MancheSTAR

Lecture 3: Reactor Design (Tokamak)

MancheSTAR nuclear fusion lecture series

Tom Hughes, Charlotte Brown 2025/6

Sign in form

Course outline (subject to change!)

1. Overview/Introduction
2. Plasma physics
3. Reactor design (Tokamak)
4. Reactor design (alternatives)
5. Tritium breeding
6. Radiation damage 1
7. Radiation damage 2
8. Superconductors
9. Control and monitoring
10. Designing and testing for fusion
11. Concerns with fusion
12. Summary and quiz

Learning Objectives

To understand:

- How plasma physics fits into reactor design
- What various sections of the tokamak reactor design are for
    - Breeder blanket
    - Magnet coils
    - Divertor
- A brief introduction to material challenges and plasma ignition methods

To have an awareness of:

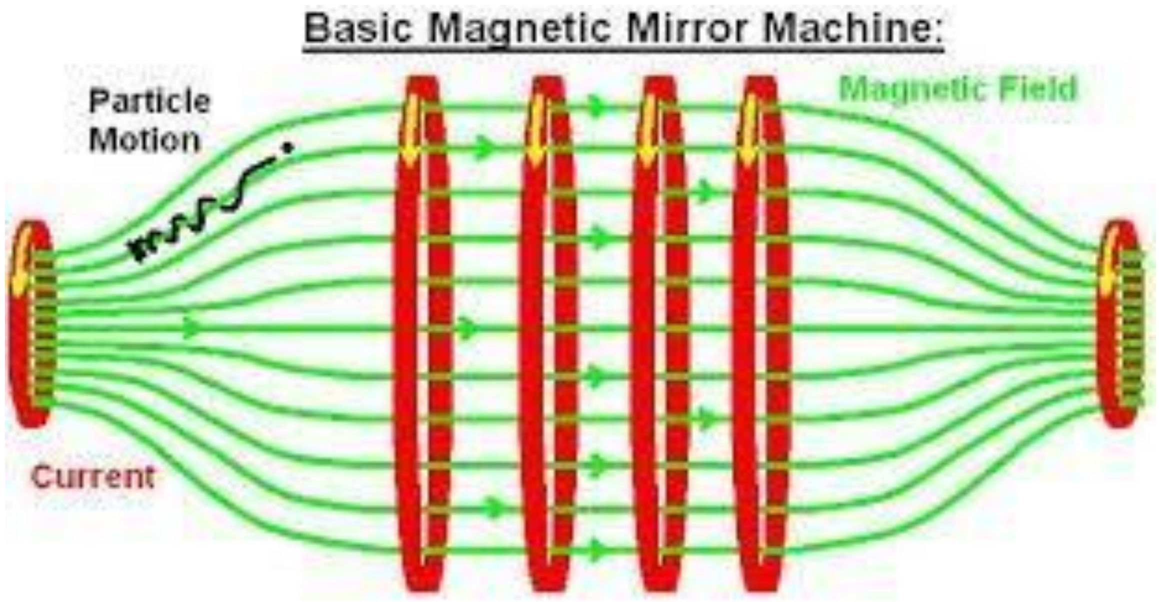
- Tokamak style plants around the world
- How JET works and what it is for (just in time for the tour on the 29th!)

Previously on MancheSTAR…

- What is a magnetic mirror?

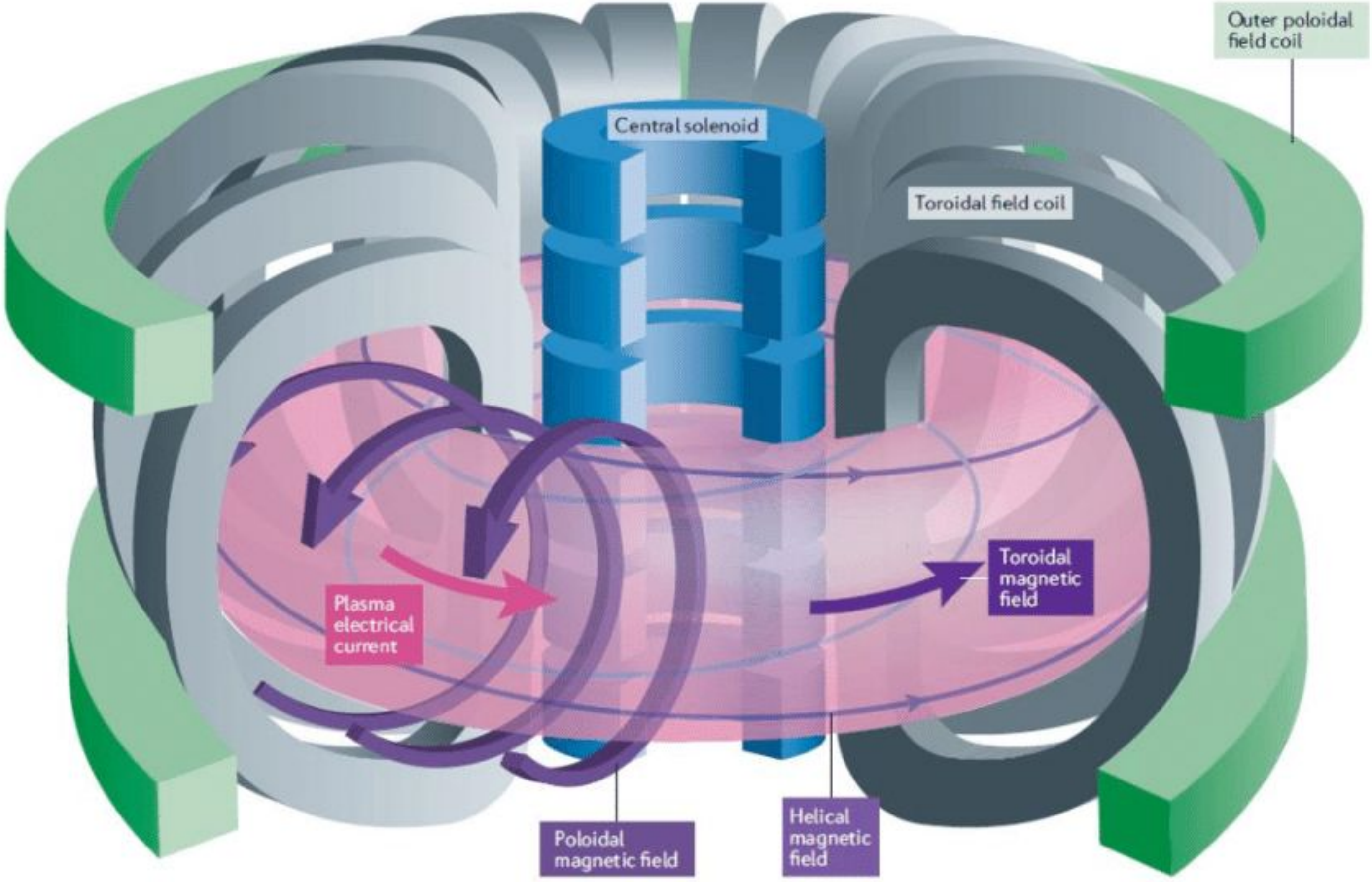
Short Answer

Magnetic mirror answer:

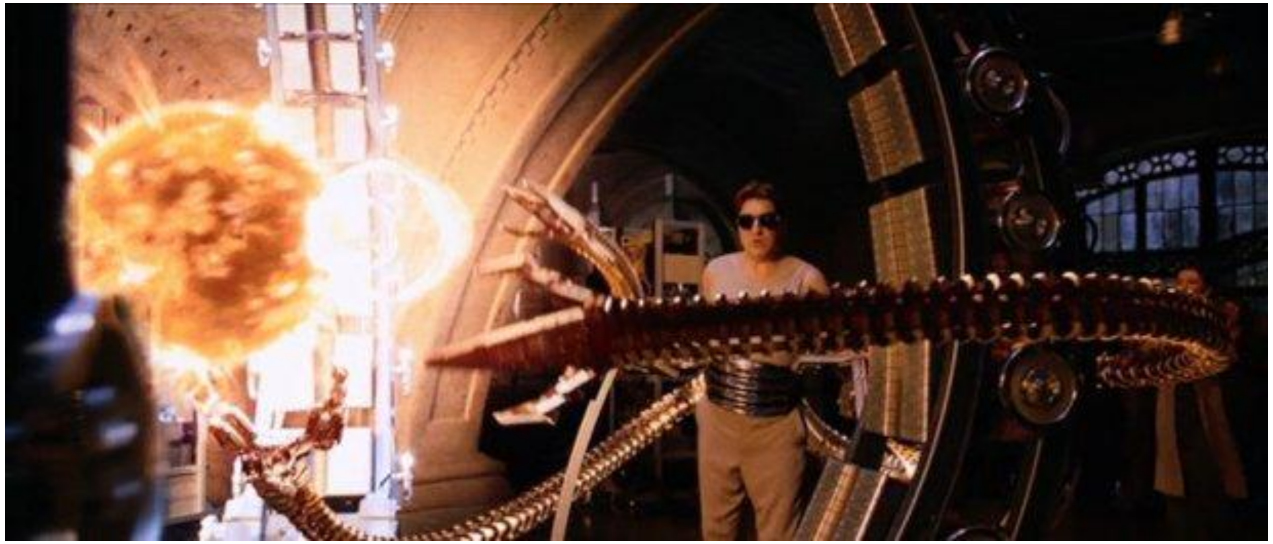


Toroidal shape

- As covered last week, if the ends of a magnetic mirror are looped, the plasma can be sustained without loosing energy
- Naturally giving a toroidal shaped device, the tokamak!



Understanding the challenges behind fusion

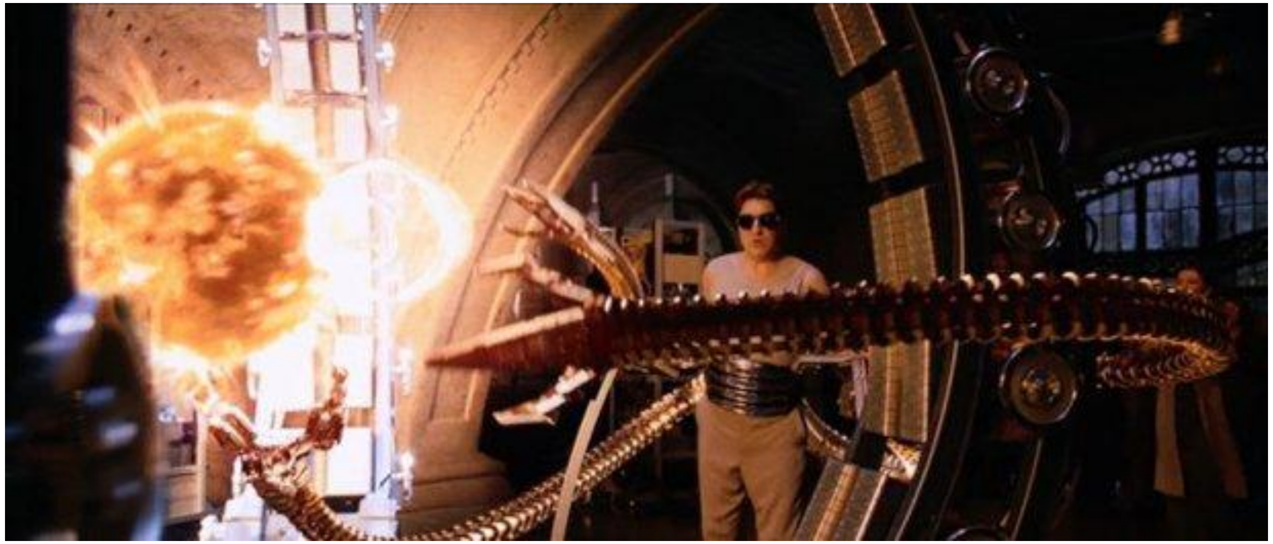


"Precious Tritium… The power of the sun in the palm of my hand" – Doctor Otto Octavius (2004)

Word Cloud

Sam Raimi, Spider-Man 2 (2004)

Understanding the challenges behind fusion



"Precious Tritium… The power of the sun in the palm of my hand" – Doctor Otto Octavius (2004)

What's right?

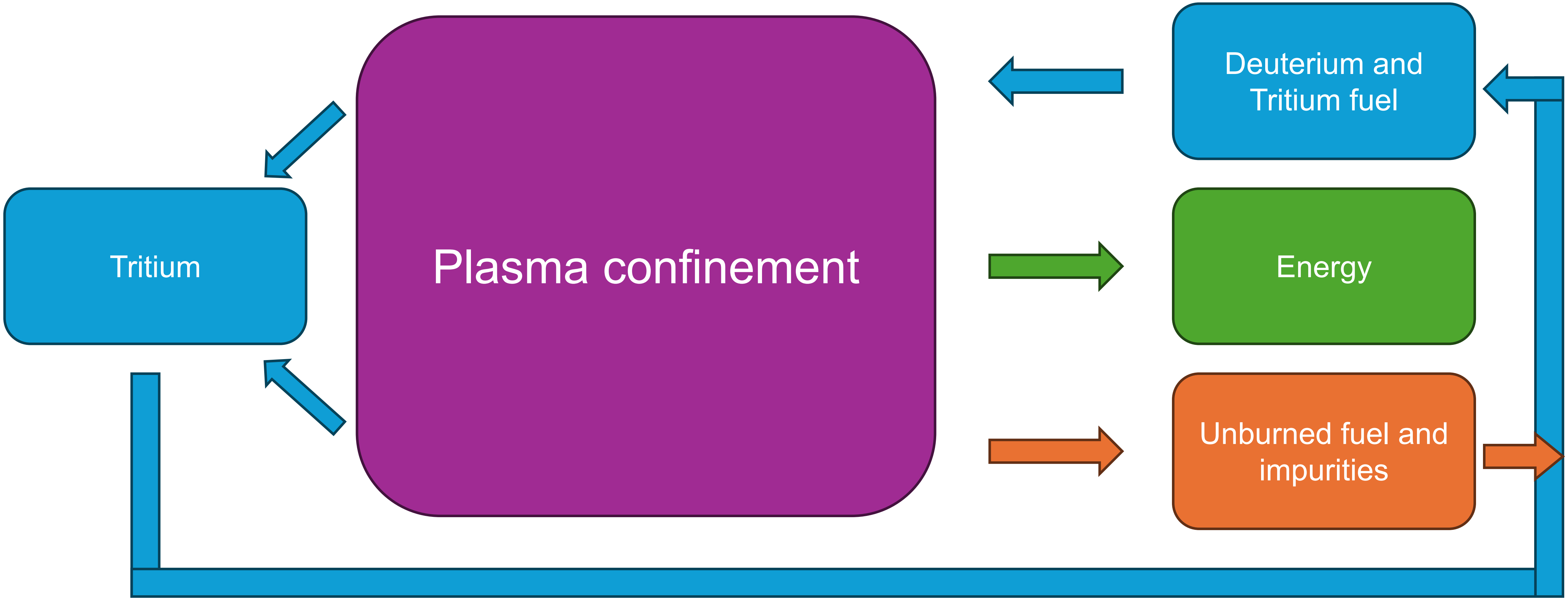
- Tritium is precious; one of the most valuable materials by mass
- Plasma is contained by magnets
- It is 'the power of the sun'

What's wrong?

- Controlling the plasma with robotic arms
- How is energy being extracted?
- Everyone in the room would be dead
    - Fusion reactors contain one of the most hostile environments on the planet

Sam Raimi, Spider-Man 2 (2004)

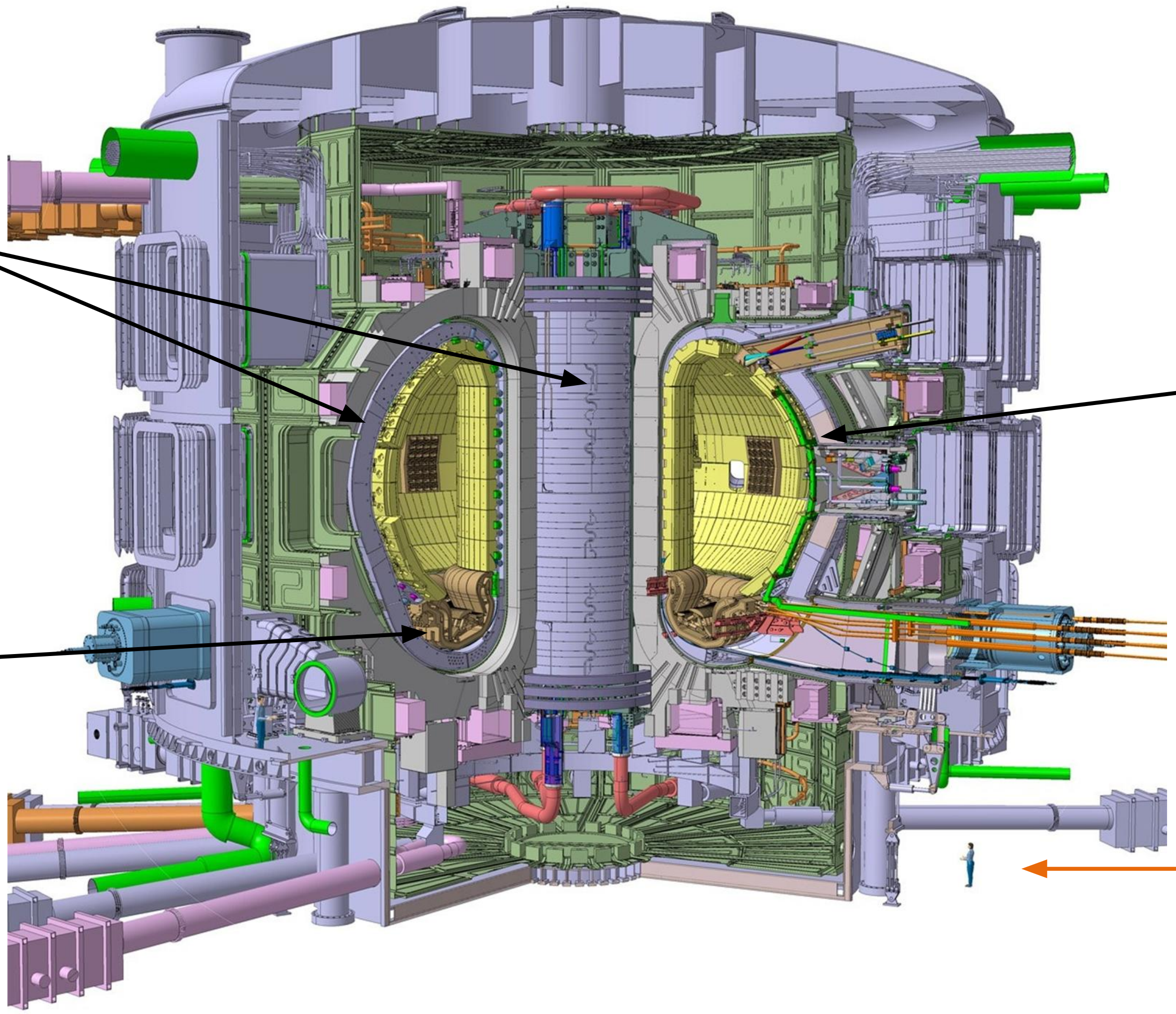
How are these problems addressed



How are these problems addressed: ITER

Plasma control:
Poloidal and
Toroidal Magnets

Energy extraction
and exhaust:
The Divertor



Tritium creation
and energy
extraction:
The breeder
blankets

Person for
scale!

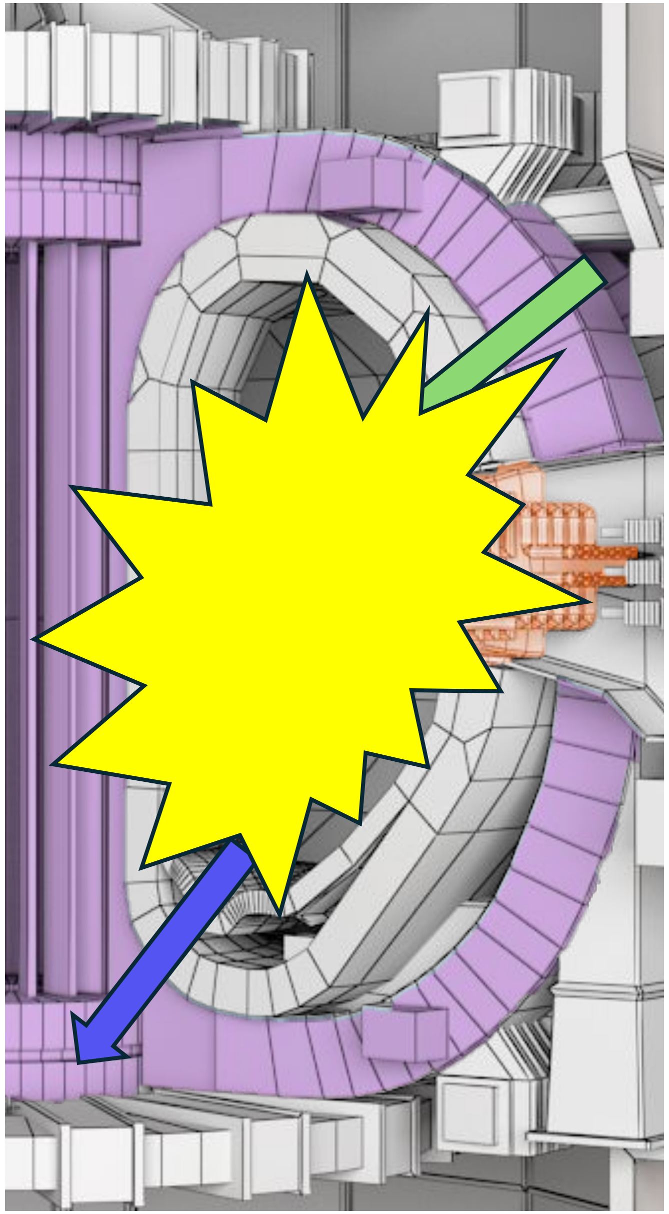
ITER Tokamak Images (greyscale – colour): Machine (iter.org)
ITER Tokamak CAD: Karlsruhe Institute of Technology -

How should we get the reaction started?

Short Answer

Ignition

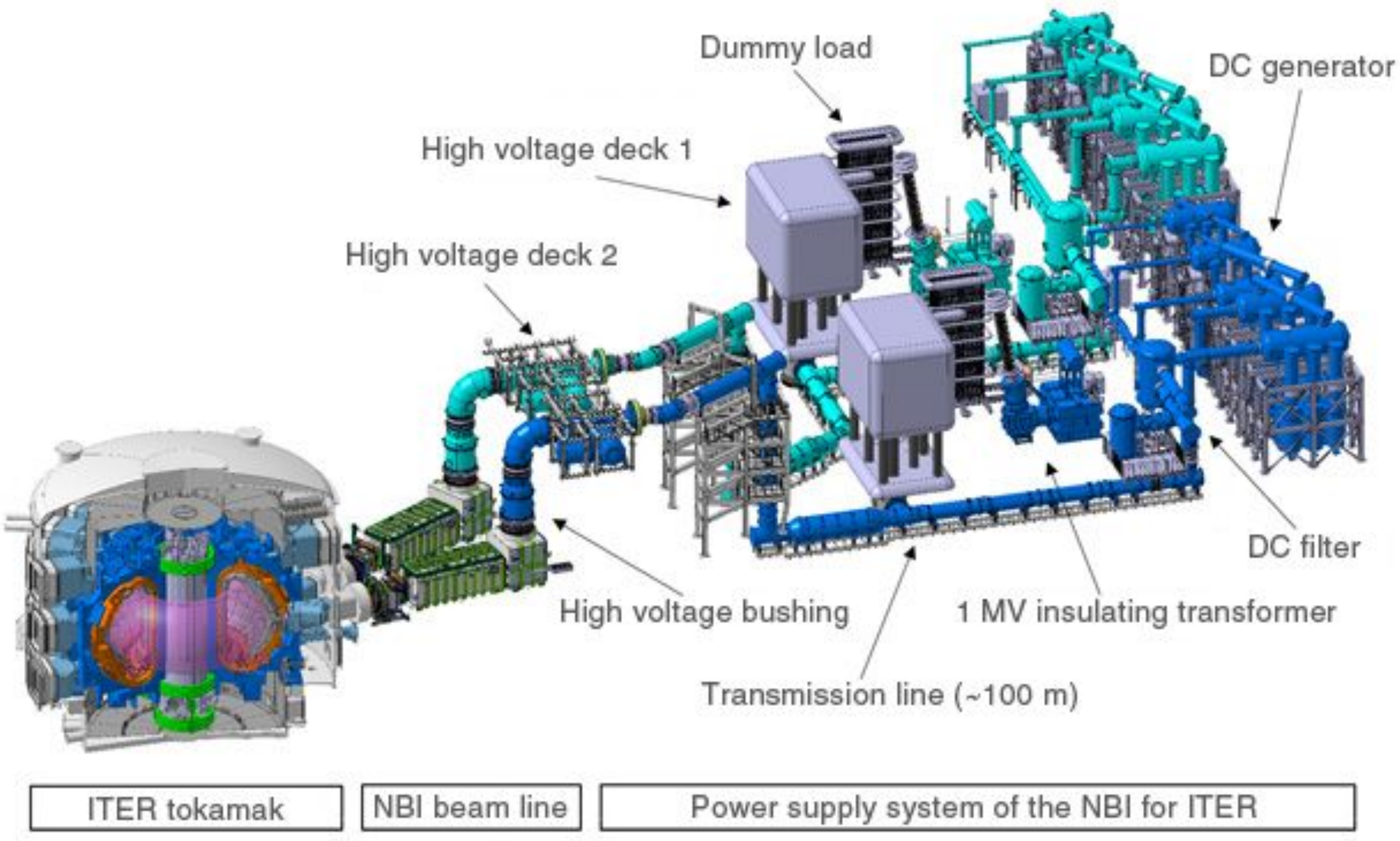
1. **Evacuation**: Air and impurities are evacuated from the chamber
2. **Magnet System Charging**: The magnet systems for plasma confinement are activated
3. **Introduction of Gaseous Fuel**: Fusion fuel as gas is introduced to the chamber
4. **Electric Current Generation**: A powerful electrical current is run through the magnets/central solenoid, ionising the gas and forming a plasma.
5. **Plasma Heating**: Auxiliary heating methods are used to bring t he plasma to fusion temperatures, typically hundreds of millions of degrees C.
6. **Fusion**: Once the plasma reaches the desired temperature, atoms of D and T have enough energy to overcome the coulomb barrier, fusing and releasing a significant amount of energy.
7. For sustaining the reaction, additional fuel is added, usually as pellets of D-T.



Ignition methods

- Ohmic heating – passing current through the plasma due to electrical resistance (previous slide)
- Neutral beam injection (NBI) – neutral atoms are accelerated to high energy, colliding with gaseus particles, transferring kinetic energy
- Radiofrequency (RF) heating – radiowaves at specific frequencies are used to excite plasma particles
- Laser heating – lasers are fired into the plasma, heating it up
  - Also proposed to be used to stabilise ongoing plasma

Ignition methods



Neutral beam injection (NBI) – HITACHI proposal for ITER

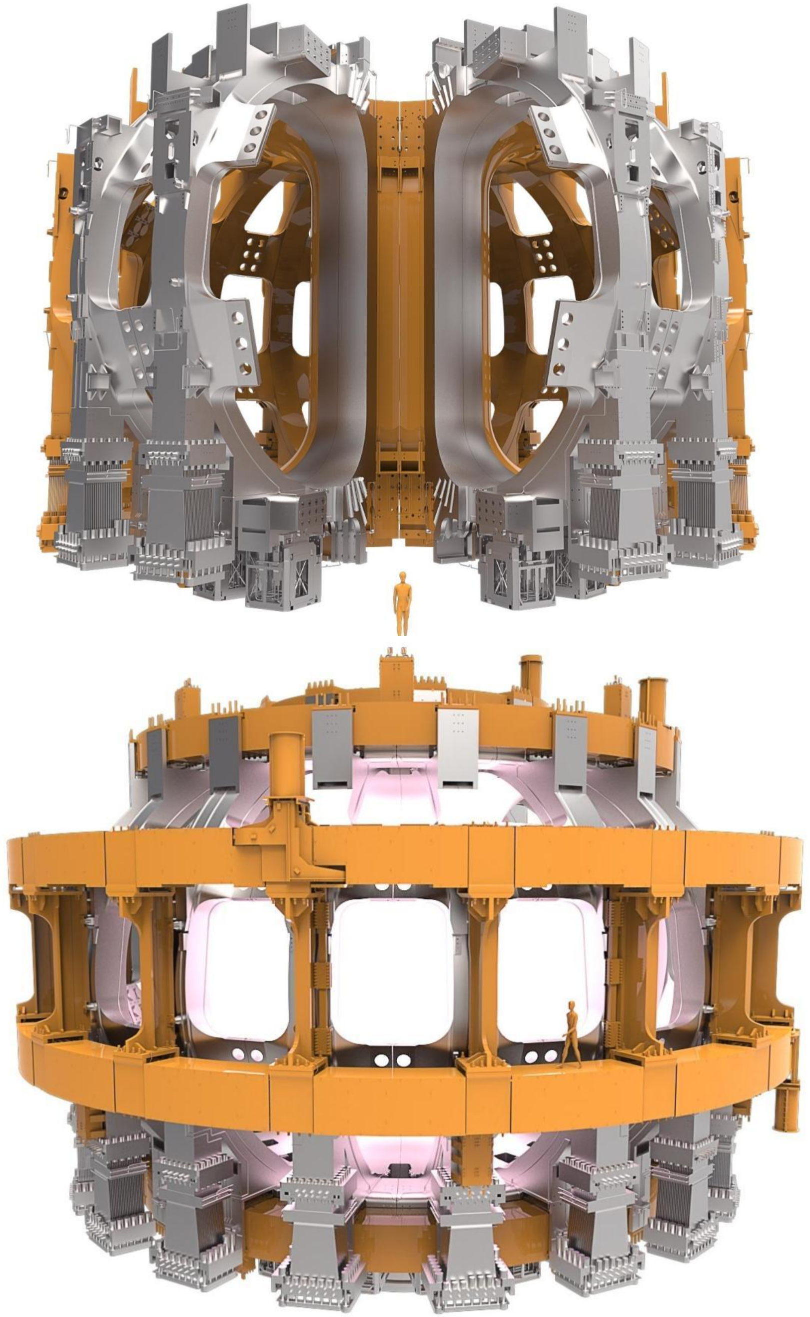
Magnets

- Superconductivity allows for strong magnetic fields of 5-20T
- This allows for the shaping of plasma
- Superconducting magnets usually require near absolute zero to operate
- HTS (high temperature superconductors) are in development to lower the amount of cryogenics required.
- ITER’s magnets will collectively produce a total magnetic energy of 41GJ.

One of ITER’s Niobium-Tin (Nb3Sn) magnets, one of 18

Plasma shape

- ‘D’ shape allows for stability and confinement away from reactor walls
- Lower energy plasma is directed towards the ‘divertor’
- For ITER, a central solenoid is used in conjunction with 18 ‘D’ shaped toroidal magnets, with 6 poloidal field coils outside in rings.
    - ‘pinches’ plasma away from walls.

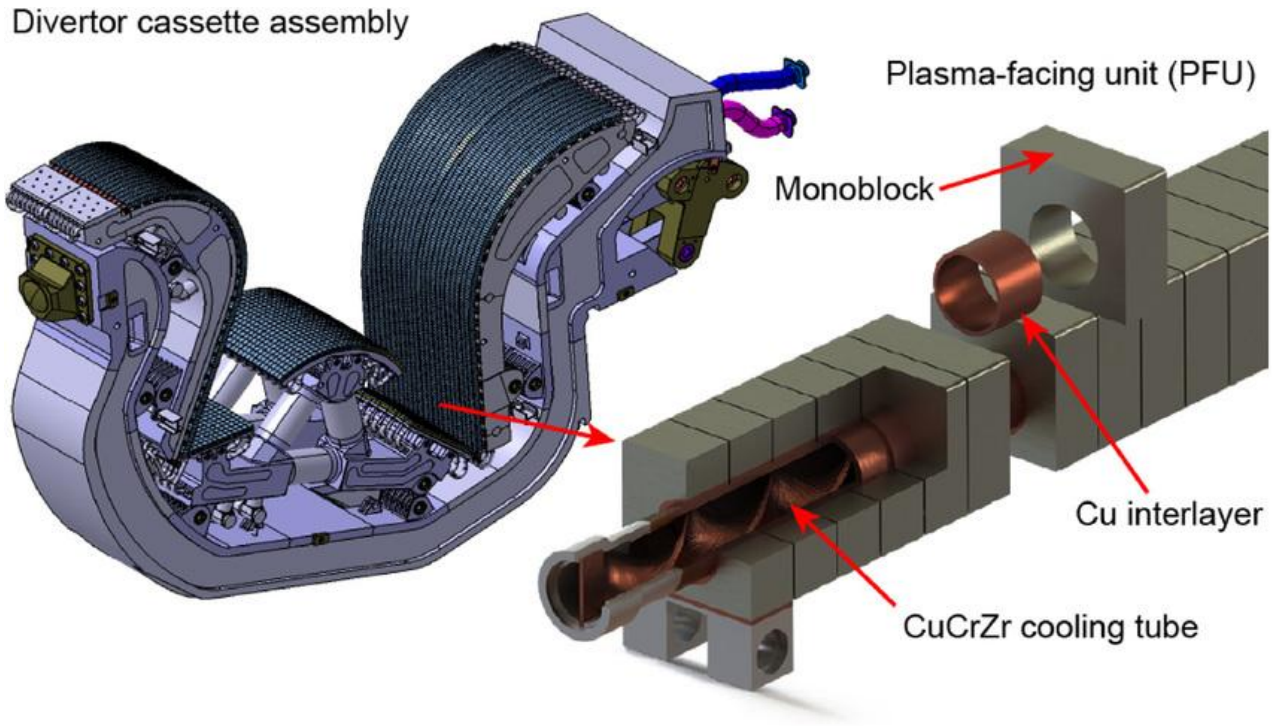


Divertor

- The plasma ‘exhaust’
- Lower energy plasma is directed for spent fuel and impurity extraction
- Undergoes arguably the highest heat load per unit area of anywhere within a tokamak
  - 10 times higher than a spacecraft entering the Earth’s atmosphere (10-20W/m2)
- A system of ‘cassettes’ that can be replaced remotely

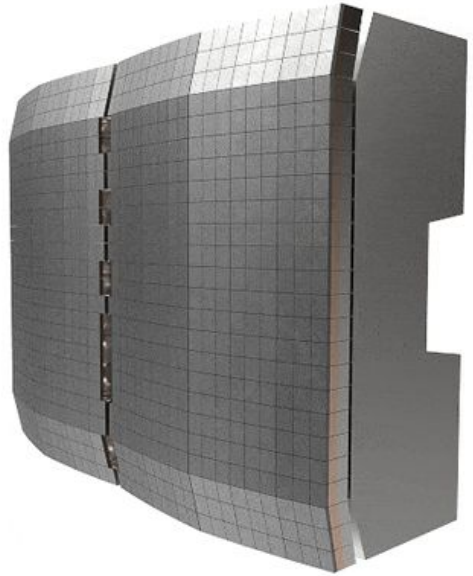
Divertor design

- Primarily made from tungsten, the material with the highest melting point
- From the W to CuCrZr, temperatures will have to drop from 1000s °C, to 350 °C or below
- Water is likely to be used as coolant, so temperature needs to drop to 150 °C.



Breeder blanket

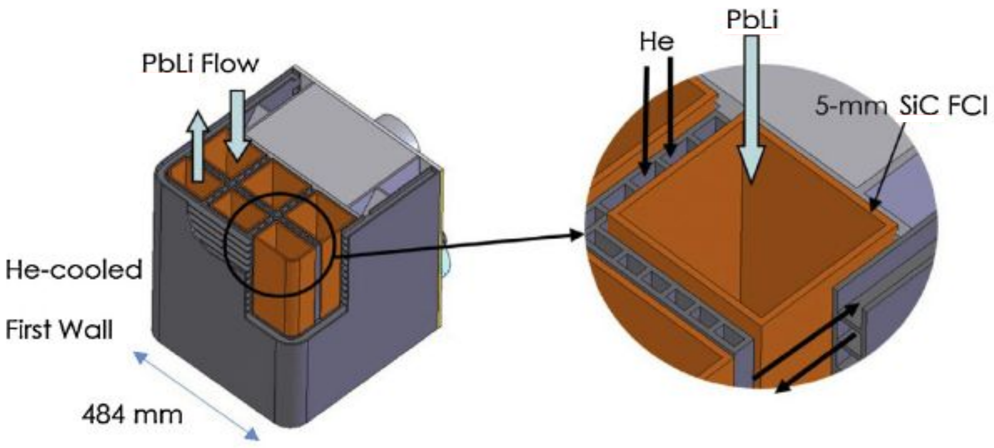
- The most important part of a fusion reactor
- Designed to breed more tritium
  - Using a neutron multiplier and lithium 6
- Acts as shielding for critical components
- Majority of energy extraction
- ITER’s blanket covers an area of 600m2, aiming to remove up to 736MW of thermal power

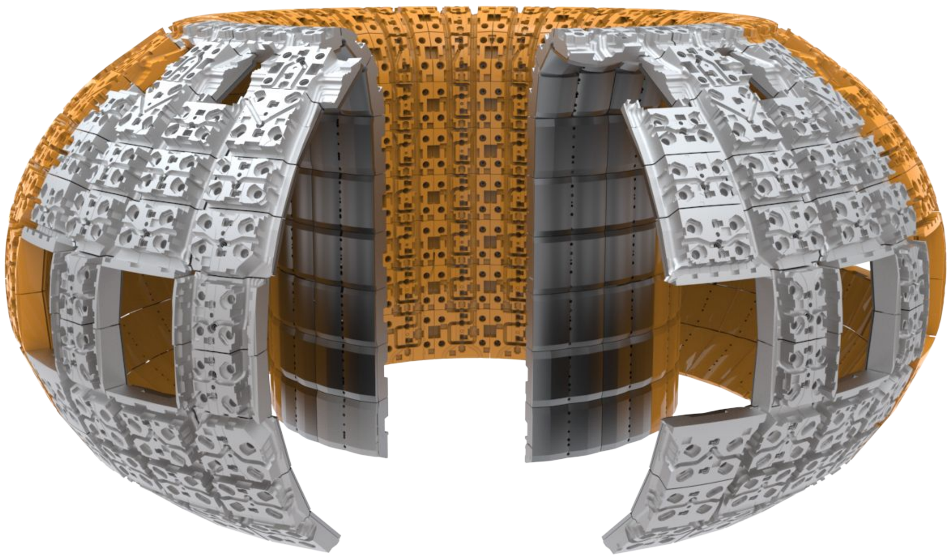


ITER first wall breeder blanket

Breeder blanket design

- Lithium and lead usually required in conjunction with shielding
- Pellets or liquid?
- Pellets:
  - Not as corrosive
  - Easy removal
- Liquid
  - No packing issues
  - Constant flow of tritium
  - Highly corrosive
- Coolant flow to extract heat energy

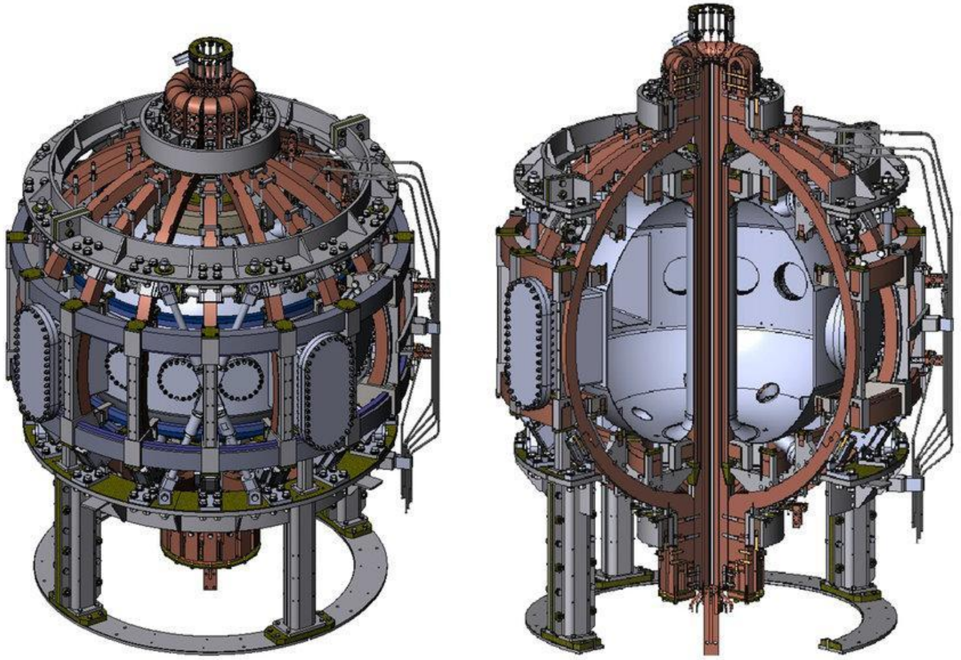


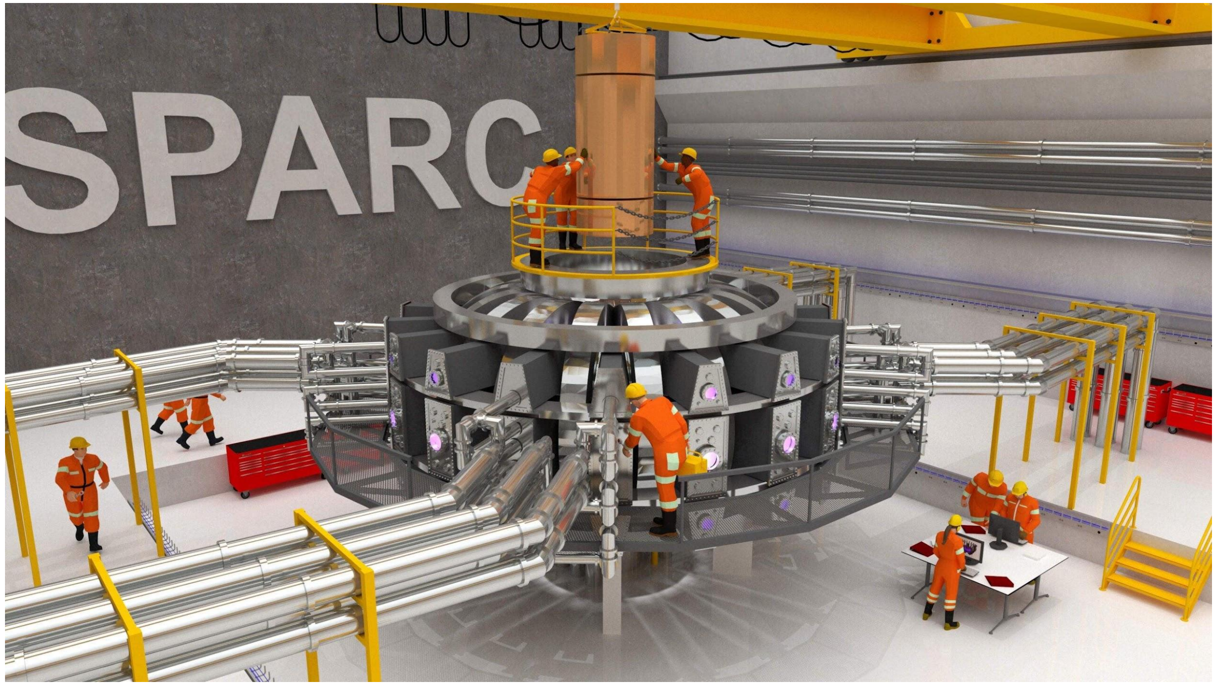


Whole powerplant scale

1. Tokamak building
3. Tritium breeding
4. Assembly hall
17. Control buildings
18. NBI power supply
19. Hot cell facility

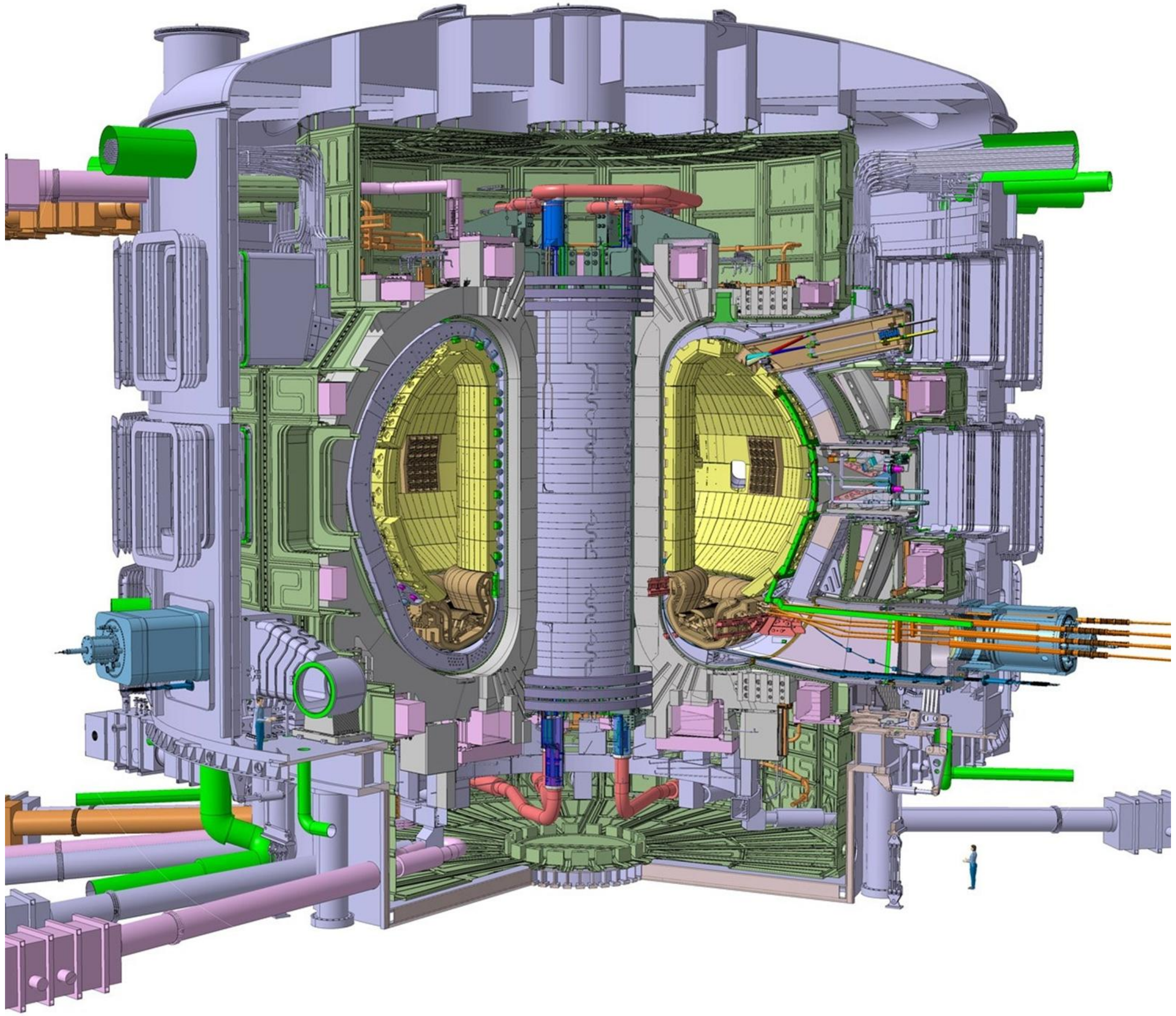
Alternative tokamak styles

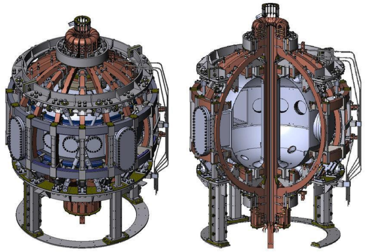




Globus-M2 spherical tokamak (left), SPARC (right)

Comparison to ITER





(This is an approximation)

Other plants to look into

- TFTR – Princeton
- JT-60SA – Japan Torus-60 Super Advanced
- EAST, WEST – Leading tokamaks with current plasma records
- DEMO – ITER 2.0
- CFETR – Commonwealth fusion energy
- K-DEMO – South Korea
- SST-1 – India

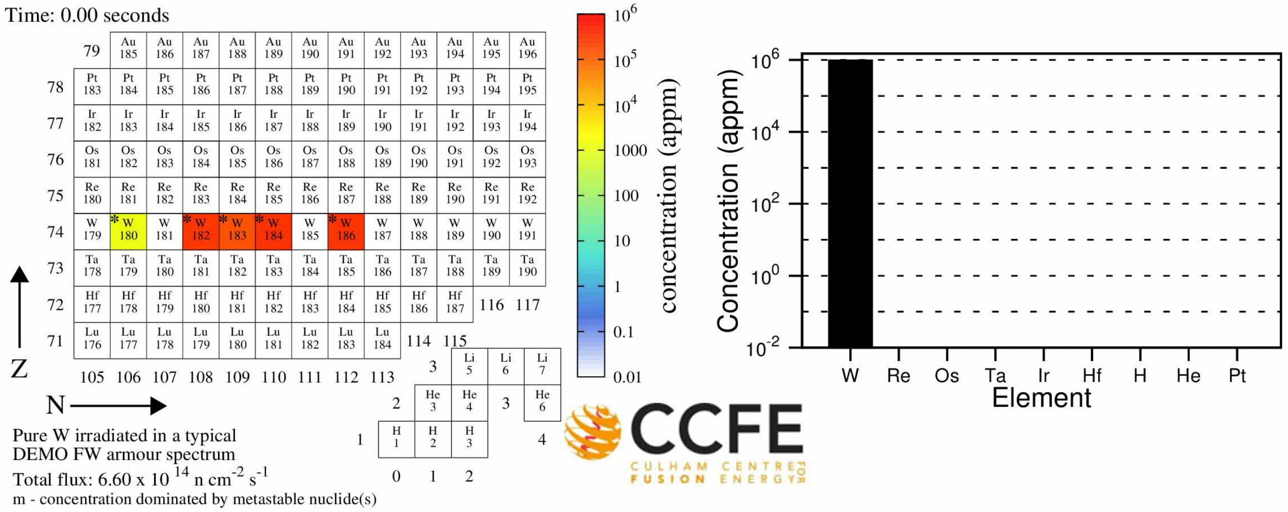
Issues

What problems do you see being a major factor over a plant's lifetime?

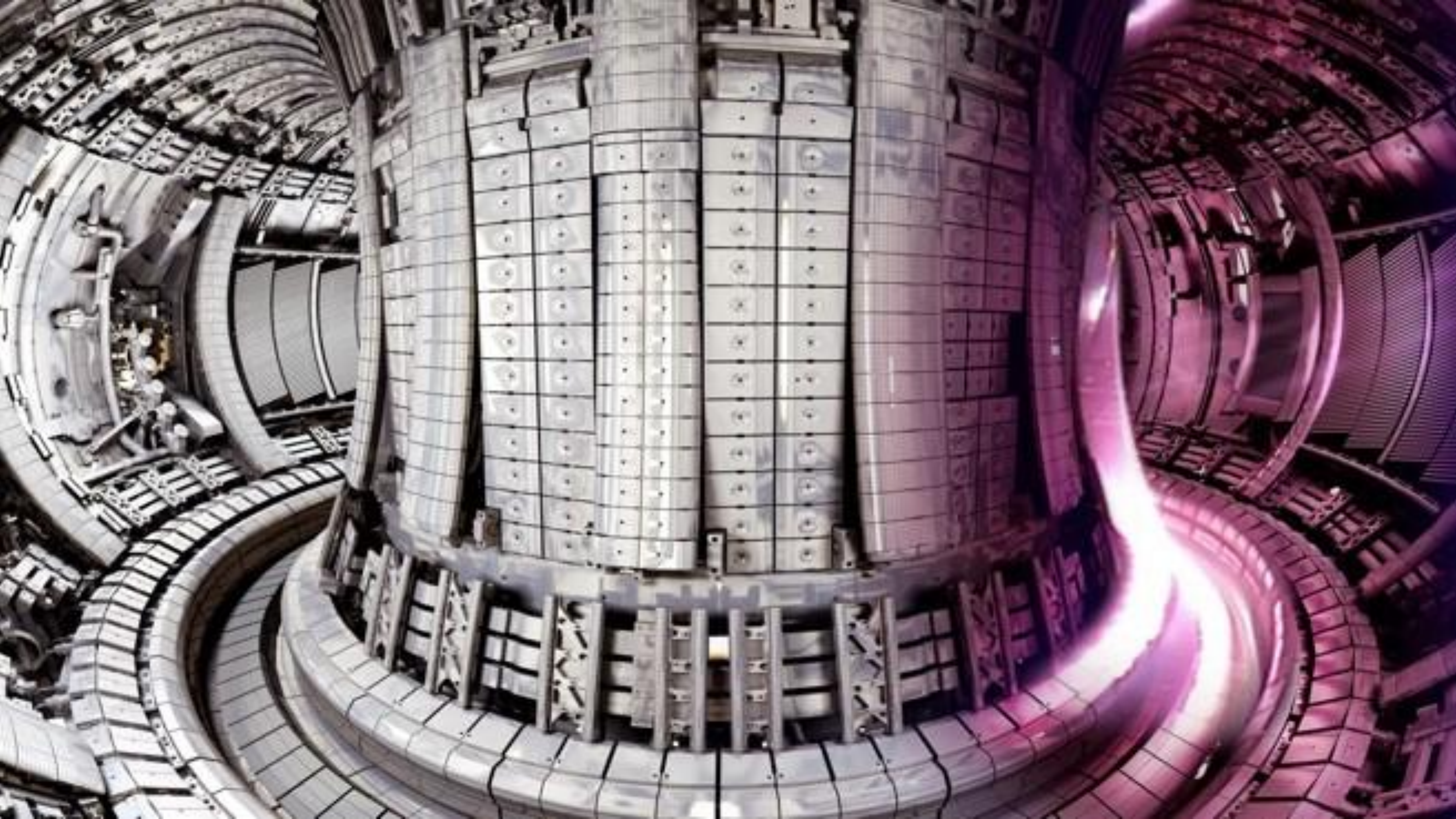
Short Answer

Plasma facing component considerations

- High heat flux
  - Erosion/evaporation of surface
- Radiation damage
  - Change in properties
  - Change in material composition
- Replacement?
- Tritium permeation
- Coolant choice – corrosion?
- And many more!

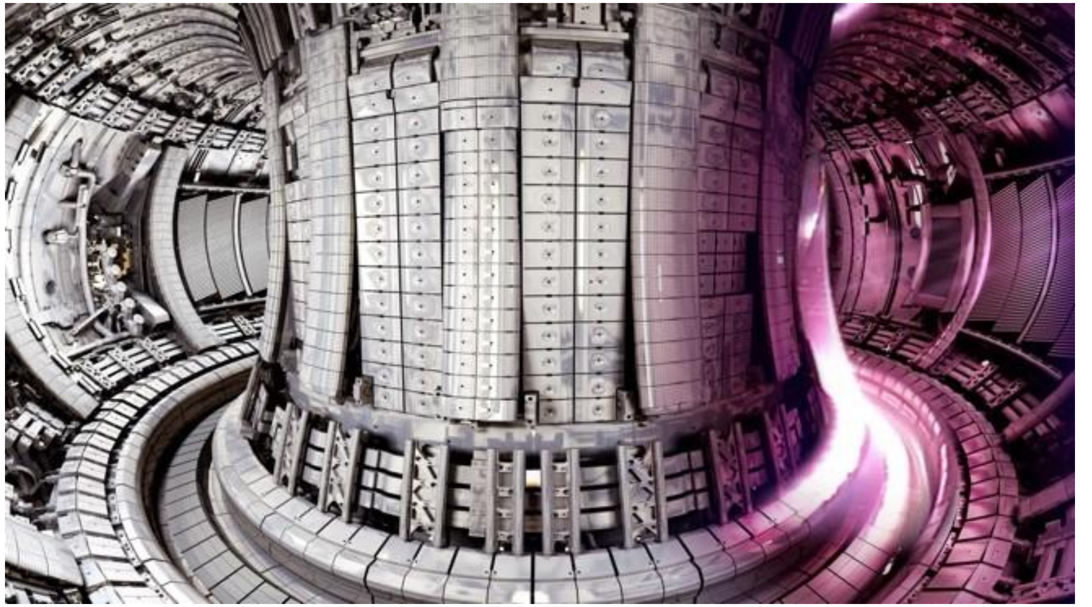


Pure W over 5 years of DEMO spectrum radiation damage



JET at a glance

- JET – the Joint European Torus, at the UKAEA, Culham.
- World’s longest running fusion experiment, first to run D-T reactions
- Previously held the record best Q factor of 0.67 (24MW-16MW)
- First fusion experiment to use a divertor
- Informed much of the design seen in this presentation
- Currently being decommissioned,
    - The first long running tritium experiment decommission
    - Very important to understand how to decommission future power plants

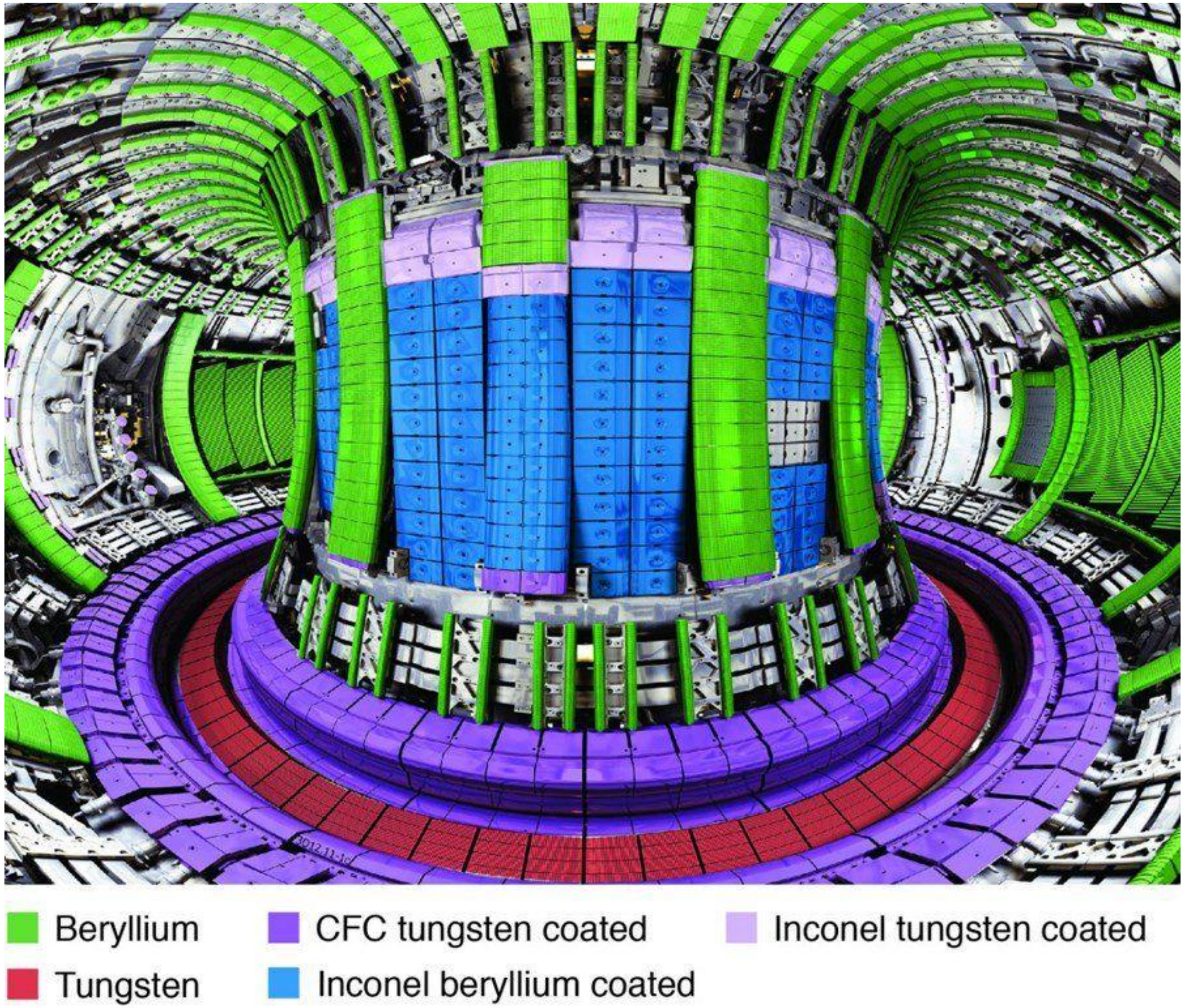


JET

2009-2011 JET was shut down for a rebuild to adopt ITER concepts

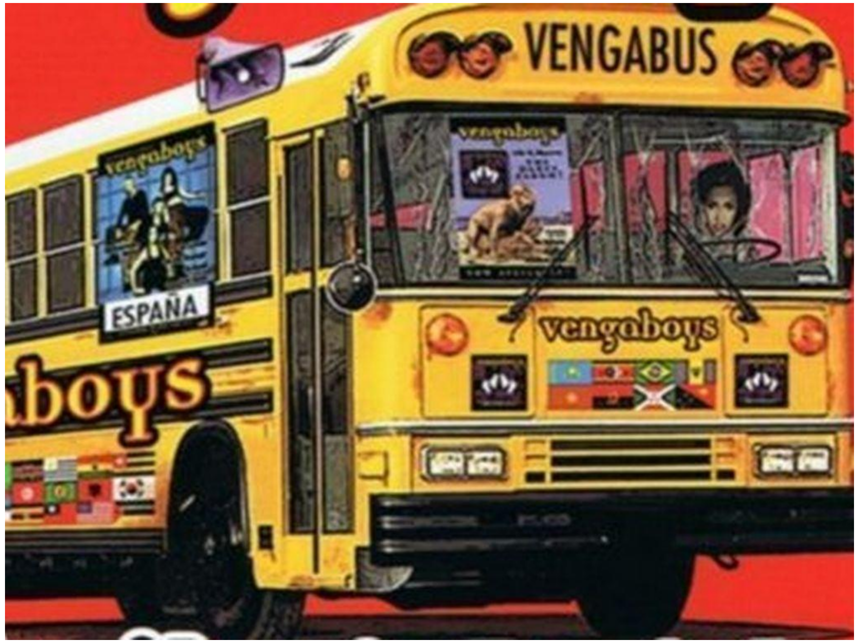
2021, second DT experiments. World record of 59MJ of sustained fusion energy.

Decommissioning expected to last until 2040



Culham trip (29th October)

- Full day tour of UKAEA campus, Culham
- Will be seeing JET and hopefully MAST (Mega Amp Spherical Tokamak) + more!
- Meet at the engineering building at **6.40am**
- Please bring some food as it will be a long day!
- Bring **valid photo ID.**
  - Eg. Passport or driver's license.



Placeholder image, tour-bus will be from a professional company

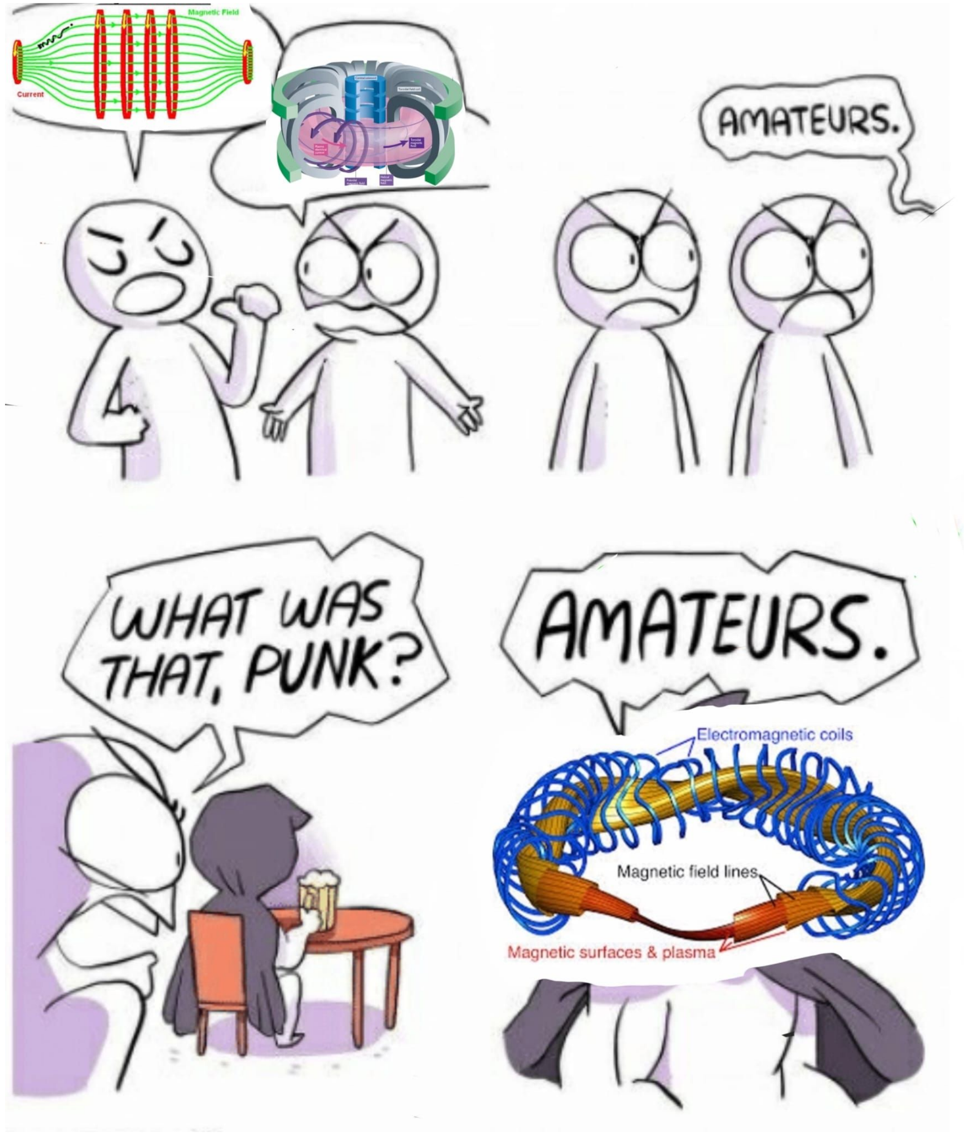
Summary

- Tokamaks are incredibly complex devices, with multiple important parts
- Ignition is difficult, but possible in many ways, e.g. lasers or NBI
- The magnet systems are immense, but required to not melt the reactor and sustain a reaction
- The divertor is a key component for extracting plasma impurities
- Without the breeder blanket, fusion reactors are not self sustaining
- ITER, whilst a good example, is not the only way to design a tokamak

Feedback

- Please fill out the form, or contact me via WhatsApp/email (thomas.hughes@manchester.ac.uk)

Meme of the week



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Lecture 4: Reactor Design (Alternatives)

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