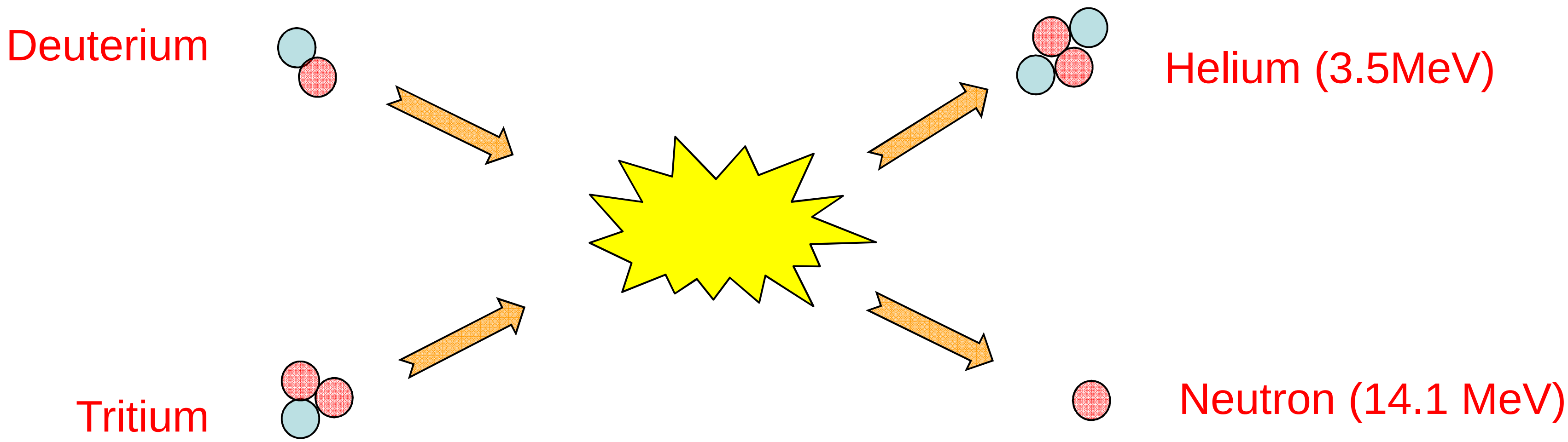
Vacuum for Fusion

Paul Flower
Culham Centre for Fusion Energy

What is Fusion?

- Fusion is the process that powers the sun.
- Of the possible fusion reactions, the easiest to achieve is the Deuterium-Tritium one:



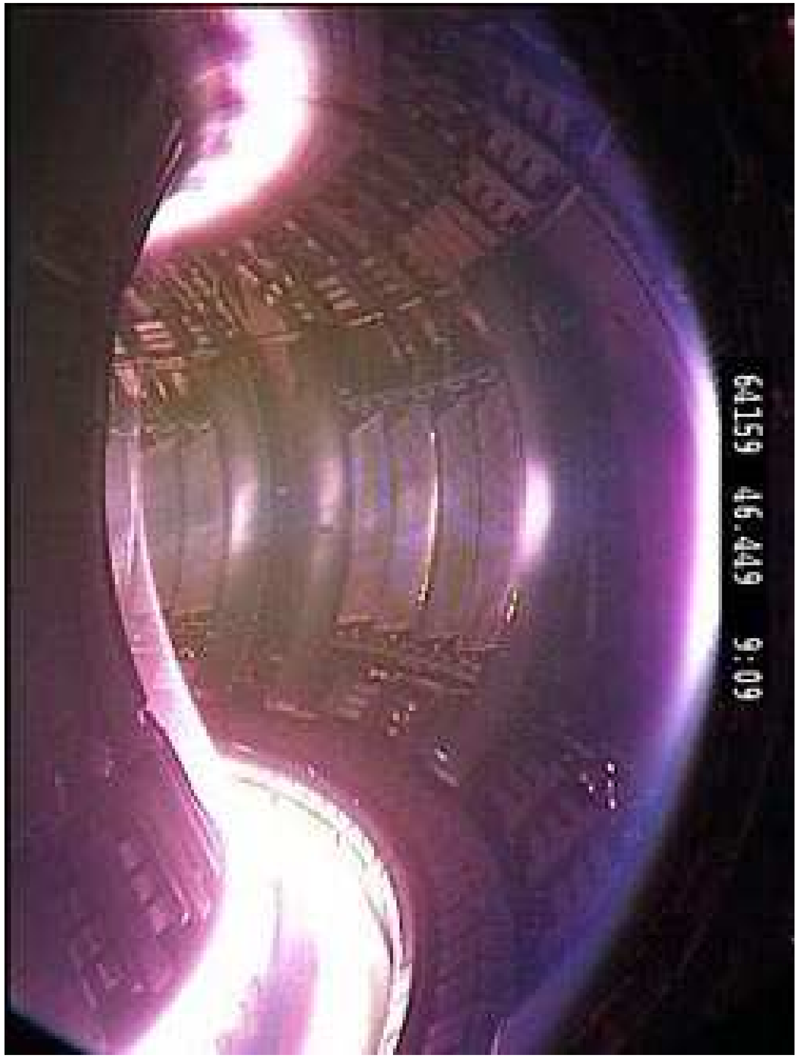
- In the process of the reaction, Mass is converted into energy following Einstein's $E=mc^2$ equation.

Why do we need it?

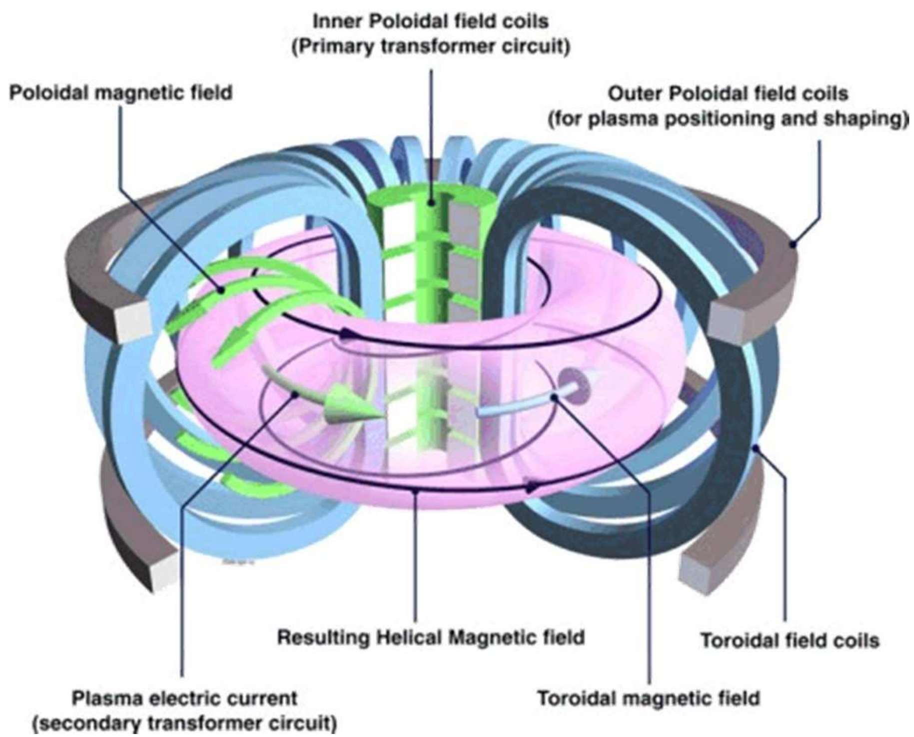
- Almost infinite fuel available
  - The oceans contain enough fuel to provide everyone on earth with 105 kWh each, every day for a million years.
- No CO_2 emissions
- No long-lived waste
  - The reactor vessel becomes radioactive over time, but will be safe for recycling within less than 100 years.
- Inherently safe
  - The very fact that Fusion is so difficult to get working means that should anything go wrong, the reaction stops almost instantly.

How do we do it?

- *We say that we will put the sun into a box. The idea is pretty. The problem is, we don’t know how to make the box.*
  - Pierre-Gilles de Gennes



How do we do it?



- The Plasma is contained inside a magnetic bottle.
- Enormous amounts of heat are applied – JET can currently apply almost 50MW for a few seconds to <1g of Hydrogen.
- Can reach temperatures of ~100,000,000℃ – about 10x hotter than the centre of the sun.

Vacuum Challenges

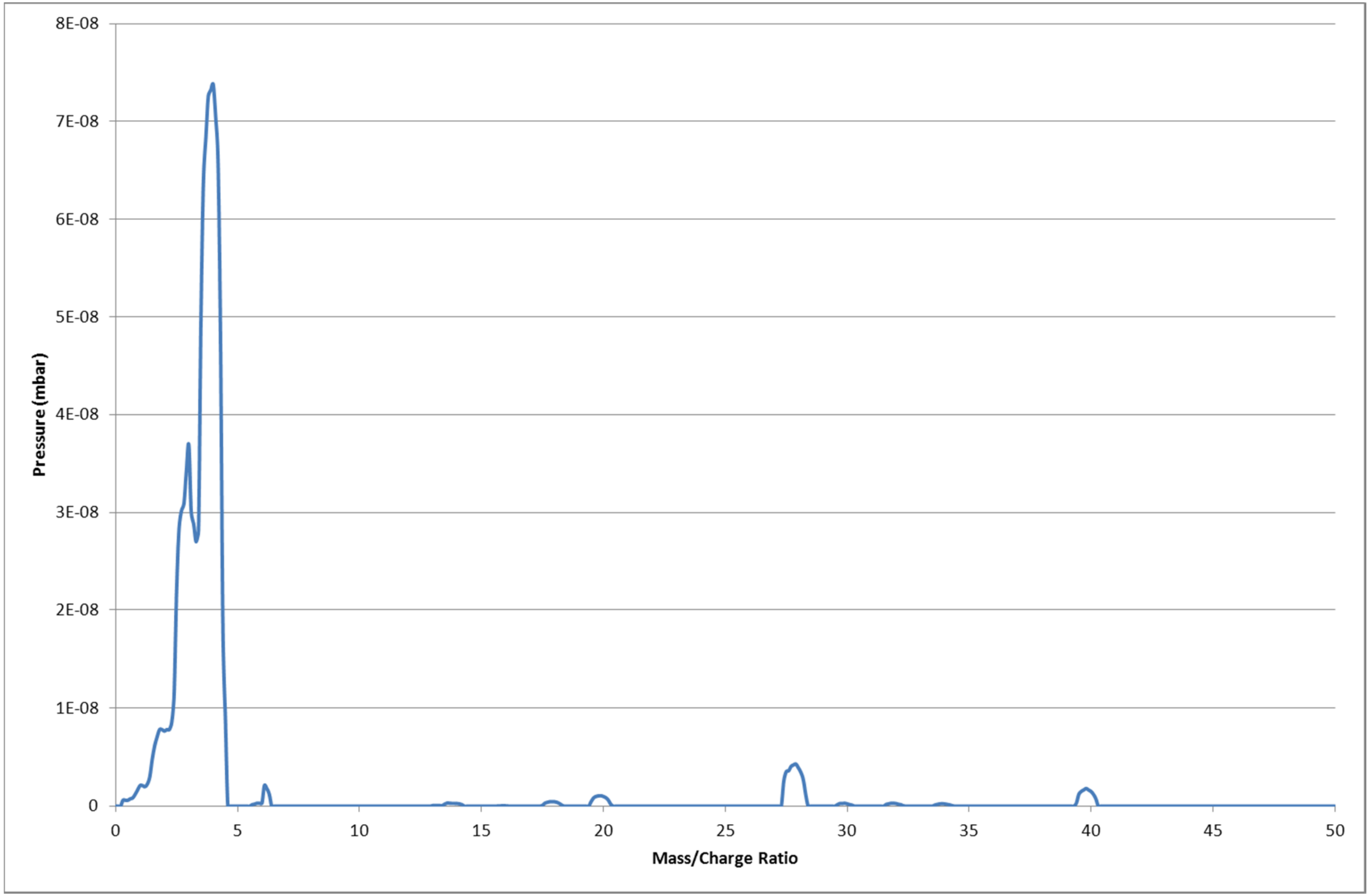
- System requires a very clean vacuum
  - Impurities, particularly heavy gases cause the plasma to cool rapidly and the reaction to halt. Some others such as Oxygen may react with the machine lining.
- High magnetic fields
  - For the next generation of machines, the magnetic fields are so high that no rotating machines can be used near the Tokamak.
- Contamination
  - Tritium (fuel gas) means we can't use any hydrocarbons on the machine.
  - Beryllium dust is toxic and tightly regulated.

Vacuum Challenges

- Leak detection
  - Very large system – leaks are often inaccessible.
  - Deuterium fuel gas is almost indistinguishable from Helium search gas.
- Reliability
  - The machine costs ~£1 Million/week to run. Venting it to fix a mistake isn't an option except in extreme circumstances!
- Enormous Pumping Speeds
  - Total pumping speed on JET is over 12,000,000 l/sec.

Cleanliness

- Residual gas mostly Hydrogen and Deuterium fuel

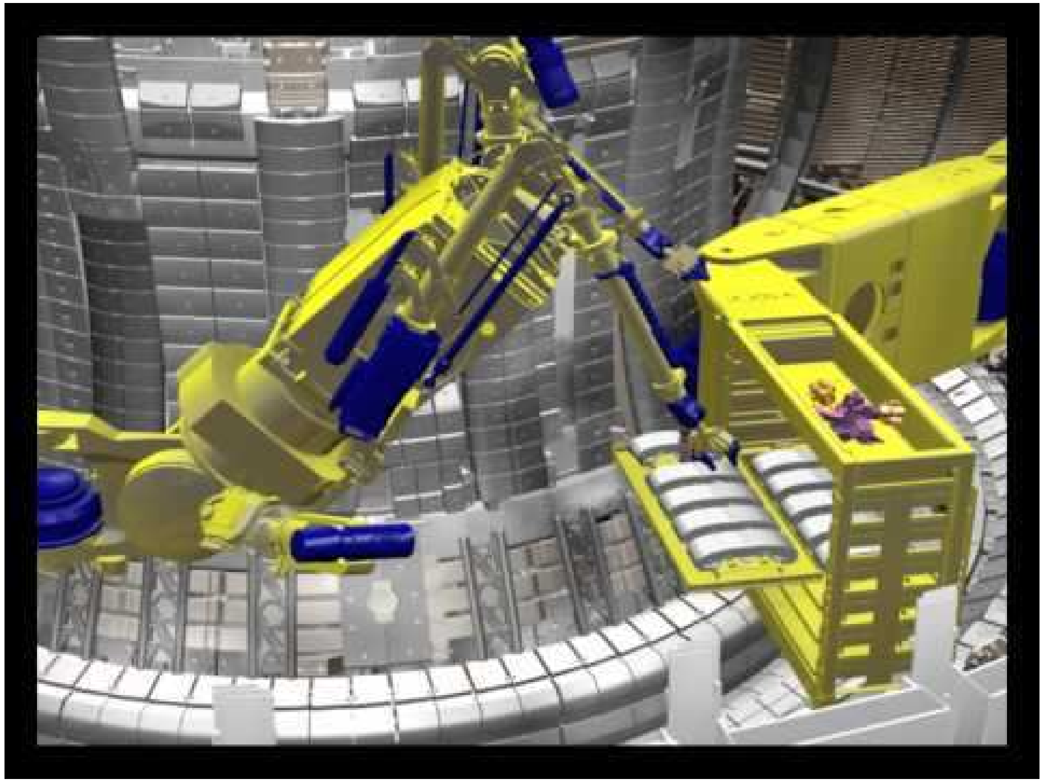


Contamination

- Tritium and Beryllium present in the machine make simple jobs much harder.
- Full face respirators or even pressurised suits are sometimes required.
- Drives many design factors, e.g. the use exclusively of metal seals.

Contamination

- We try to do all current in-vessel work by remote handling to reduce exposure and gain experience.
- When ITER starts Tritium operations, all work to the outside of the vessel will need to be done by remote handling.
  - Leak Detection
  - Maintenance
  - Modifications



Leak Detection

- Need a total leak rate of less than 10^{-4} mbar l/sec on a machine the size of a small block of flats.
- Much of the machine is covered in insulation, or otherwise inaccessible.
- When the machine is operating, Deuterium is used as a fuel gas.
  - This has a mass of 4.028 AMU, while Helium is at 4.003 AMU. Very few instruments are capable of measuring this difference, and those that are find the Deuterium tends to swamp the Helium signal.
  - Conventional leak detection is all but impossible with lots of Deuterium in the machine.

Leak Detection

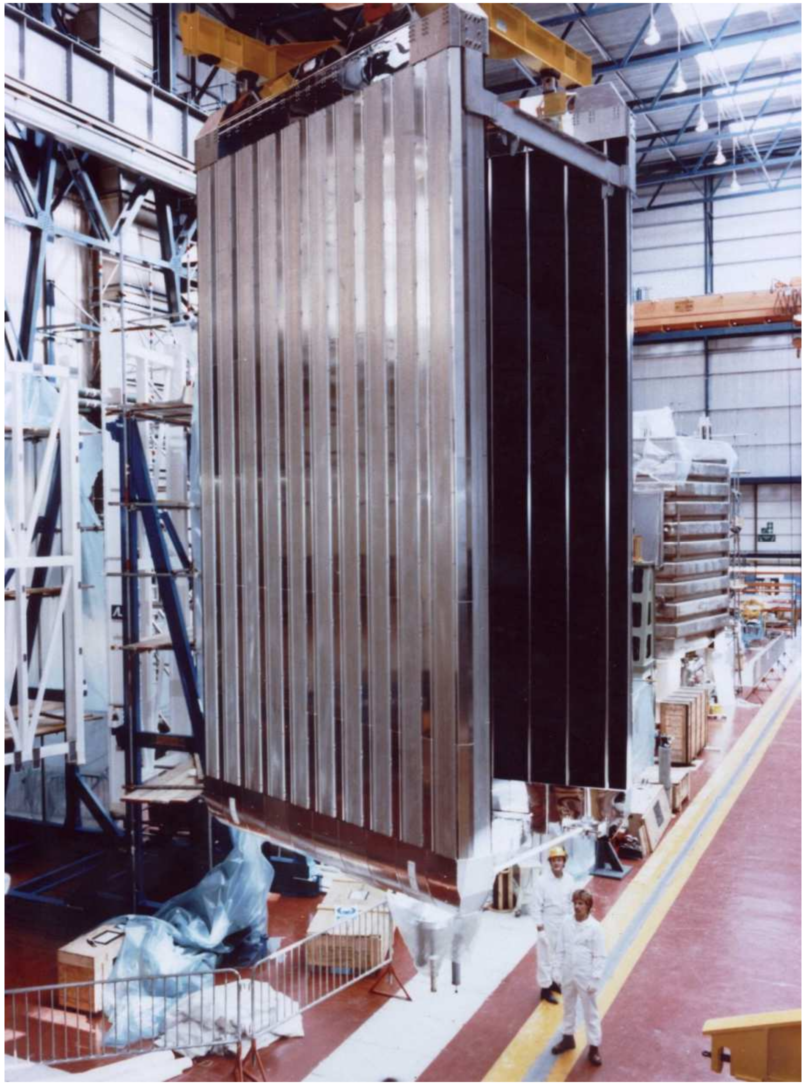
- Methods used
  - Helium
    - Liquid Helium Cryopumps to reduce the amount of Deuterium in the machine.
    - Getter pumps at the leak detector inlet to reduce the amount of Deuterium reaching the detector head.
    - Lots of Helium!
    - Extremely sensitive RGAs which should be able to distinguish between Helium and Deuterium.
  - Argon
    - Flooding the Torus Hall with Argon, measure the total machine leak rate by comparing Torus Argon concentration before and after on an RGA.
    - Building tents/bags over suspected parts of the machine, flooding with Argon then watching concentration on an RGA.

Reliability

- High cost of delays puts premium on fixing problems externally where possible.
  - External pumped interspaces – if the leak is at 10^{-3} mbar externally, leak rate is a million times lower than if it were exposed to atmosphere.
  - Seal leaks externally with putty/spray where possible. This can only be done in some circumstances.
- Large stock of spares kept on site.
  - If something needs replacing, start immediately rather than wait for it to be fabricated.

Pumping - Cryo

- The two Neutral Injection Beams each have a 6,000,000 l/sec cryopump.
- There are two 100,000 l/sec cryopumps in the Torus Divertor.
- Use both Nitrogen and Helium for cooling.
  - Helium panels are regenerated weekly, Nitrogen panels at the end of an experimental campaign.



Pumping - Turbomolecular

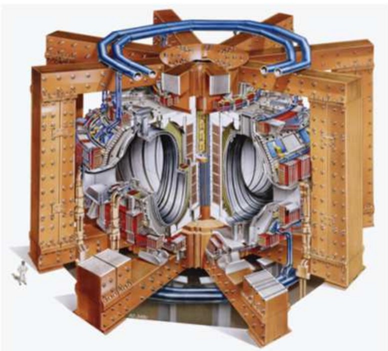
- There are 8 x 2,000 l/sec turbopumps on the Torus
  - Provide Helium Pumping, pump regenerated gas from Cryopanels.
  - High magnetic fields are a reliability challenge.
  - Pumps need to be specially adapted for use with Tritium (all metal seals, etc.)
  - Can't send pumps back to the manufacturer for routine servicing!

Pumping - Forevacuum

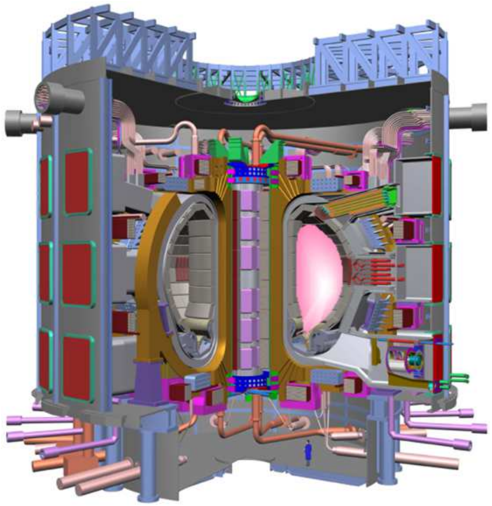
- Due to Tritium content, can't just vent exhaust gas to atmosphere
  - Entire building dedicated to extracting Tritium from exhaust gas.
  - Can't use oil-sealed backing pumps as Tritium will swap with Hydrogen atoms in the oil and produce highly contaminated oil.
  - There is currently no commercially available pump suitable for use on ITER and beyond.

The Future

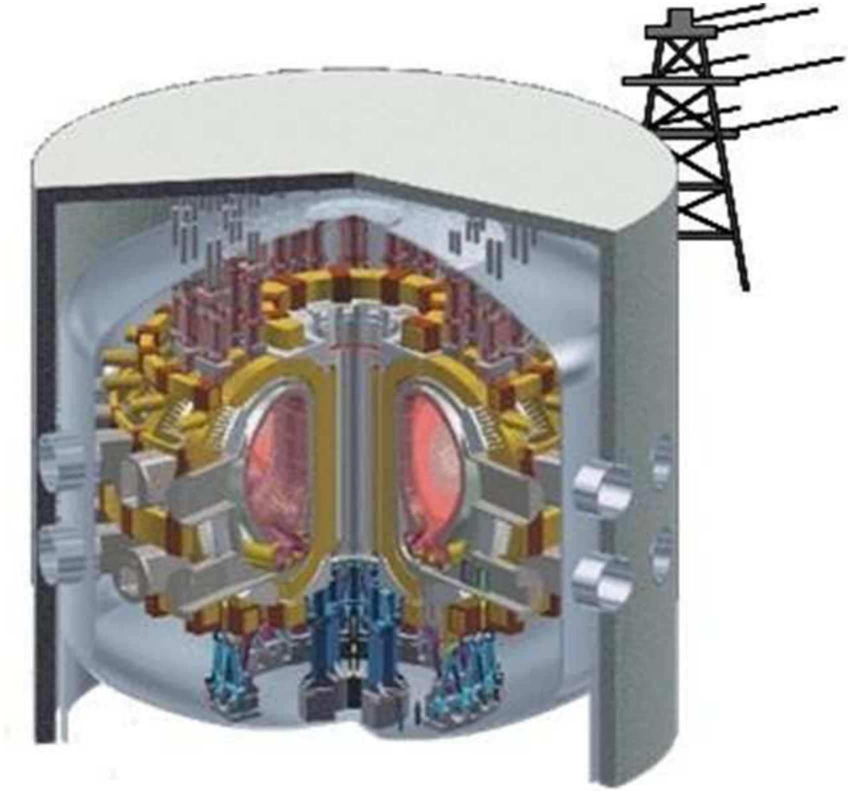
- Moving from Big Science to Big Engineering?
  - First prototype power station, DEMO, expected to start building around 2040.



JET



ITER



DEMO?

Big Engineering?

- Current generation of machines are built as science experiments, not power stations.
  - Heavily instrumented, requiring a large staff of highly skilled people to run.
  - Requirements for a power station are very different!
- Should DEMO be a success, there is no technical reason that a large number of fusion power stations could not be built very quickly.
  - EFDA predicts Fusion will provide 36% of world electricity supplies by the year 2100.
  - Will require an industry capable of making the needed parts in large quantities.