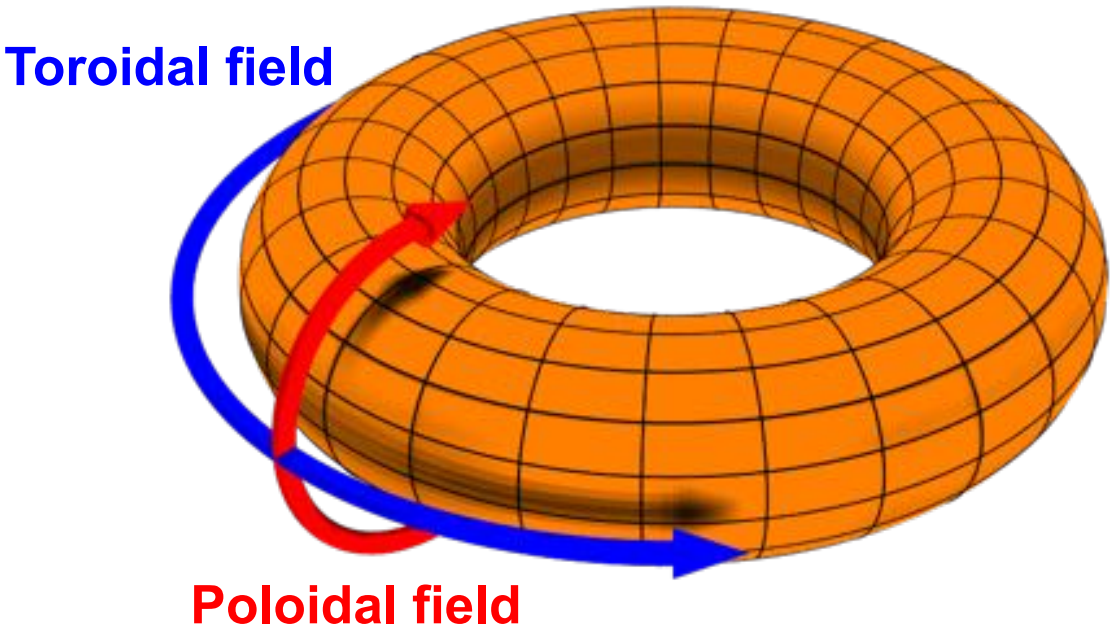
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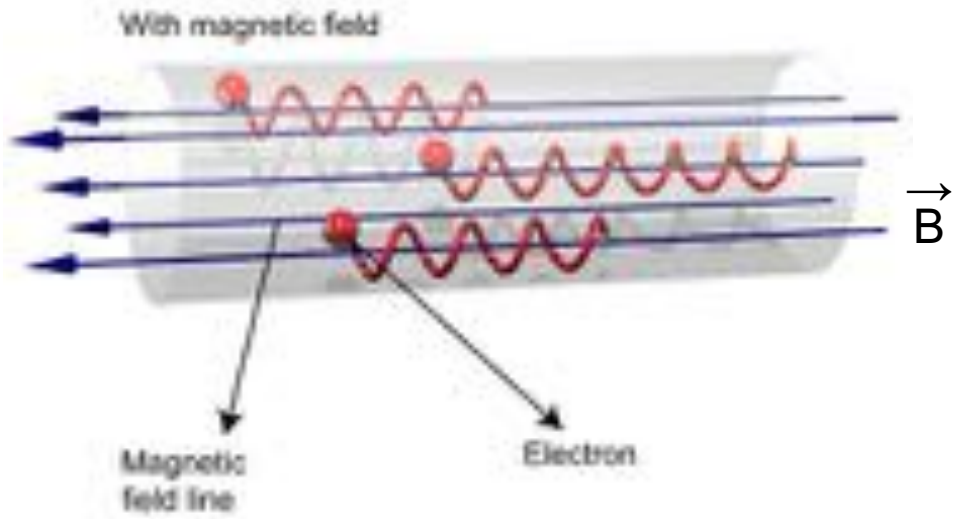
A tokamak magnetic field



Solution: bend the field into a donut shaped torus

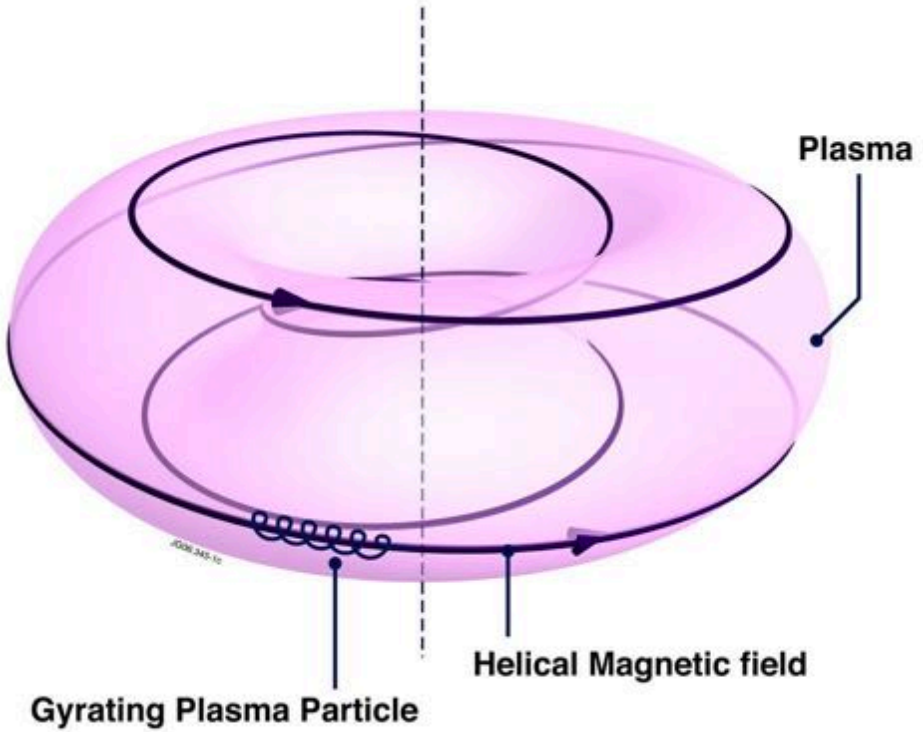
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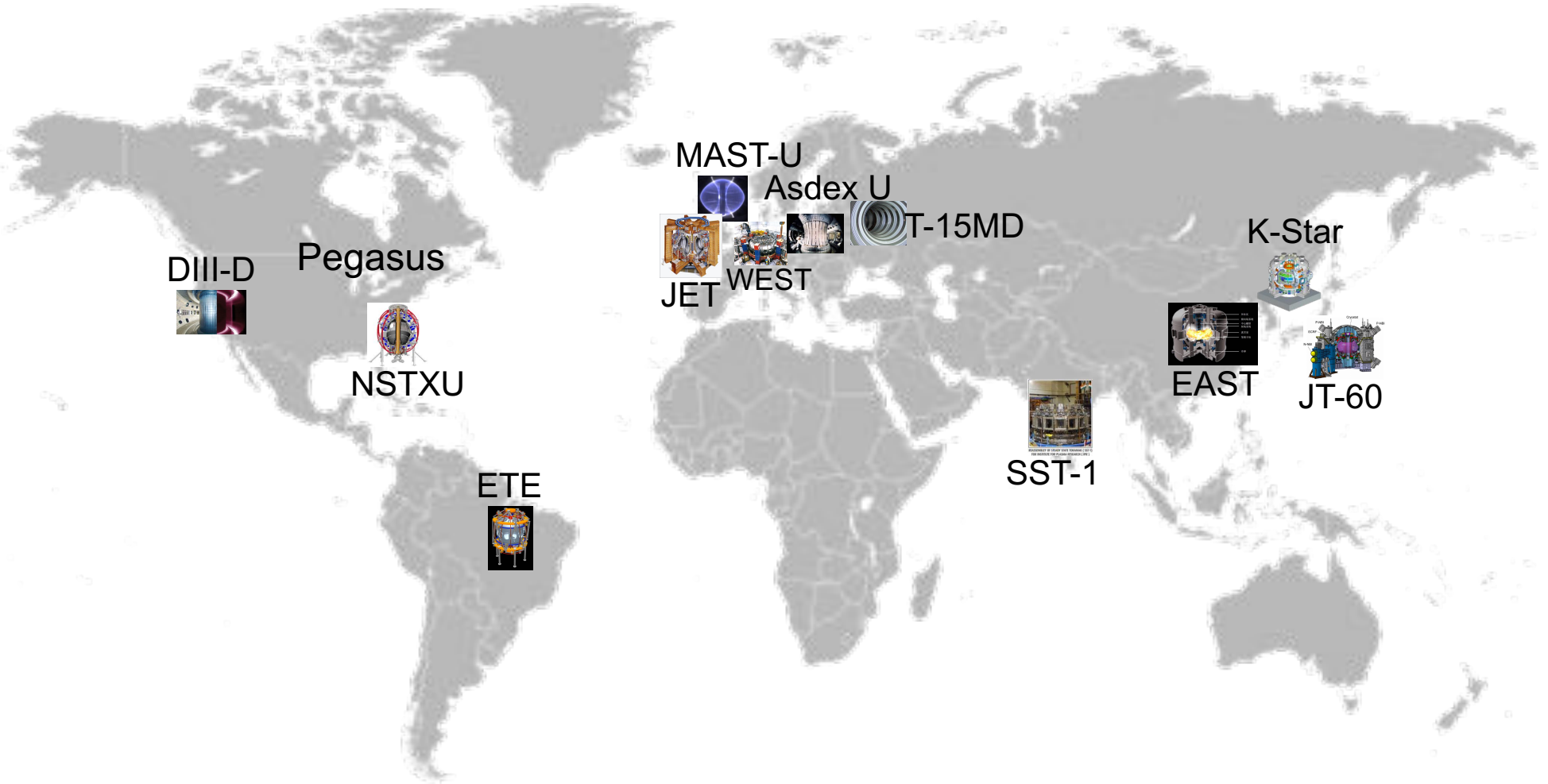
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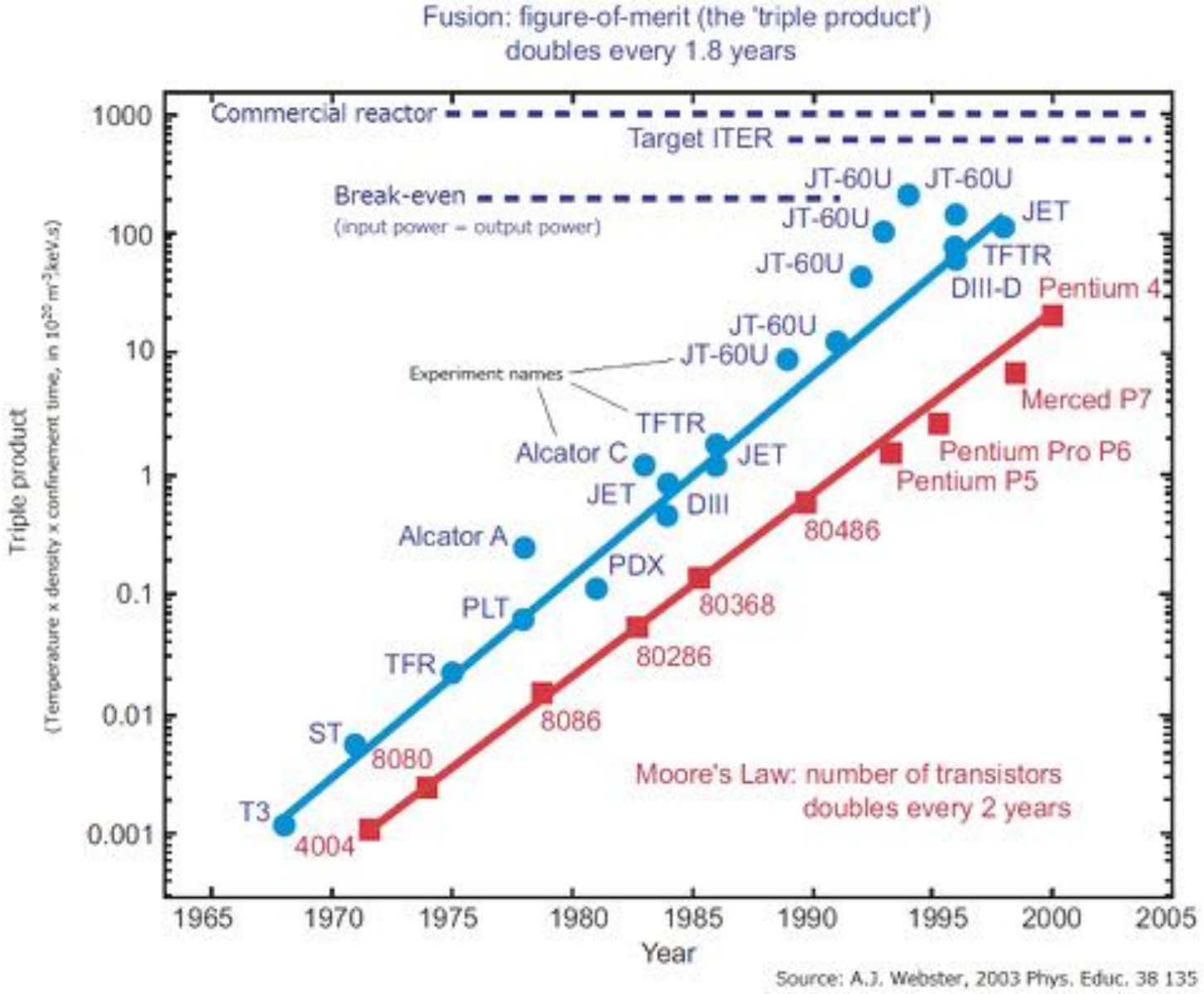


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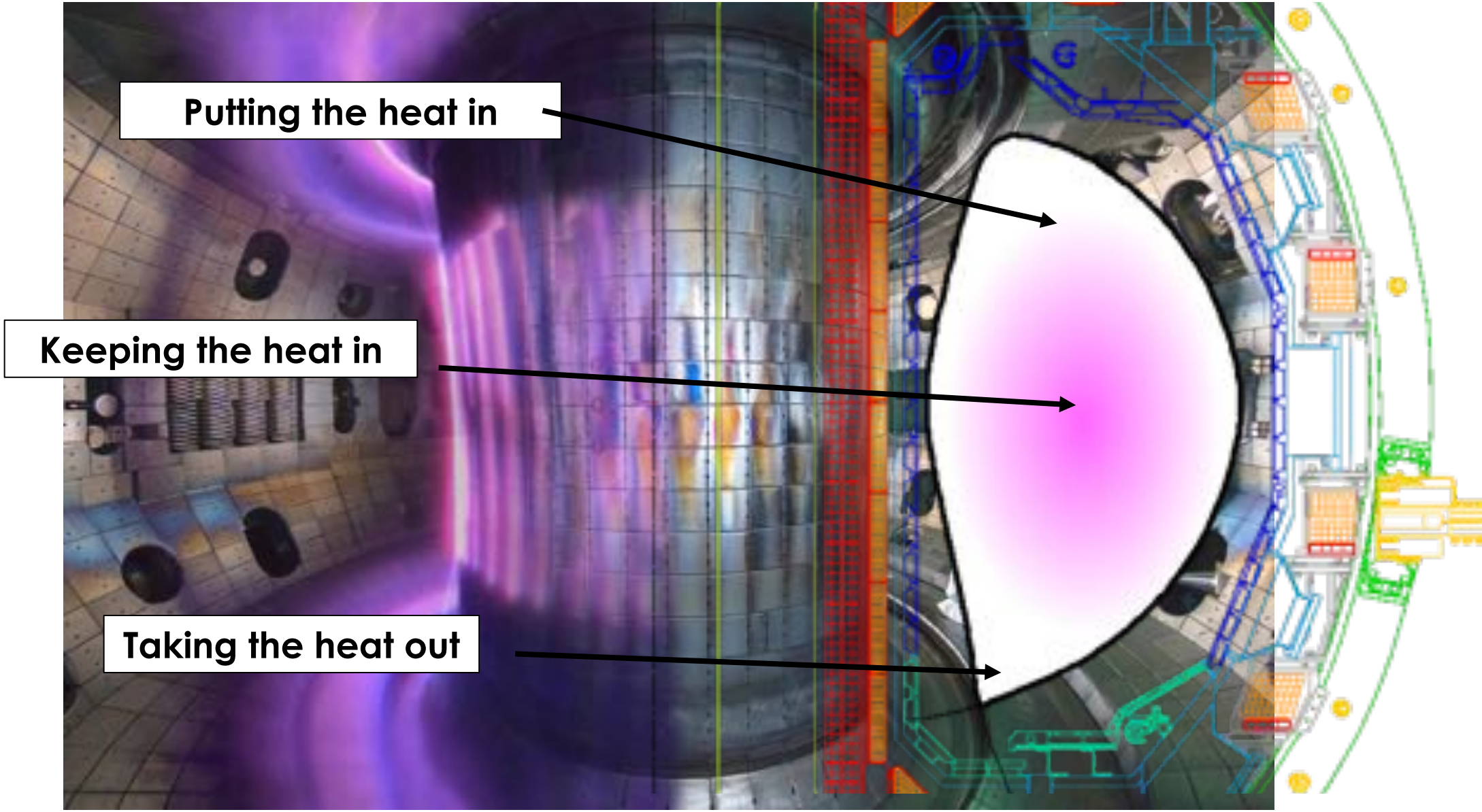
There are many tokamaks around the world studying different plasma phenomena and shapes



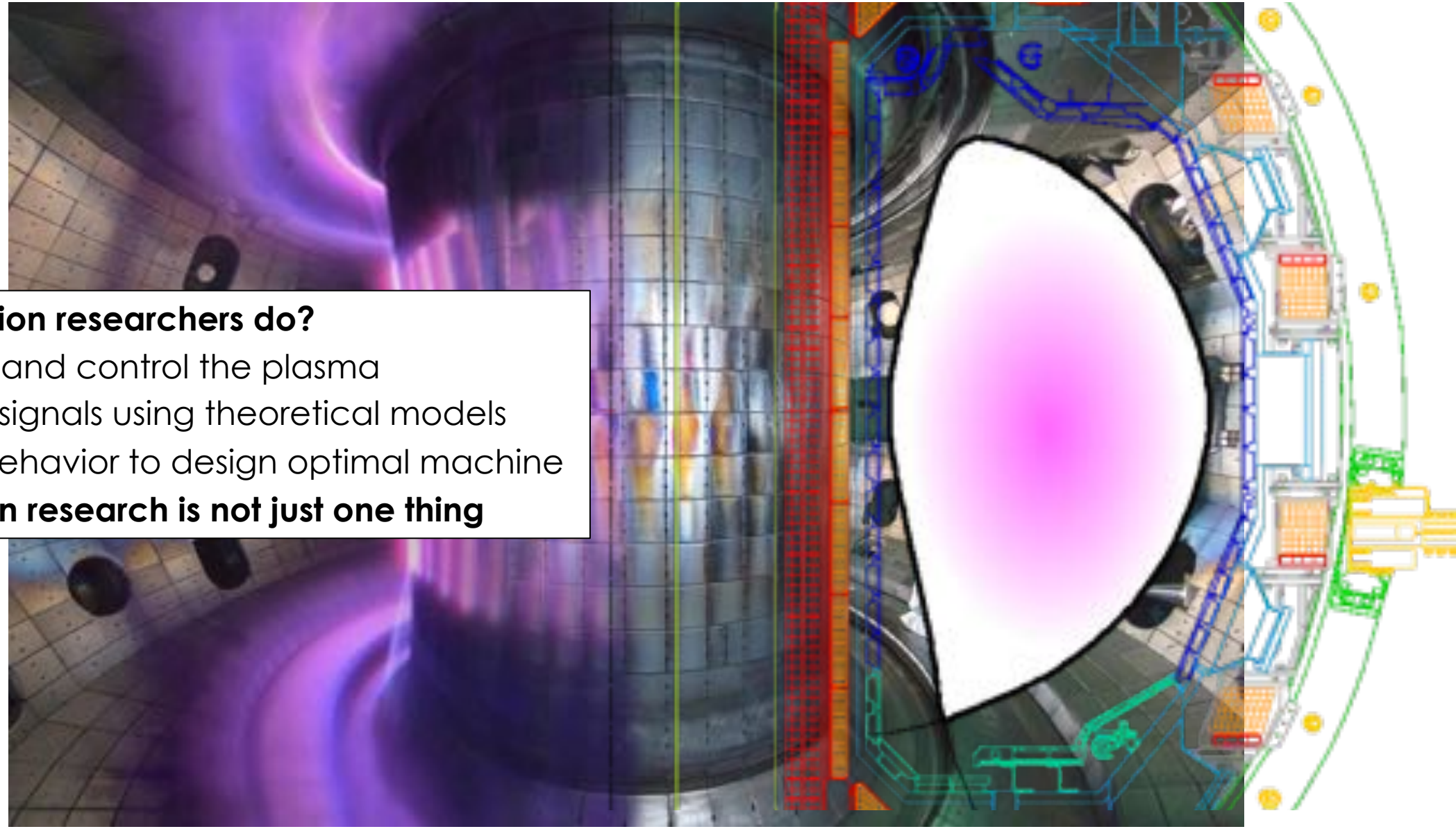
We've been making great progress in confining plasmas



There are many challenging problems for fusion



There are many challenging problems for fusion

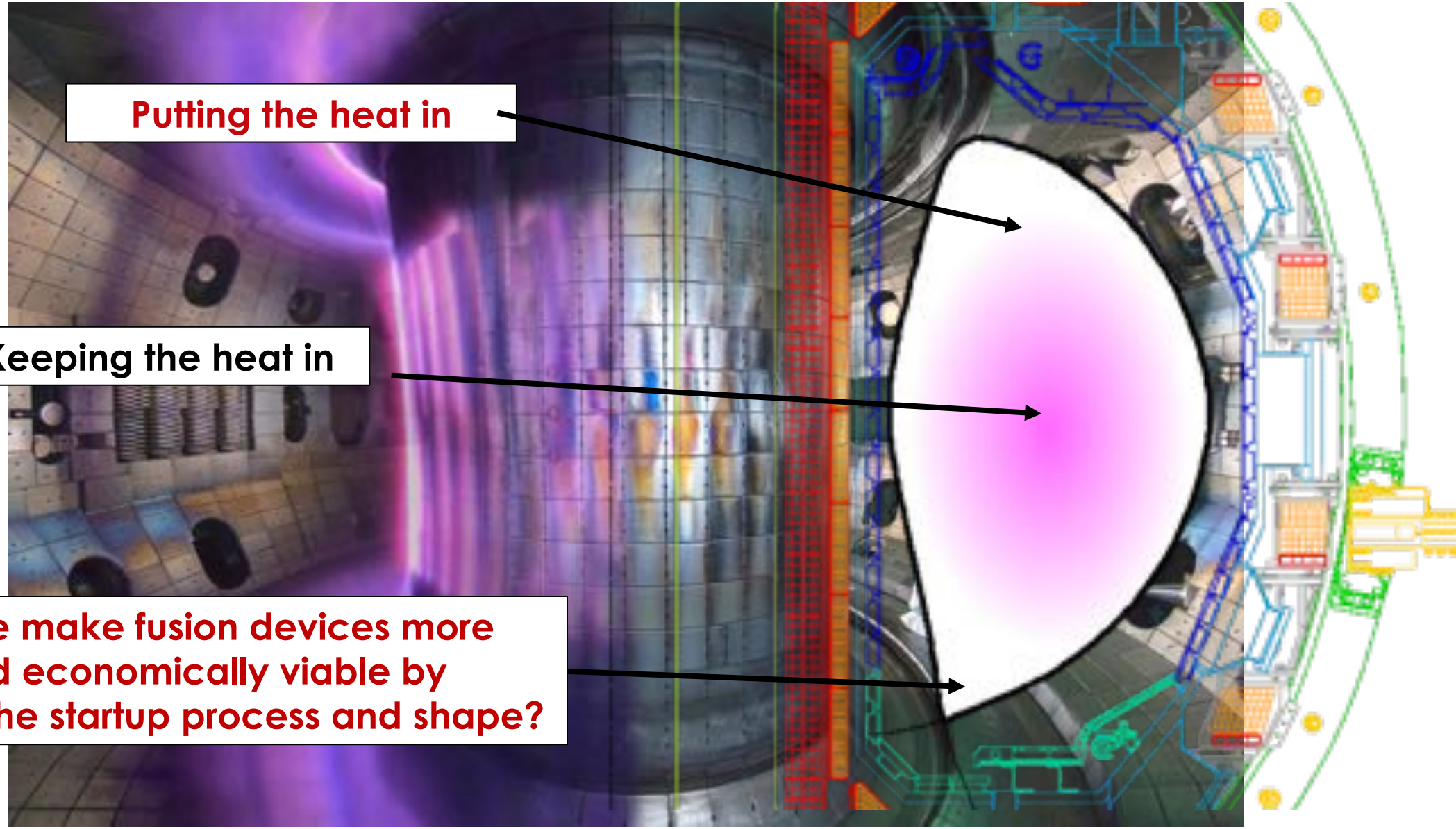


What do fusion researchers do?

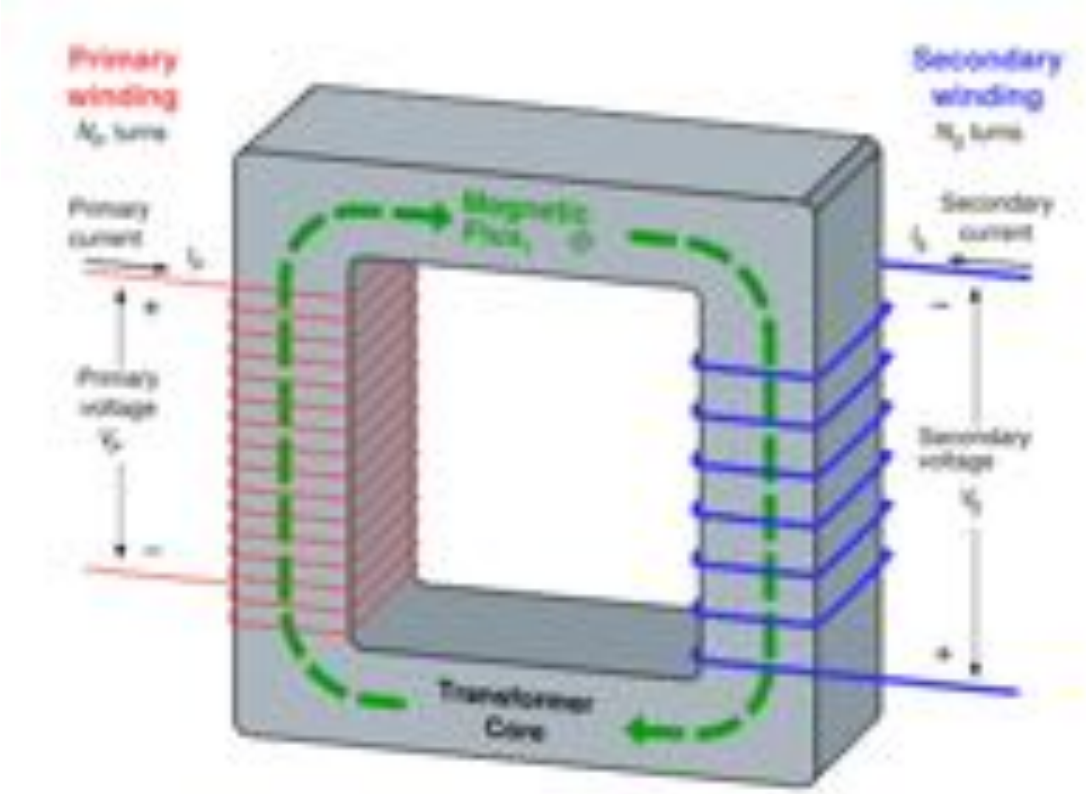
- Measure and control the plasma
- Simulate signals using theoretical models
- Predict behavior to design optimal machine

Fusion research is not just one thing

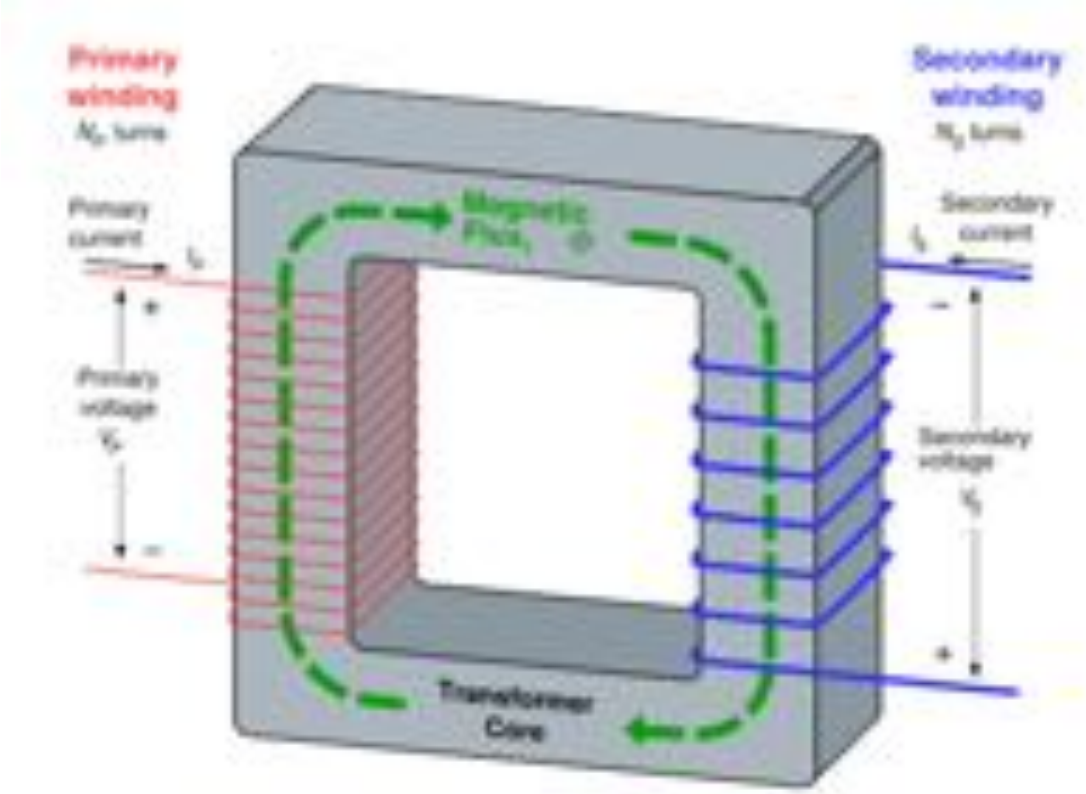
There are many challenging problems for fusion

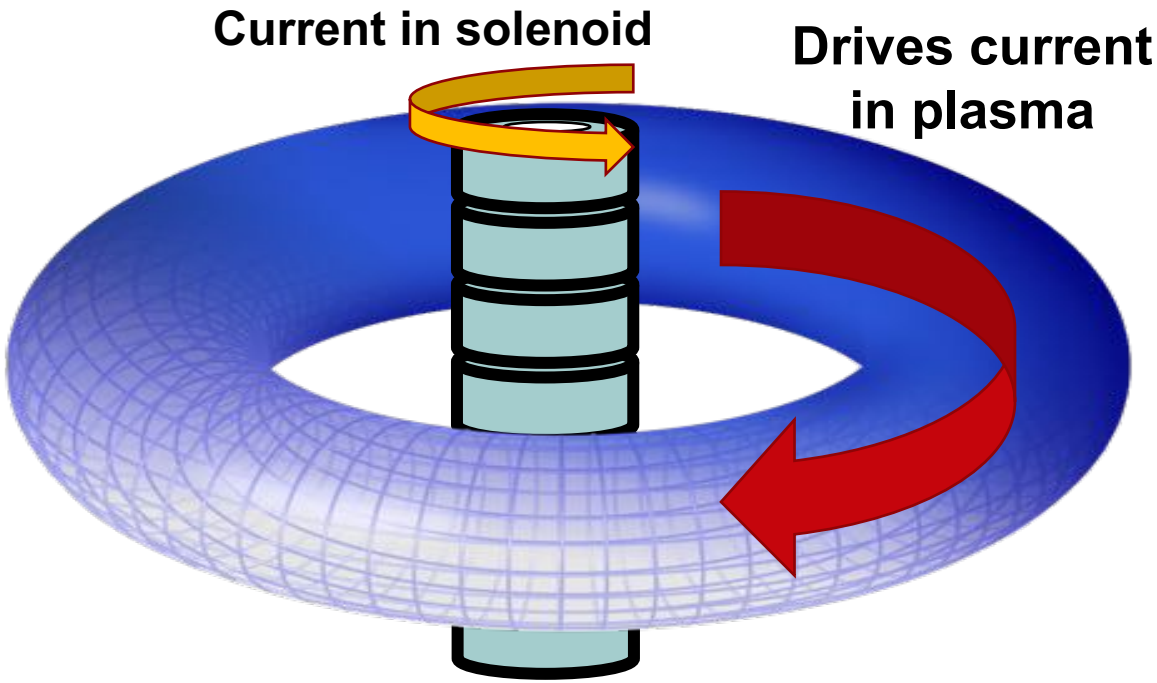


Tokamaks rely on magnetic induction to start



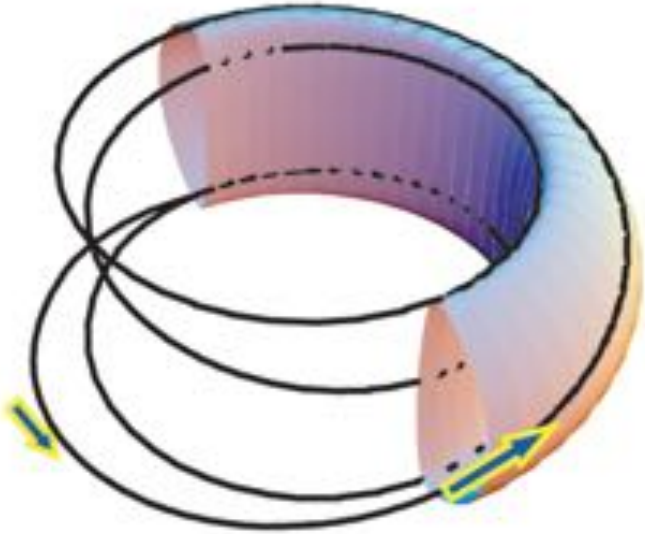
Tokamaks rely on magnetic induction to start





- Takes up space, only used to start so really want to optimize as much as possible in reactor to improve efficiency, cost

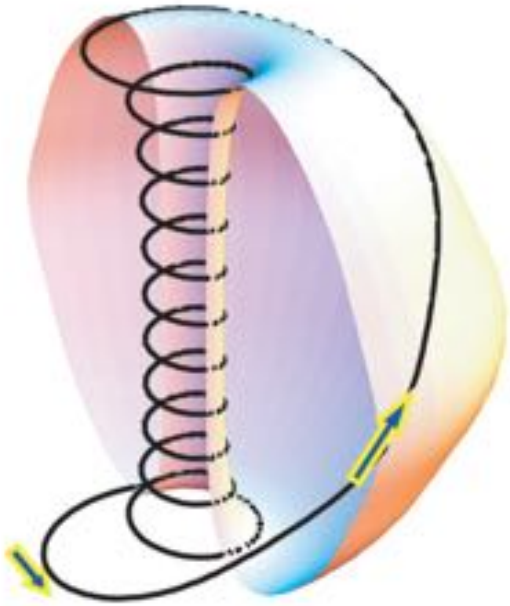
Compact tokamak shapes attractive for fusion energy



Tokamak

Shrinking central column

provides some advantages



Spherical Tokamak

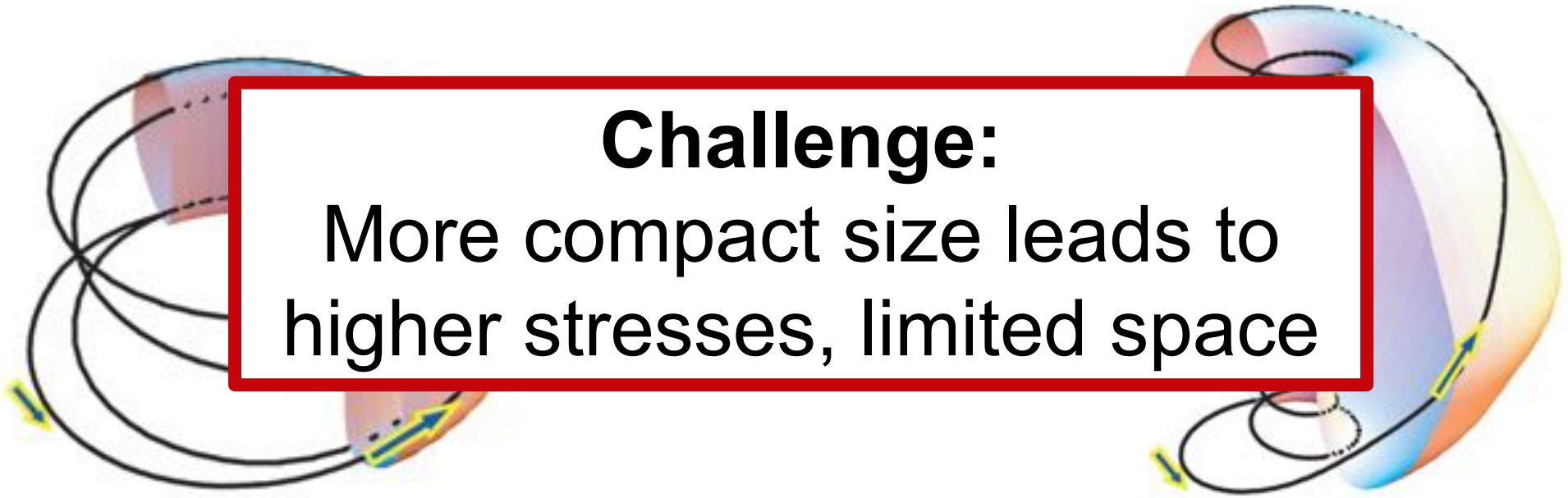
Compact tokamak shapes attractive for fusion energy



Tokamak **Spherical Tokamak**

- Average field line curvature optimizes plasma stability for given toroidal field
  - Also, device cost (B_T ~ $$)
- Efficiency leads to high β_T = (plasma pressure)/(magnetic pressure)

Compact tokamak shapes attractive for fusion energy



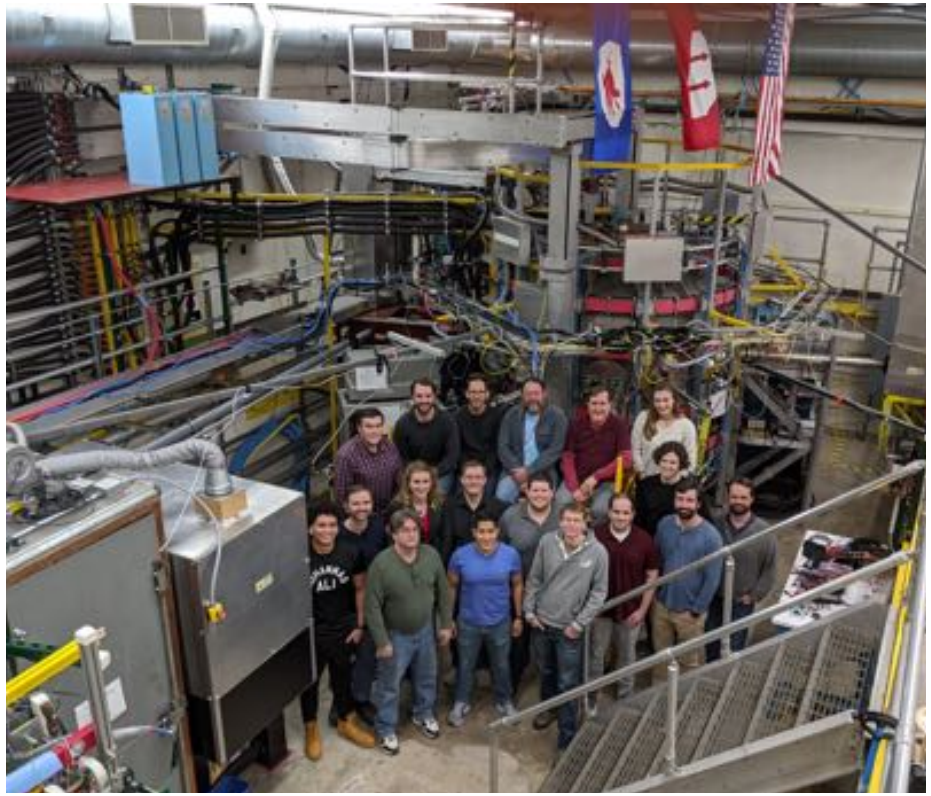
Challenge:
More compact size leads to higher stresses, limited space

Tokamak **Spherical Tokamak**

- Average field line curvature optimizes plasma stability for given toroidal field
  - Also, device cost (B_T ~ $$)
- Efficiency leads to high β_T = (plasma pressure)/(magnetic pressure)

PEGASUS-III – lighting a match for fusion

- Future spherical tokamaks call for solenoid-free operation
  - Need to minimize solenoid due to shielding/cost
- Solenoid removal simplifies tokamak design
  - Potential cost reduction
  - More space for shielding/blanket
  - Lower electromechanical stresses



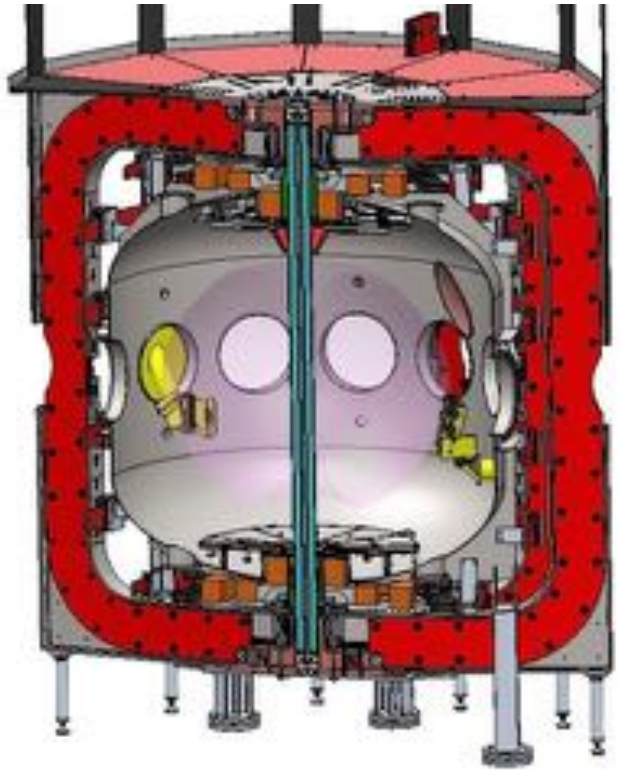
PEGASUS – Research in fusion energy and plasma science, UW-Madison Engineering Physics Department

PEGASUS Website: Publications, Presentations
http://pegasus.ep.wisc.edu

PEGASUS-III – lighting a match for fusion

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- Solenoid removal simplifies tokamak design
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  - Lower electromechanical stresses
- Major upgrade to PEGASUS facility underway to study several innovations in plasma startup
  - Local & coaxial helicity injection
  - Microwave startup and sustainment

PEGASUS-III:
Solenoid-free ST

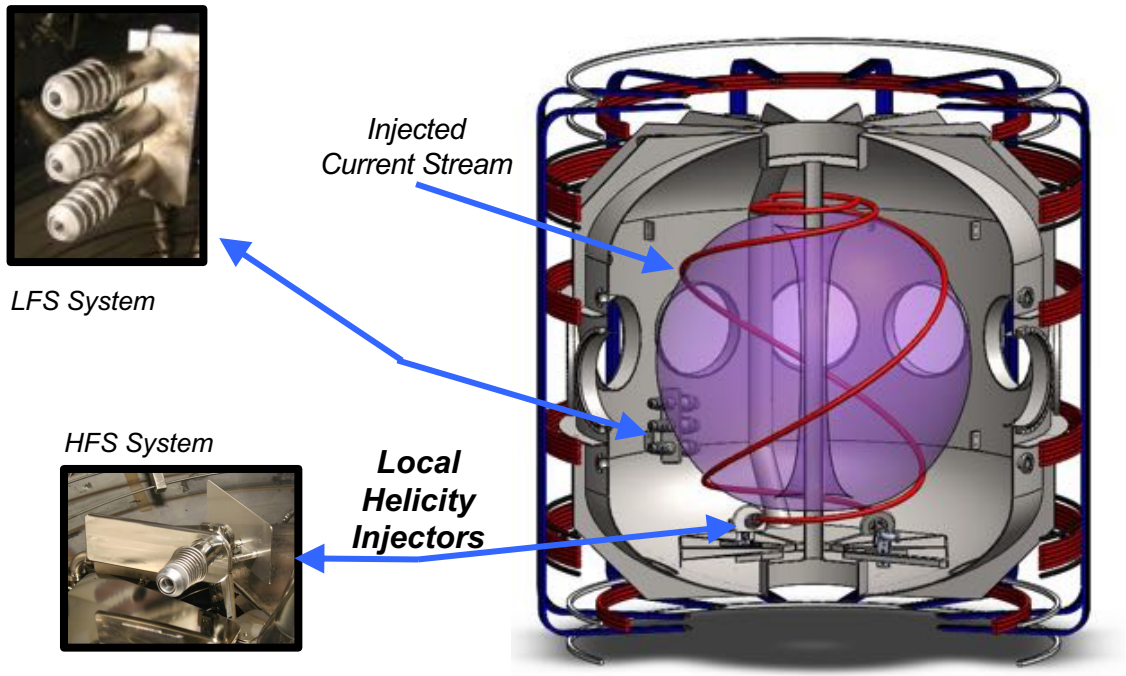


WISCONSIN UNIVERSITY OF WISCONSIN–MADISON
UNIVERSITY of WASHINGTON
OAK RIDGE National Laboratory
PPPL

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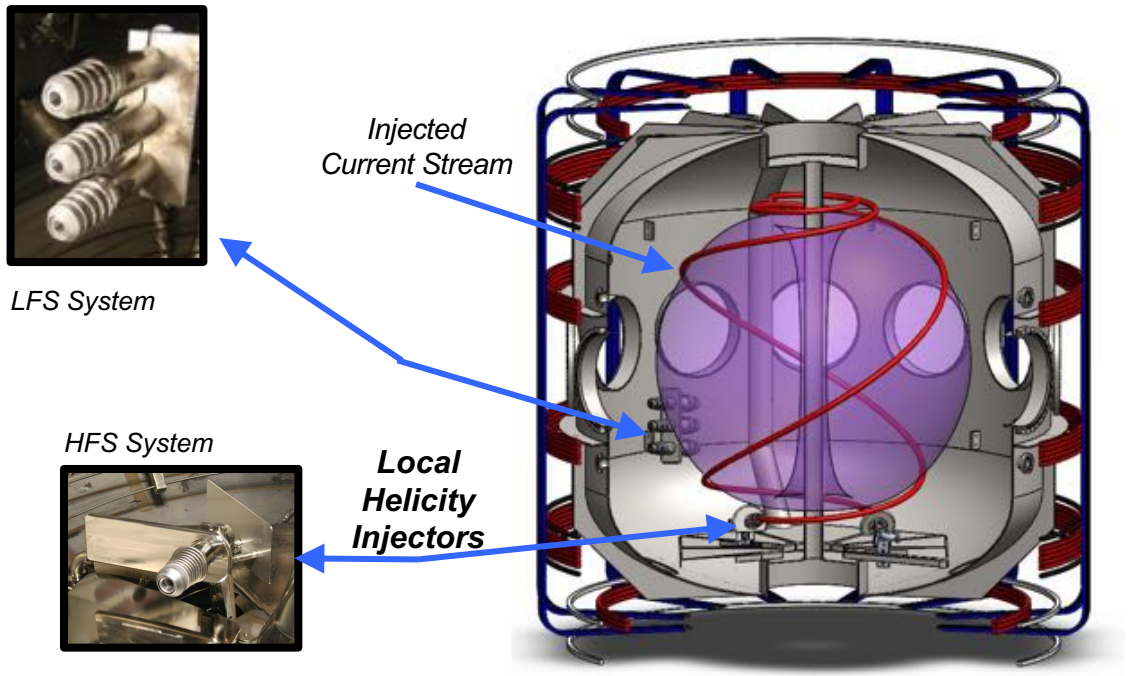
Localized arc plasma sources are a promising non-solenoidal startup technique

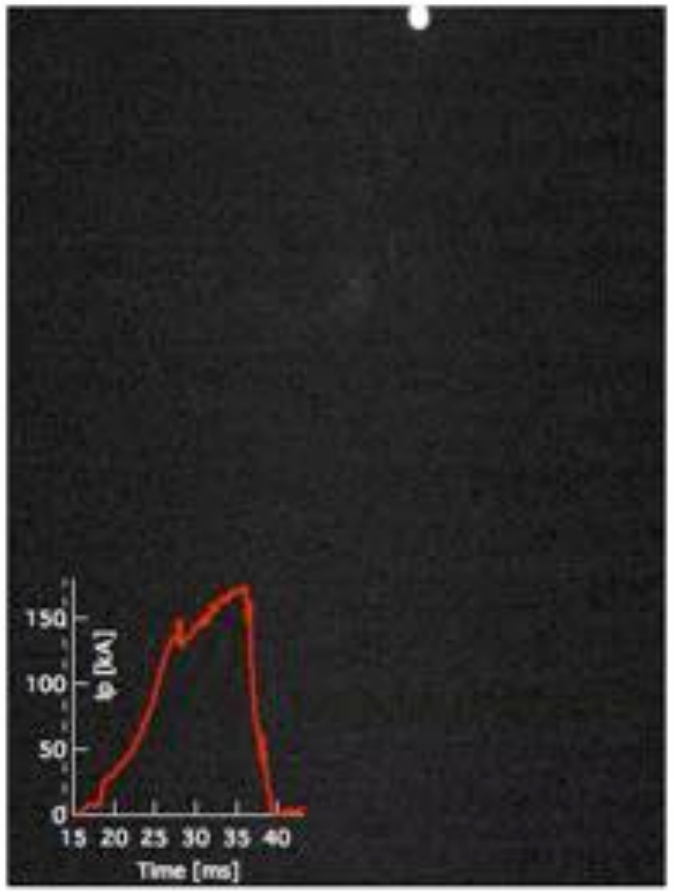
- Edge current extracted from injectors
  - Relaxes to a tokamak-like state
- Used routinely for startup on PEGASUS



Localized arc plasma sources are a promising non-solenoidal startup technique

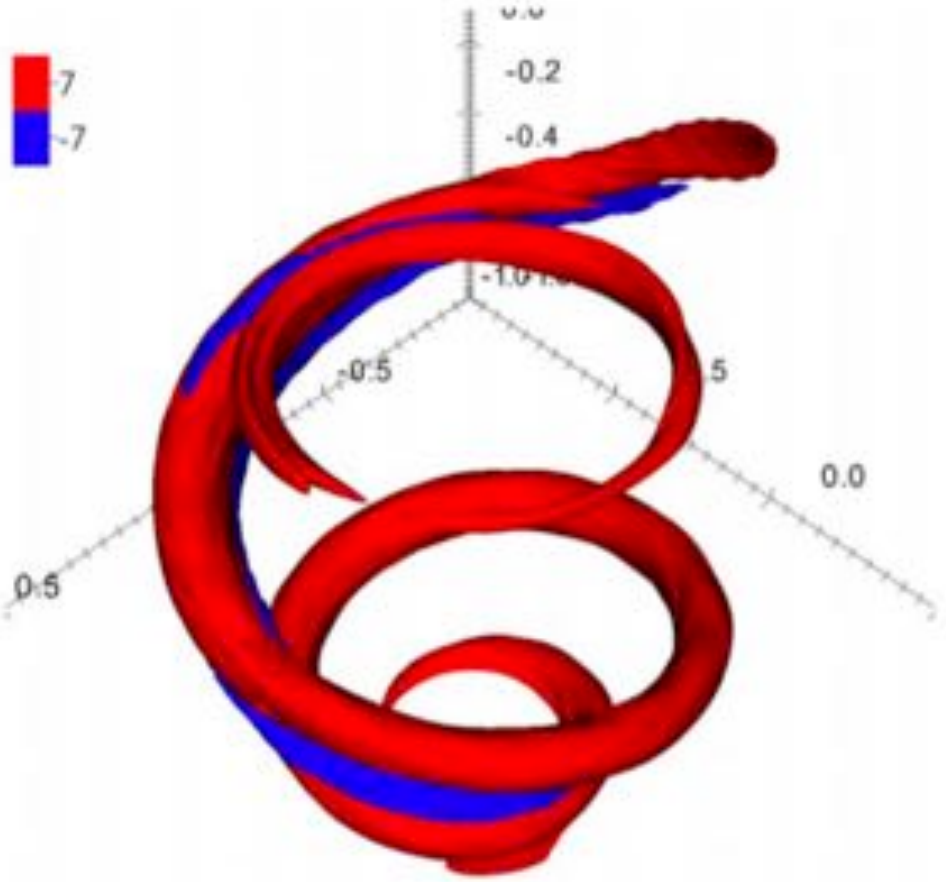
- Edge current extracted from injectors
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Simulations provide understanding and projections to guide experiments

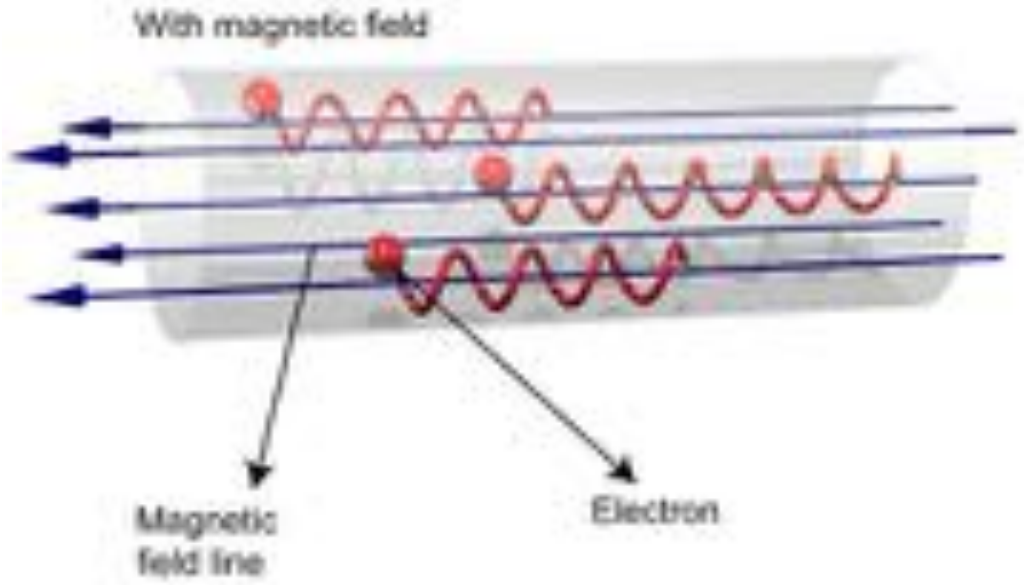
NIMROD Simulations Showing Current Ring Formation From A Helical Current Stream

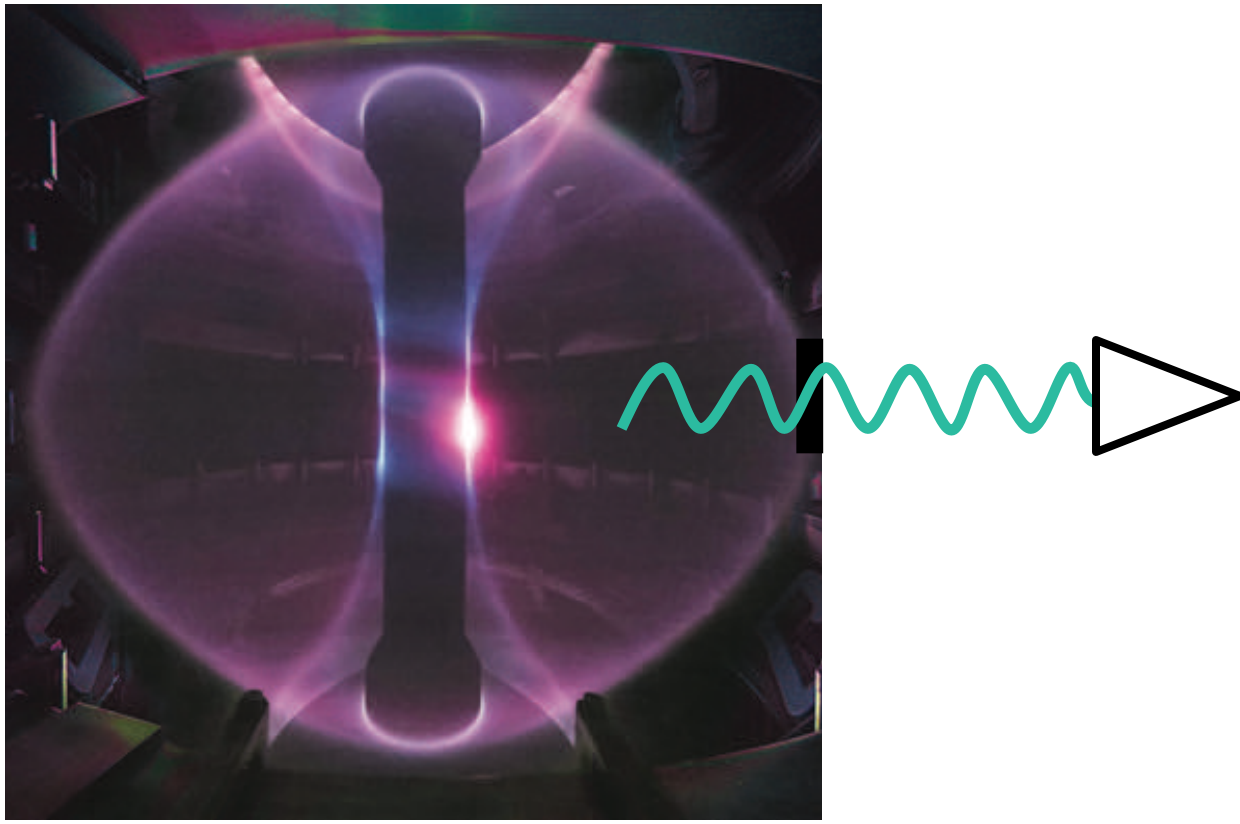


J.O. Bryan et al. 2012 *Phys. Plasmas* **19** 080701



Microwave injection provides plasma heating and drives current

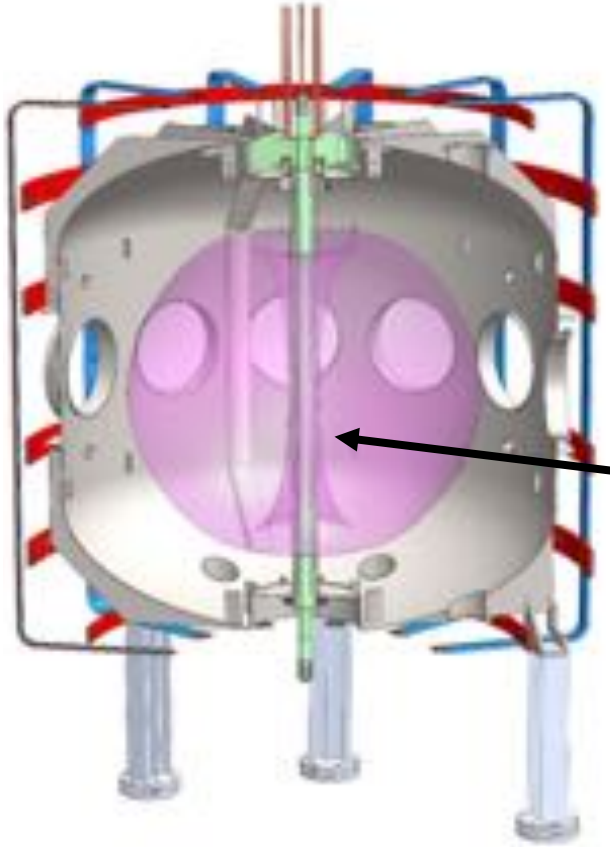




- Choose microwave frequency to natural frequency of the plasma to transfer energy

Facility upgrade to PEGASUS-III underway!

PEGASUS

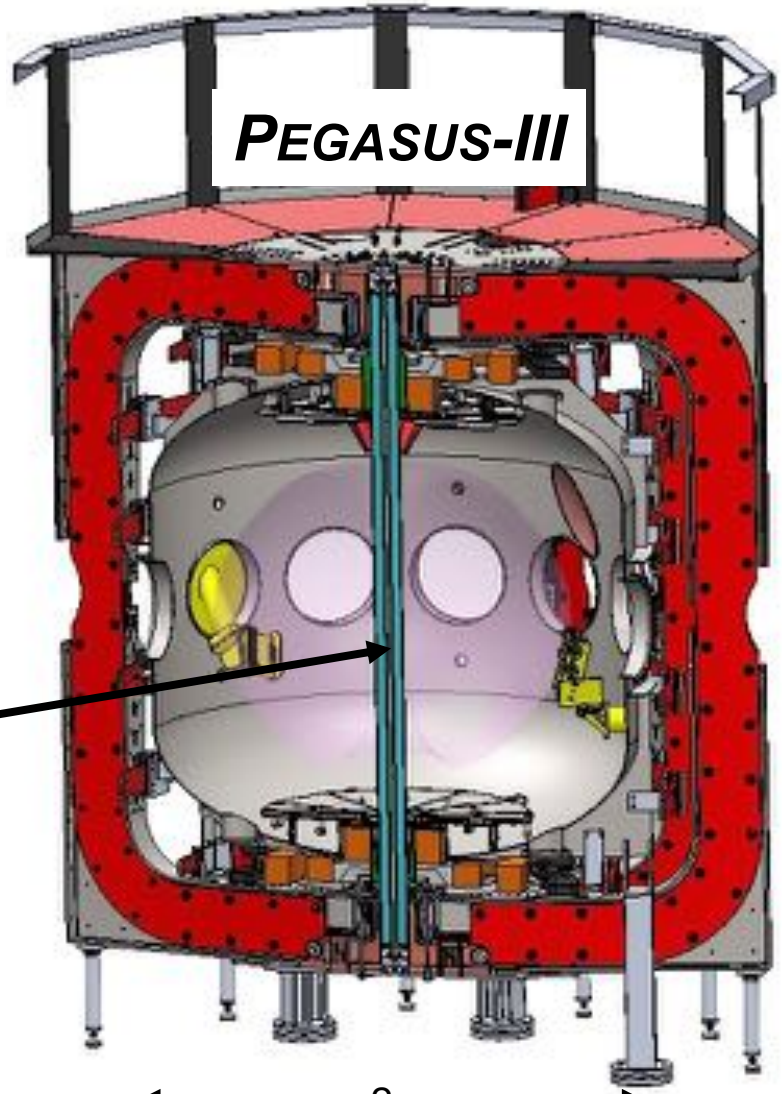


PEGASUS-III:

- No central solenoid leaves more space for magnetic coils

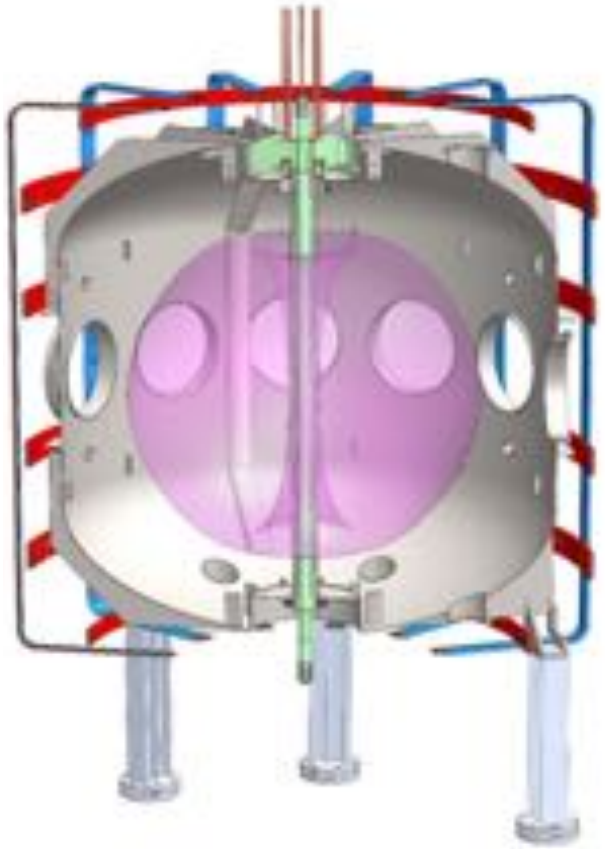


PEGASUS-III



Facility upgrade to PEGASUS-III underway!

PEGASUS

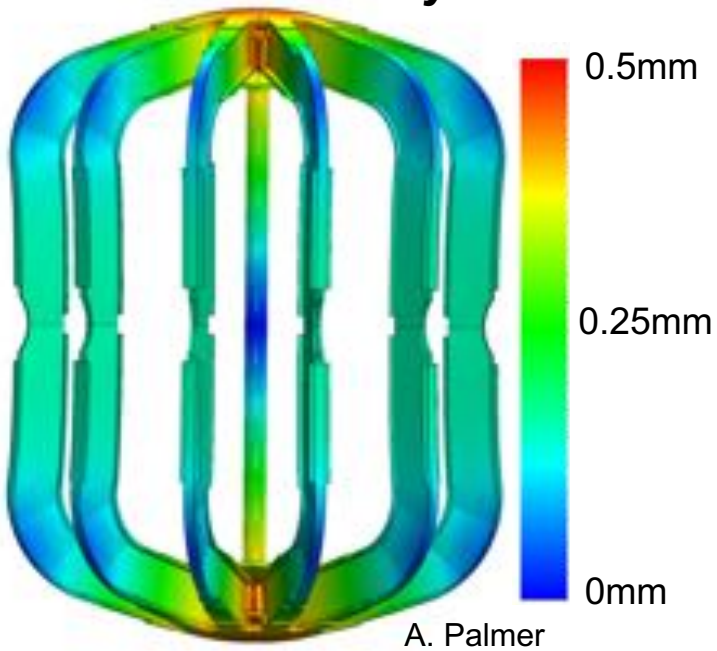


2 m

PEGASUS-III:

- Stronger support structure handles stress from increased field

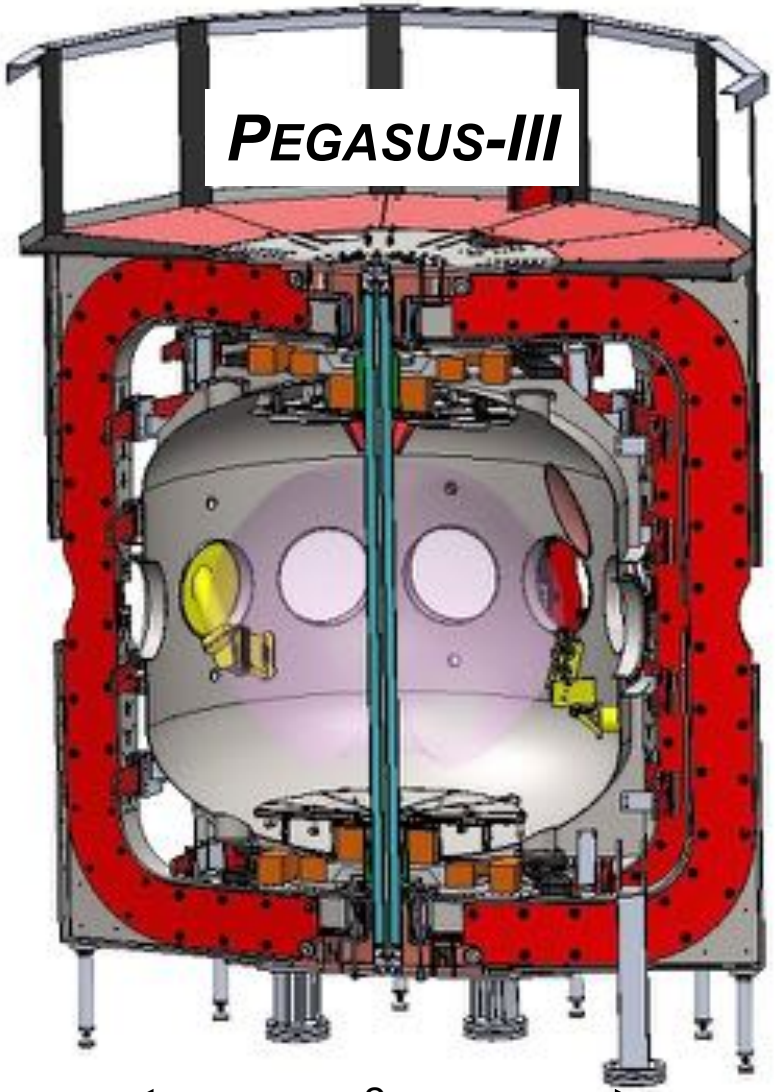
Stress analysis



A. Palmer

Flex joint relieves thermal stresses while opposing magnetic stresses

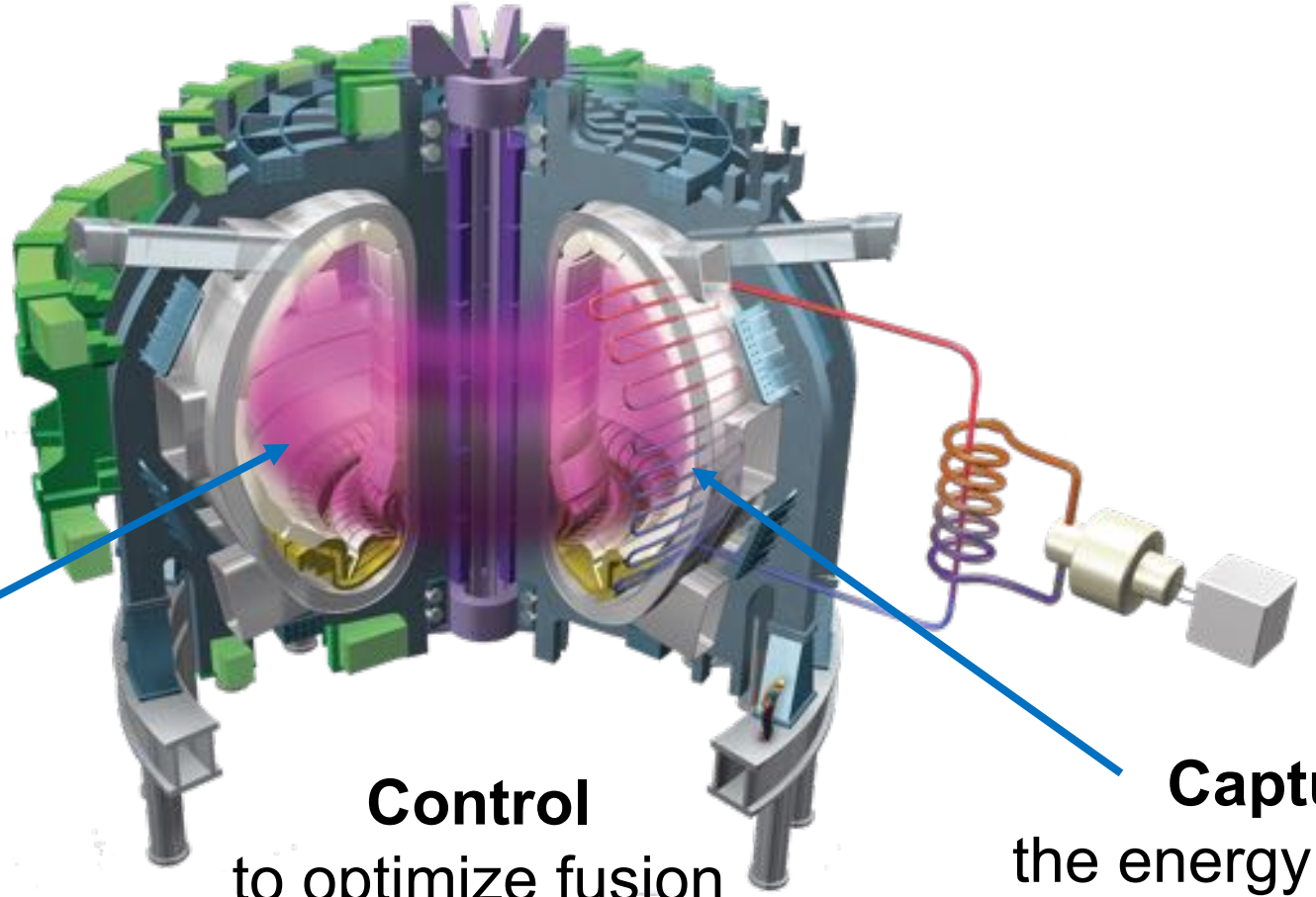
PEGASUS-III



2 m

Great! How do we make a fusion power plant?

We have to develop science and engineering to:

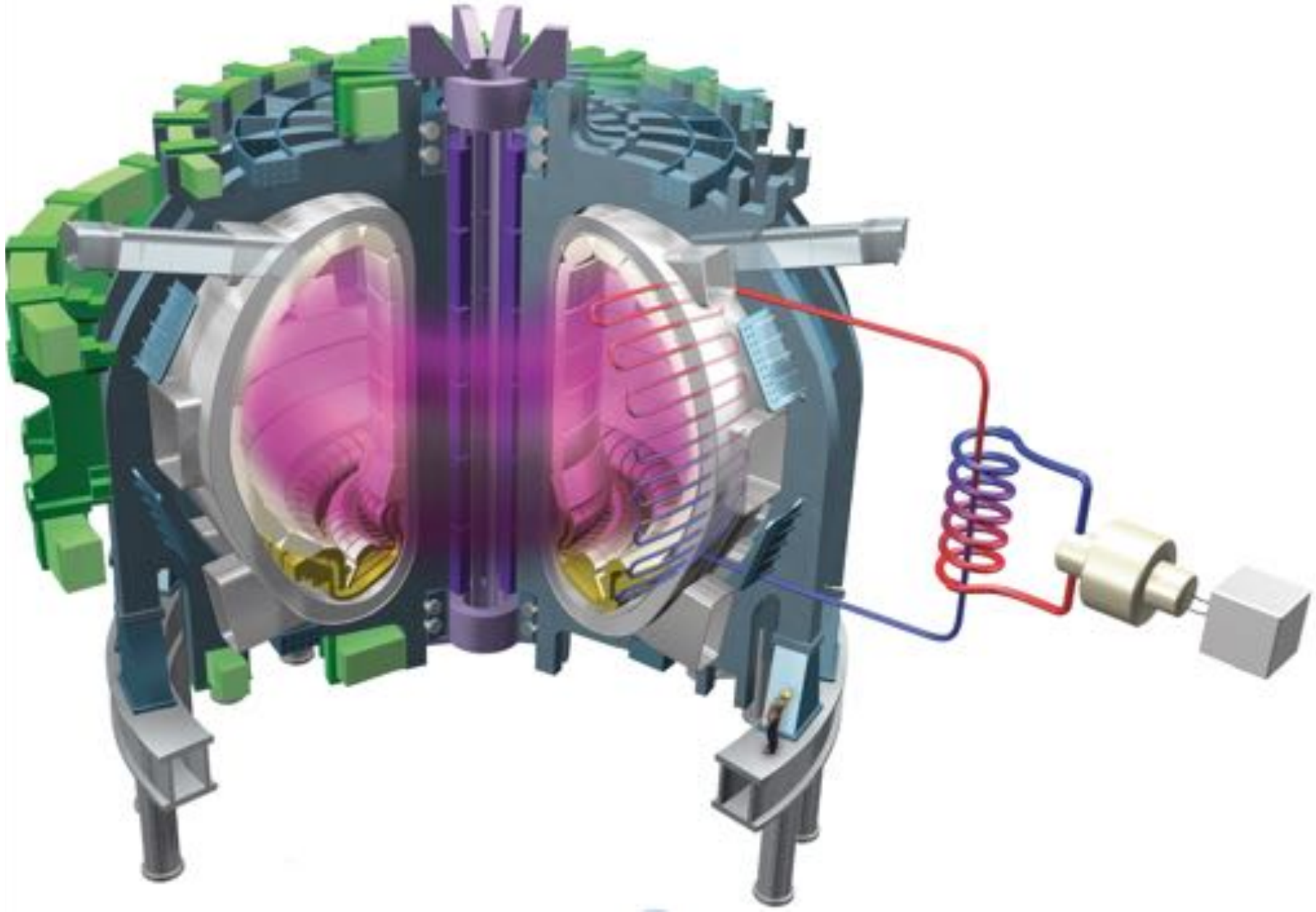


Create
the conditions for continuous fusion reactions

Control
to optimize fusion reactions

Capture
the energy from the reactions

The challenge: demonstrating net energy gain



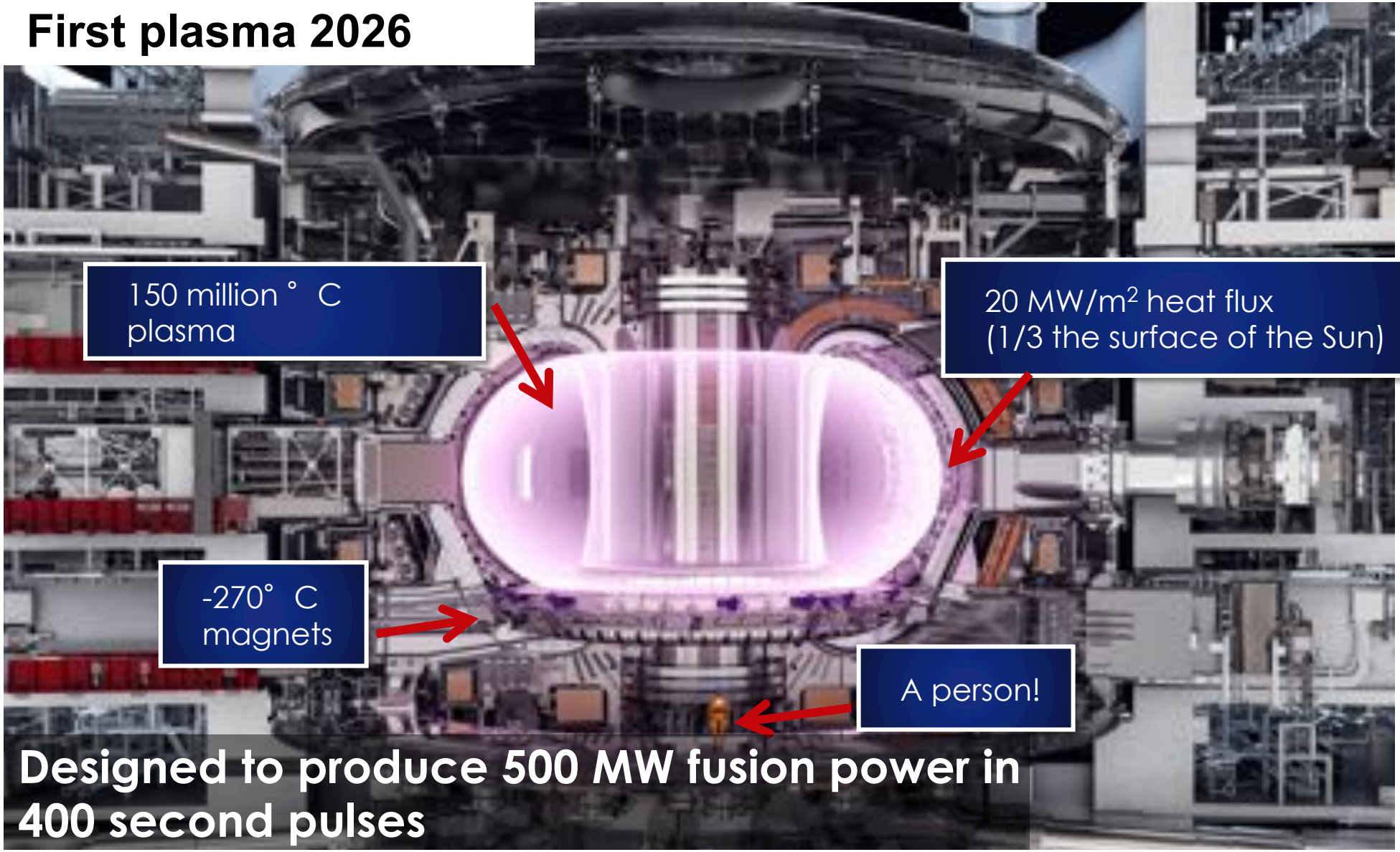
ITER: The first self-heated fusion device is over 70% built!

Millions of components must be assembled with mm precision



ITER's Mission: To demonstrate x10 fusion energy gain

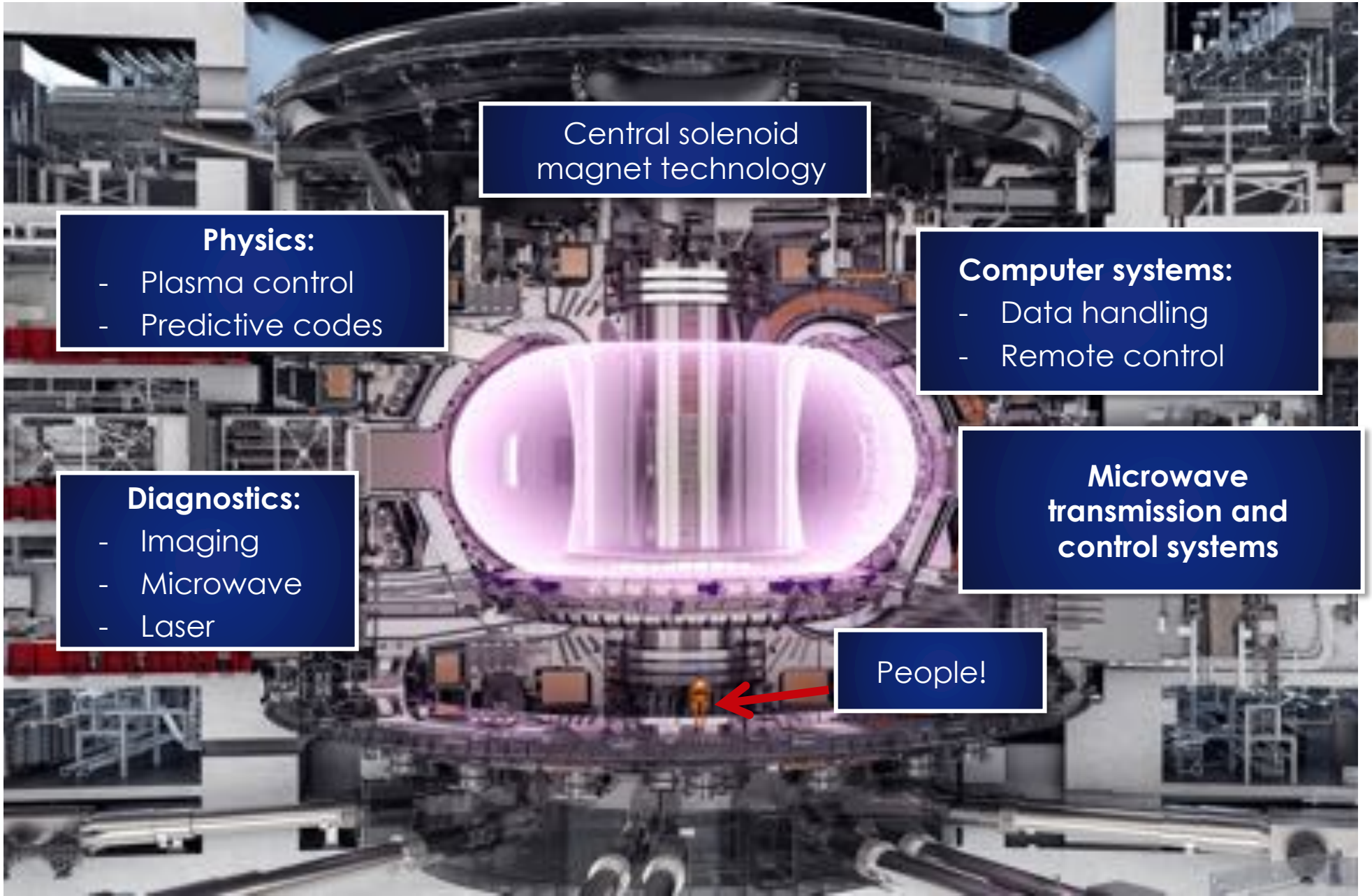
First plasma 2026



Designed to produce 500 MW fusion power in 400 second pulses

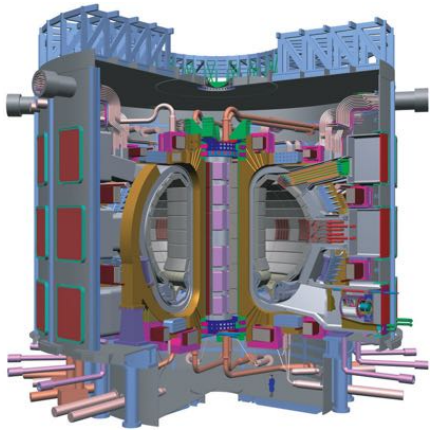
Partnership between USA, EU, Japan, Russia, China, Korea and India

The U.S. is making key contributions to ITER

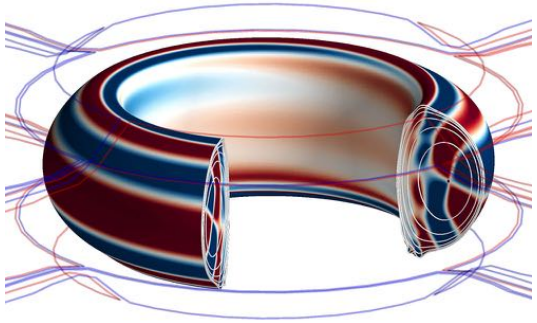


Recent advances have made great progress towards practical, economical fusion energy

ITER: Access to burning plasma



Advanced plasma control



J-K Park, PPPL

Exascale computing



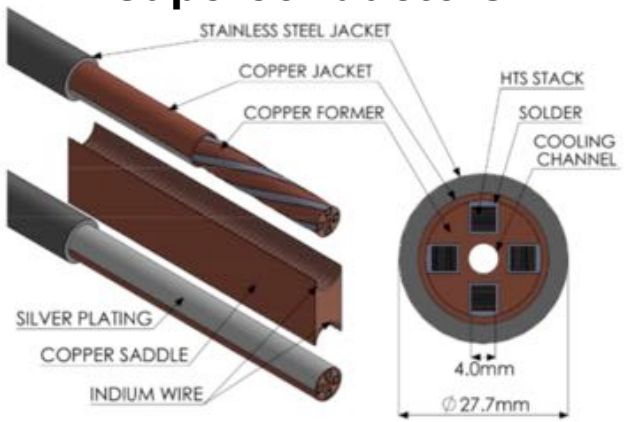
A. Bhattacharjee

Additive/Advanced manufacturing



A. Seltzman, APS-DPP (2020)

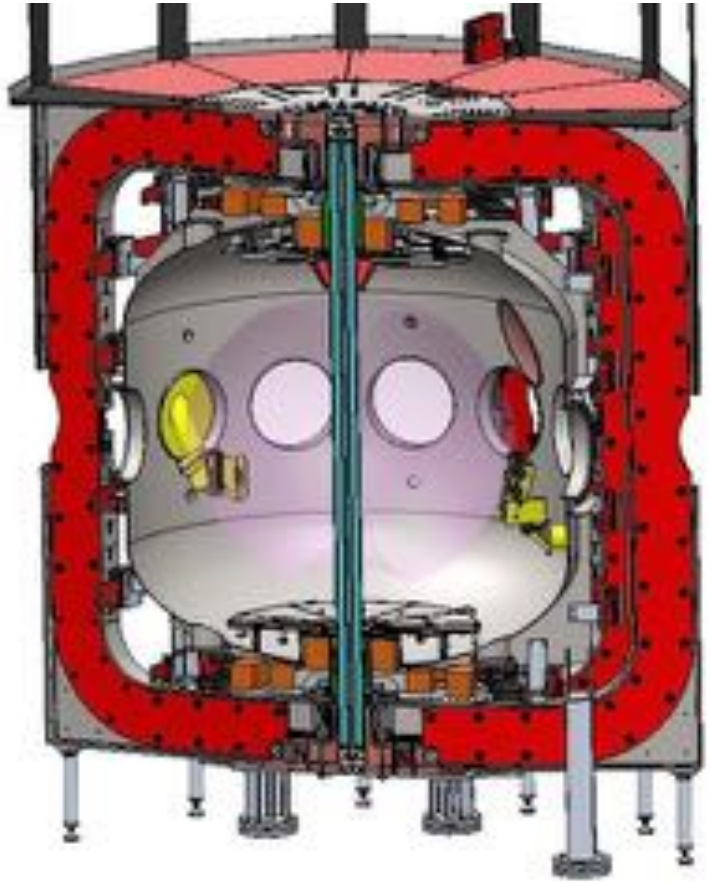
Hight temperature superconductors



Z. Hartwig, et. al., Supercond. Sci. Technol. 33 (2020) 11LT01

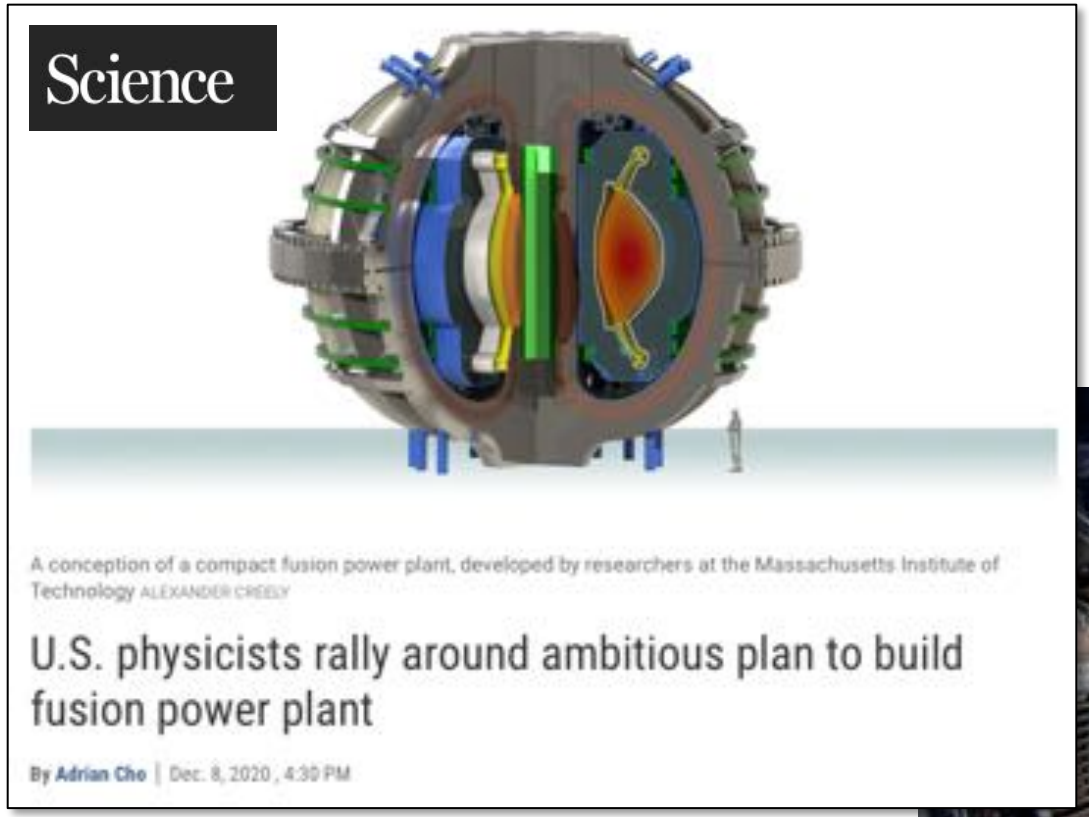
Fusion offers a promising solution for clean energy

- The progress in magnetic fusion energy research has been immense – ITER is the next evolution on the horizon!
- Numerous US, international institutions and private companies focused on solving remaining challenges to bring fusion energy to the market
- New PEGASUS-III facility will investigate innovative tokamak startup methods
  - Bold test using reactor relevant techniques



PEGASUS-III – Research in fusion energy and plasma science, UW-Madison Engineering Physics Department

Thank you!



Want to see what it's like to run a tokamak?



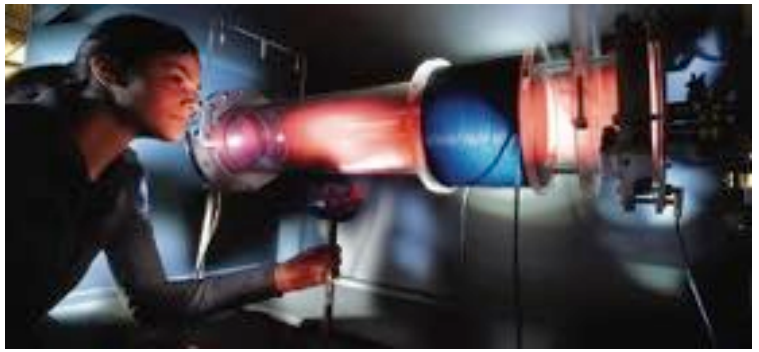
Contact for this talk:
Steffi Diem, email: sjdiem@wisc.edu

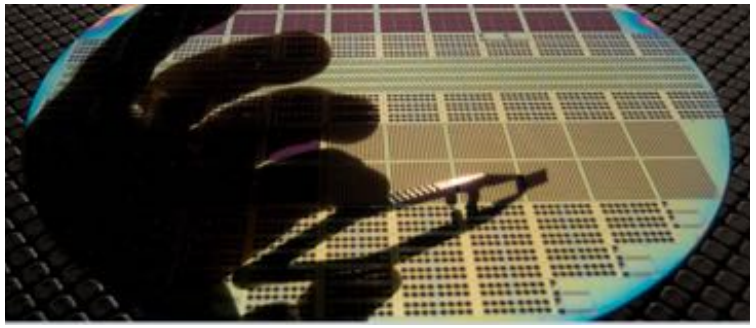


Extra slides

Plasmas and fusion have many applications and connections to other areas of science

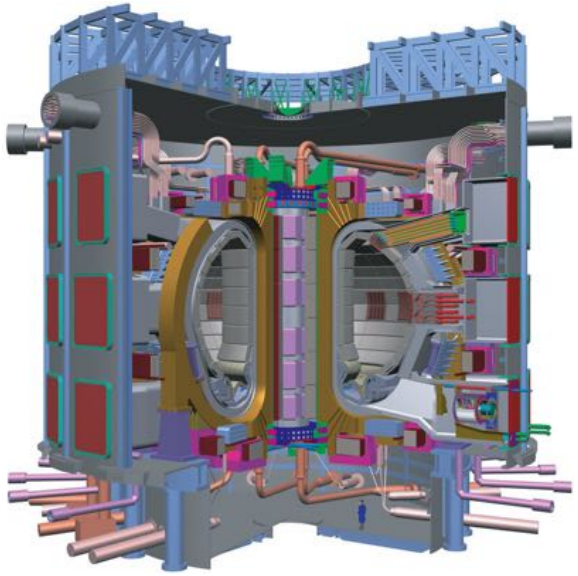
- Fusion reactions
  - Small portable neutron sources
  - Materials diagnosis
- Plasma physics
  - Semiconductor etching
  - Plasma materials processing
  - Space thrusters/propulsion
  - Driver for superconductivity development
    - HTS cables for electrical grid
    - HTS for more compact fusion devices
  - Isotope separation
  - Rail guns
  - Astrophysics, ionospheric physics







Fusion is expensive? Cost in perspective



ITER construction cost
estimated EUR 17 billion



Single CVN-78-class aircraft carrier:
$9.8 billion

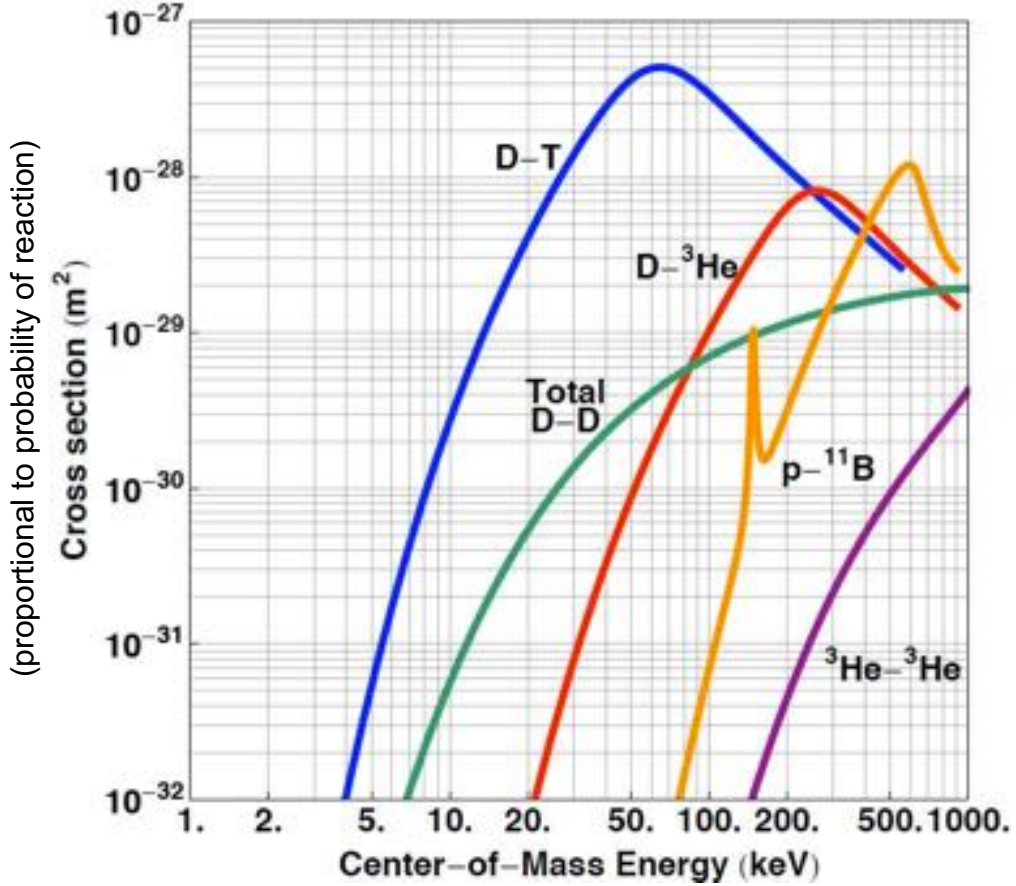


Single B-2 Spirit: $737 million



In total, the F-22 Raptor cost
$79.2 billion to develop

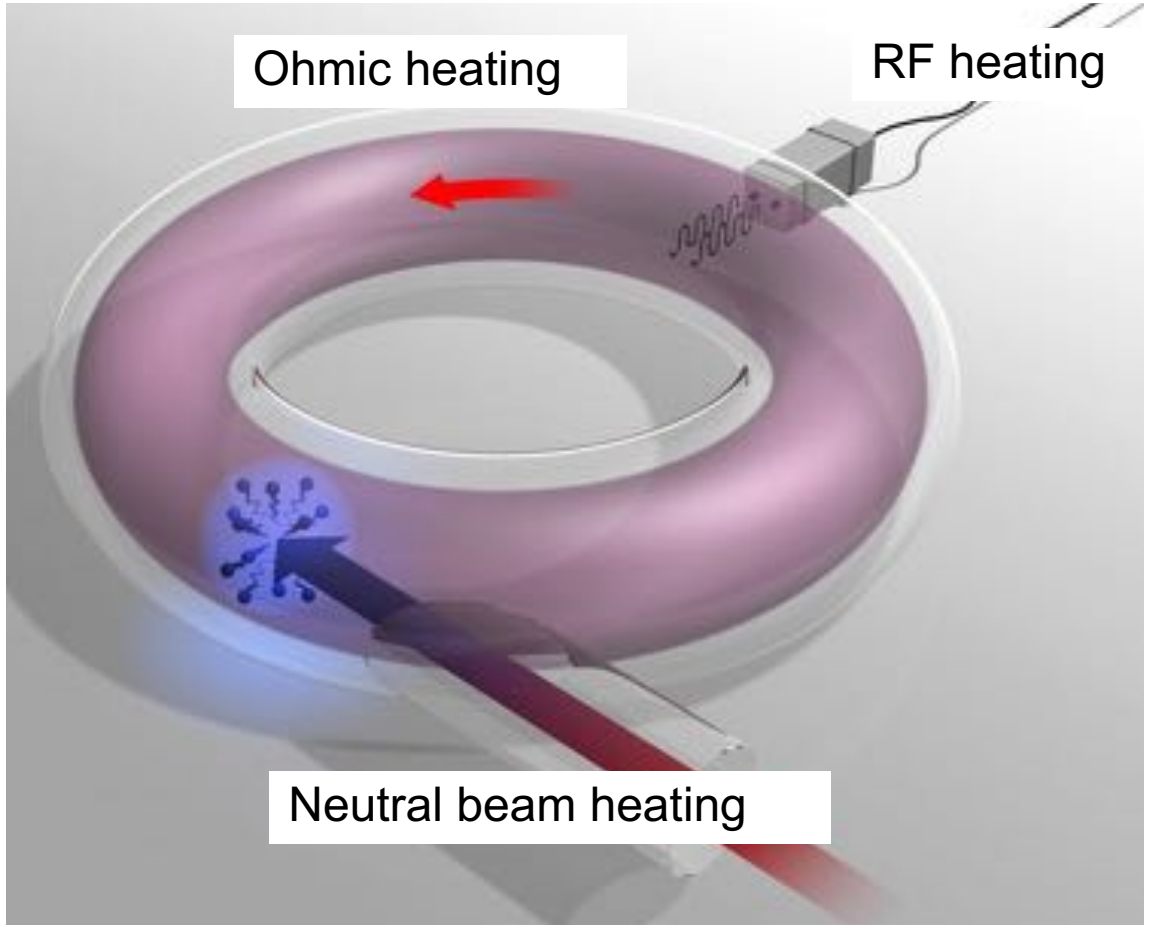
To overcome repulsion, fuel must be at extreme temperatures



- Temperature required for practical fusion devices is ~ 15 keV, ~150 million Kelvin!
  - Center of the sun is ~15 million Kelvin
- At these extreme temperatures, matter is in the plasma state
  - Gas becomes ionized (plasma) at T > 10,000 K (1 eV)

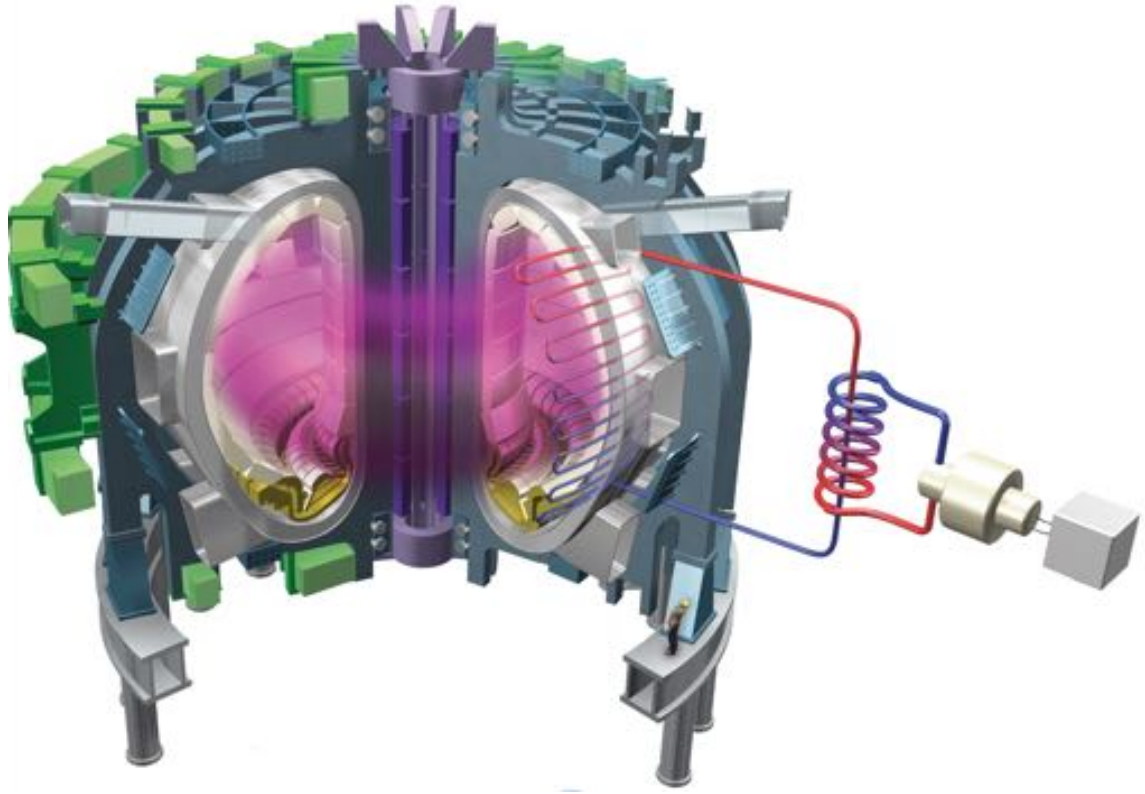
External heating required to reach fusion temperatures

- Ohmic heating
  - Magnetic induction using plasma as secondary winding of a transformer
  - Resistive heating similar to driving current in wire, creates poloidal field
- Neutral beam injection
  - Energetic, neutral particles injected and are ionized, transferring energy to plasma via collisions
- RF heating
  - Radiofrequency heating uses waves to transfer energy to electrons and/or ions
  - Variety of frequency ranges used – wide use is in the microwave frequency range



Challenges for burning plasmas research

- Bulk of research to date has been dedicated to creating a burning plasma
- Engineering challenges still need to be addressed to bring fusion power to the grid
  - Closing the tritium breeding cycle
  - Neutral beams take up valuable tritium breeding blanket
  - Handling a 14 MeV neutron environment
- Long pulse operations
  - Lifetime of internal components
  - Handling extremes of power flux, temperature variations
  - Heating, vacuum pumping, neutral beams, etc. that operate at long pulse



Fusion research is not one thing: It's engineering, experimental physics, theoretical physics, materials science…. All coming together to make a product