The Fusion Challenge

Martin O'Brien

Fusion Programme Manager
UKAEA Culham, Oxfordshire

on behalf of Chris Llewellyn Smith,
Director UKAEA Culham
& Head of the Euratom/UKAEA Fusion Association

http://www.fusion.org.uk/

OUTLINE

- The Energy Challenge
- Fusion – its potential advantages and disadvantages
- Status of Fusion
- Next steps - ITER and Materials Research

The World Energy Challenge

- Large increase in energy use needed for rising living standards and population growth
  - doubling of world power requirement in 40 years (IEA)
  - Chinese capacity expands by a GW every few weeks
- Only fossil fuels, nuclear fission, solar and potentially fusion can give the required response on a global scale
- But increased use of fossil fuels not sustainable as it drives potentially catastrophic climate change and fossil fuels will run out sooner or later
- Desperate need to increase efficiency, and seek cleaner ways of producing energy on a large scale
- Global energy market ~ $3Trillion p.a. – response should be proportionate

WHAT IS FUSION ?

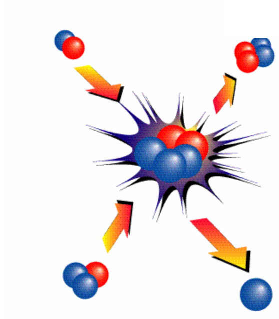
Fusion is the process that produces energy in the core of the sun and stars

It involves fusing light nuclei (while fission ⇒ splitting heavy nuclei)

The most effective fusion process involves deuterium (heavy hydrogen) and tritium (super heavy hydrogen) heated to above 100 million °C :

Deuterium

Tritium



Helium

+ energy (17.6 MeV*)

Neutron

A "magnetic bottle" **called a** tokamak **keeps the hot gas away from the wall**

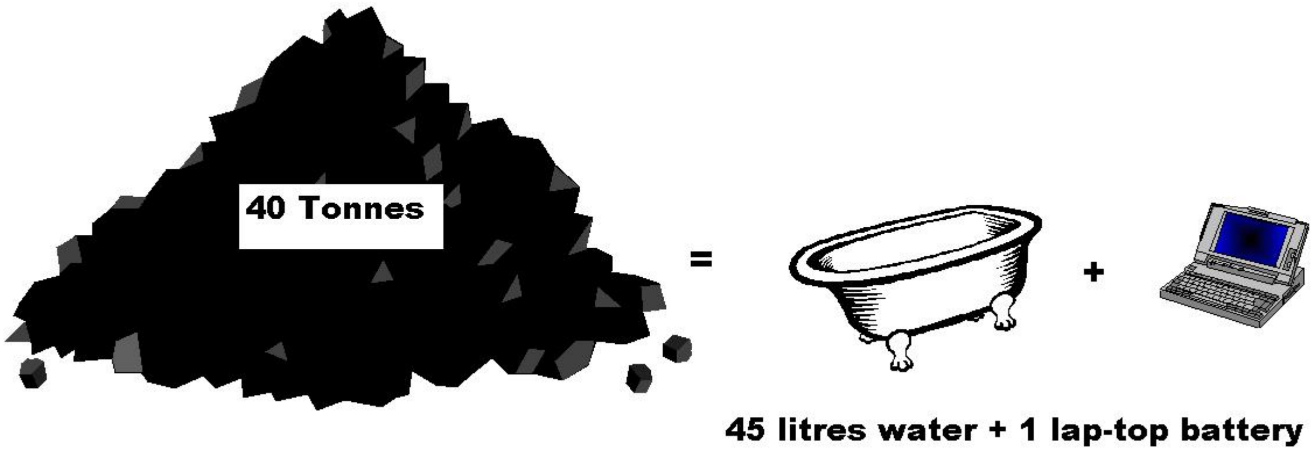
Challenge**: make an effective "magnetic bottle" (now done ?)**

and a robust container

* ten million times more than in the chemical reactions in burning fossil fuels ⇒ a 1 GW fusion power station would use 1 Kg of D + T in a day, compared to 10,000 tonnes of coal in a coal power station

Fusion Fuel

Raw fuel of a fusion reactor is water and lithium*

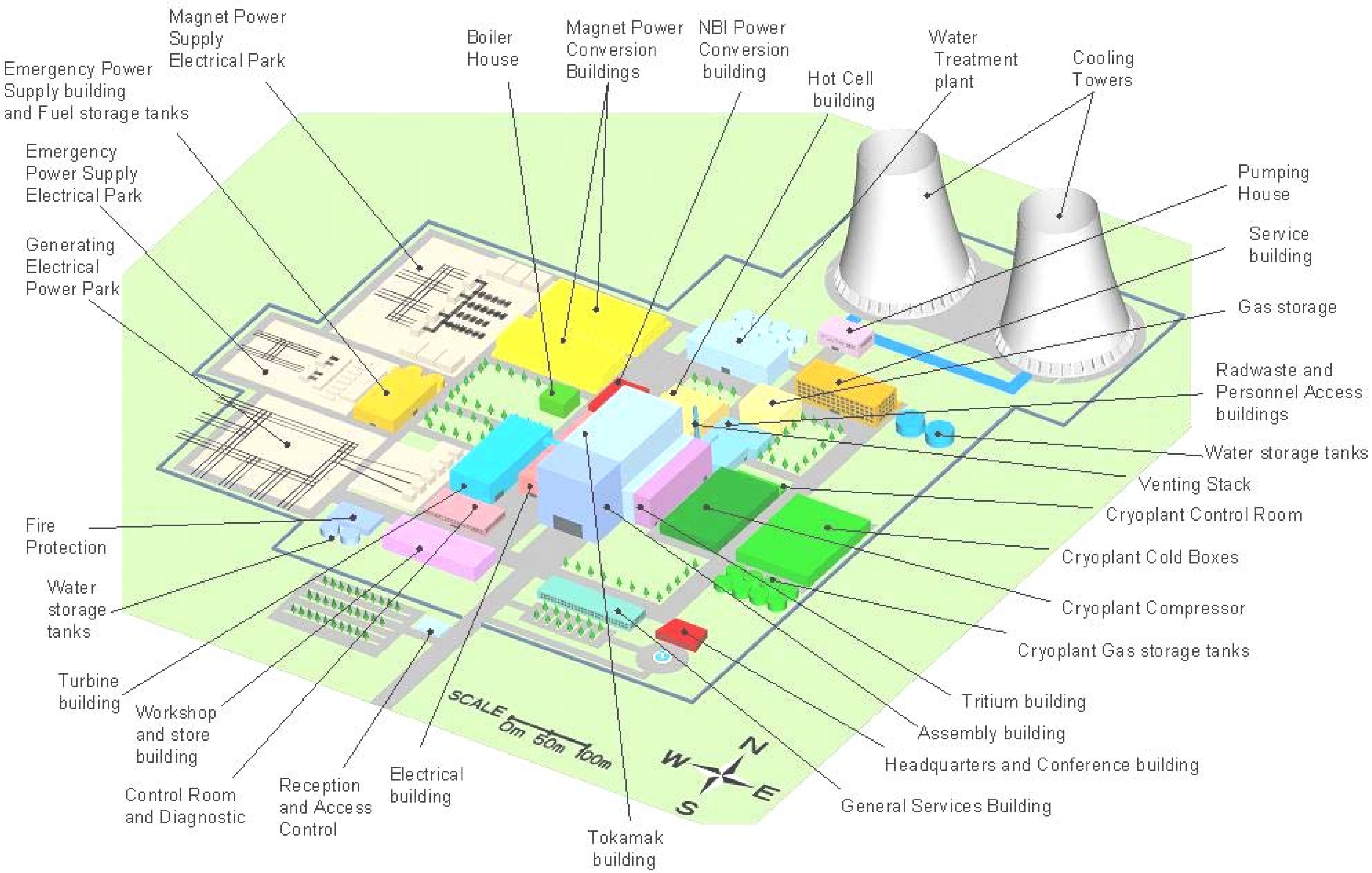


Lithium in one laptop battery + half a bath-full of ordinary water (-> one egg cup full of heavy water) ⟹ **200,000 kW-hours**
= (current UK electricity production)/(population of the UK) for 30 years

* ⟹ *deuterium/hydrogen = 1/6700*
+ tritium from: neutron (from fusion) + lithium → tritium + helium

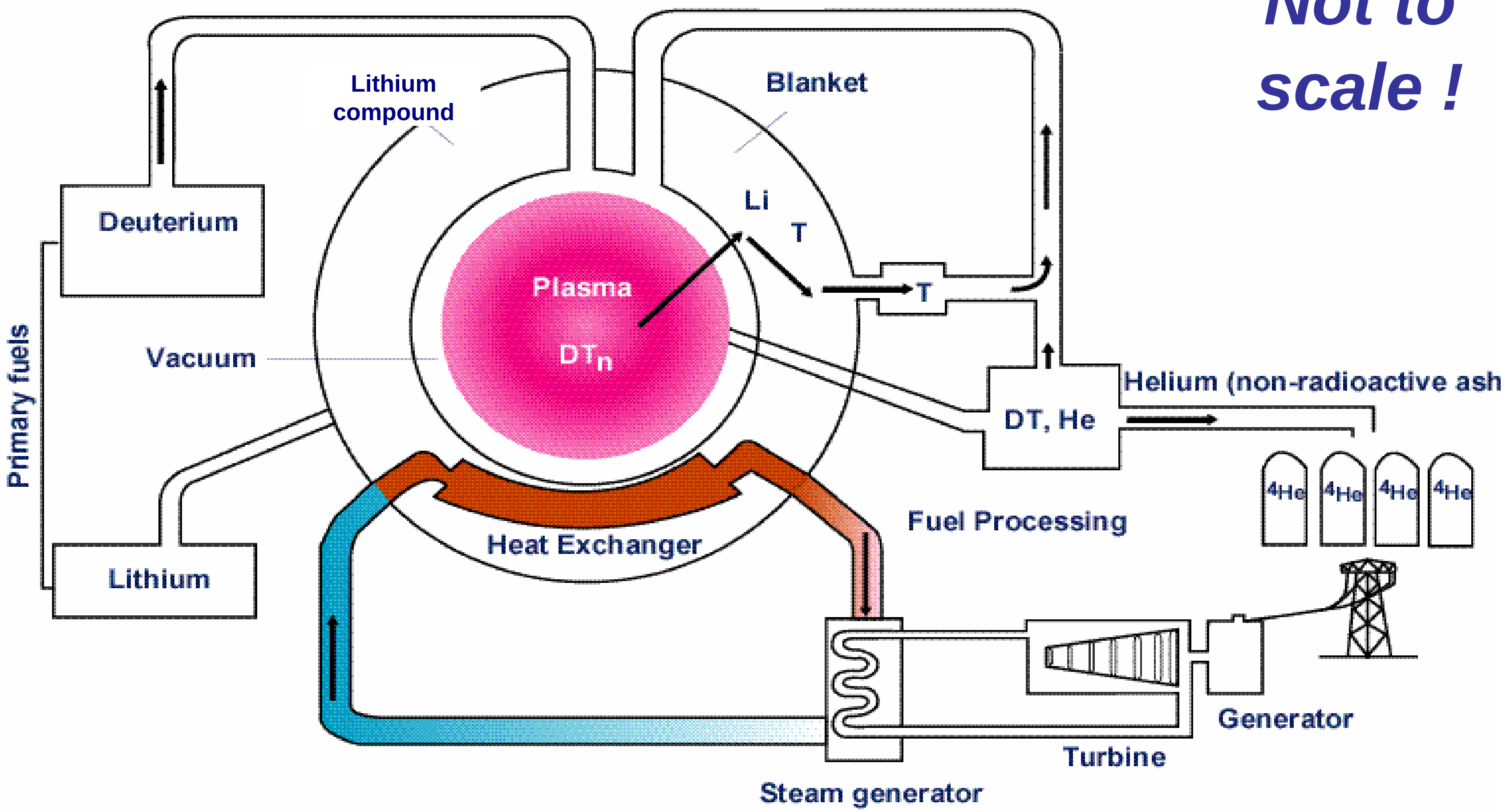
What would a fusion power station look like ?

Layout of Fusion Power Station – half is conventional



A Fusion Power Station would be like a conventional one, but with different fuel and furnace

Not to scale !



Recent European Fusion Power Plant Conceptual Study

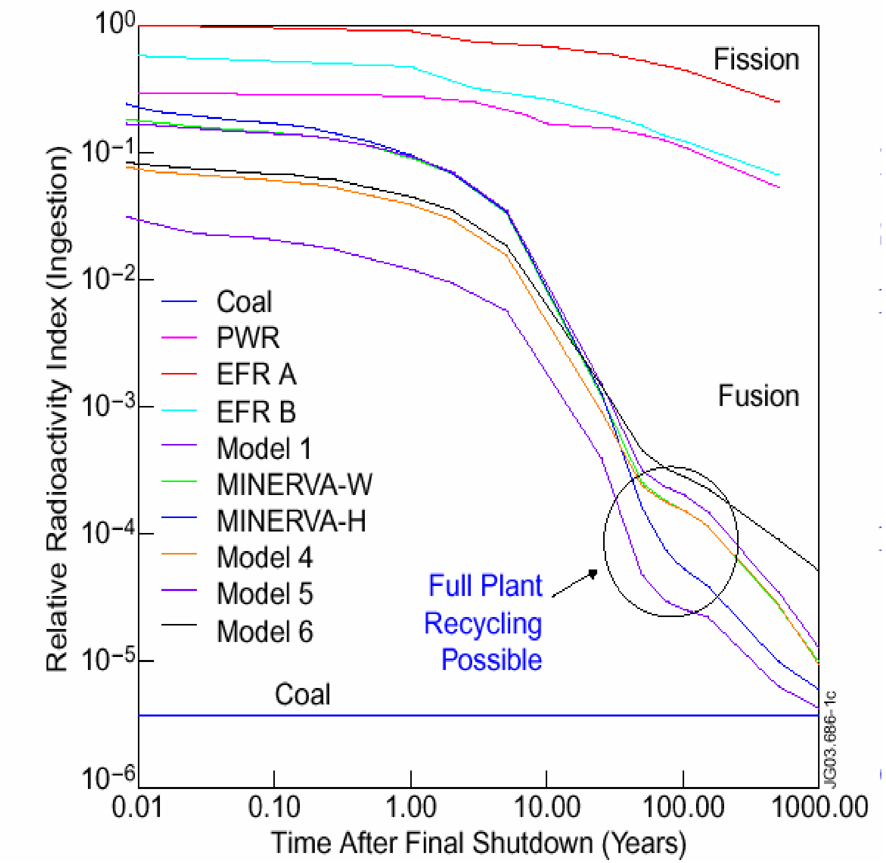
- Four designs with varying extrapolations from present physics and technology. $P_{electricity}$ ~ 1.5 GigaWatt optimised to give lowest generation costs
- Results confirm good safety and environmental features
- Cost of electricity is reasonable (9 €-cents/kW-hour for early model A; 5 €-cents for early model D - lower with mature technology)

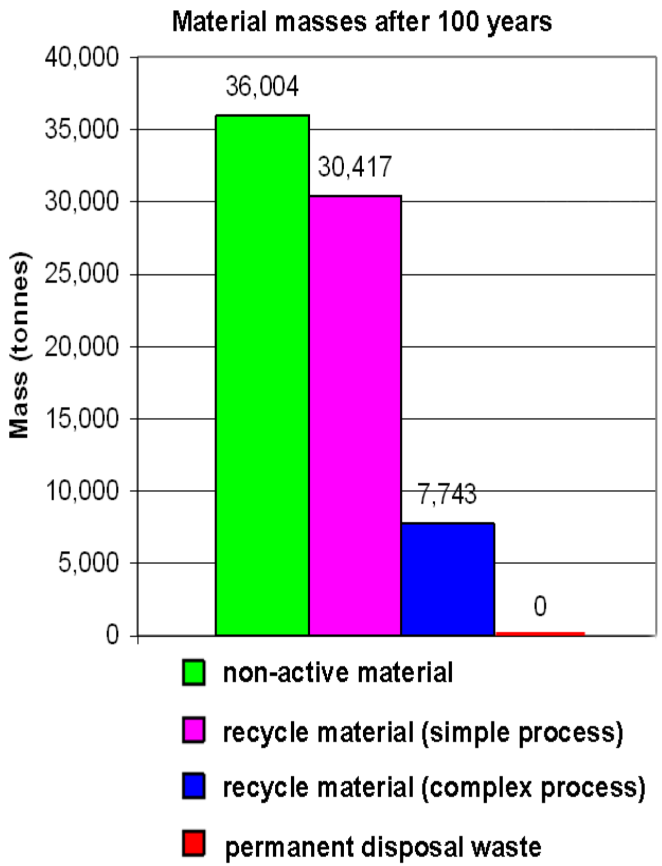
FUSION'S ADVANTAGES

- essentially unlimited fuel
- no CO_2 emissions or air pollution
- major accidents impossible
- no radioactive "ash" and no long-lived radioactive waste
- competitive electricity generation cost if reasonable availability (e.g 75%) can be achieved - and essentially zero "external" cost (impact on health, climate)

FUSION DISADVANTAGES

- More research and development needed
- Residual radioactivity in the blanket and wall – but no equivalent of core of fission reactor, no actinides (long-lifetimes)



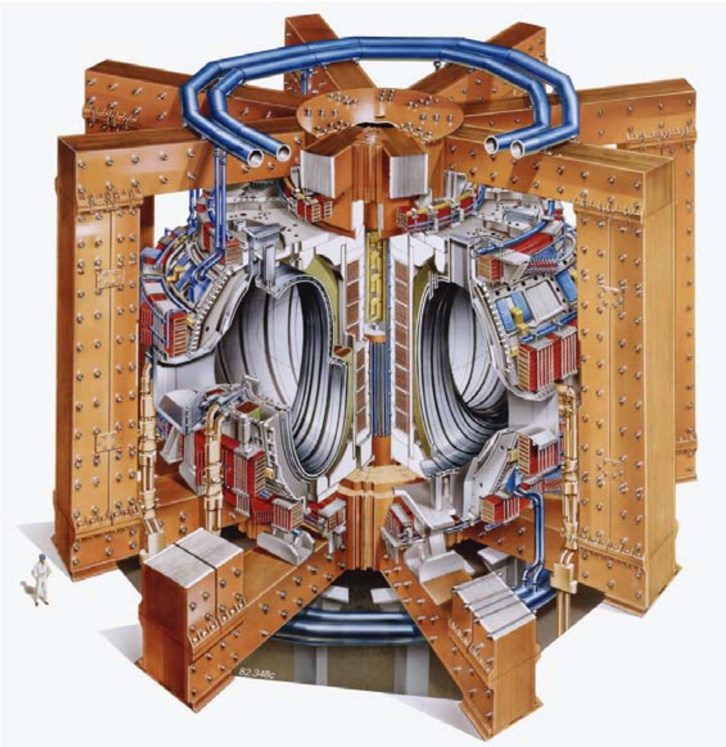


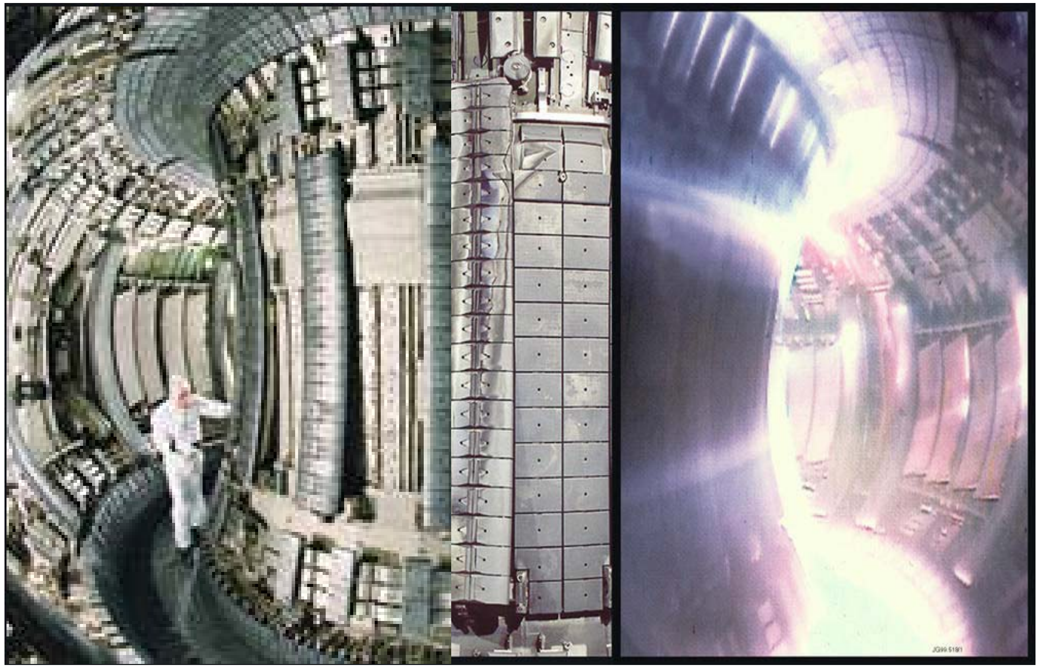
What is the status of fusion research ?

UKAEA Fusion Working in Europe

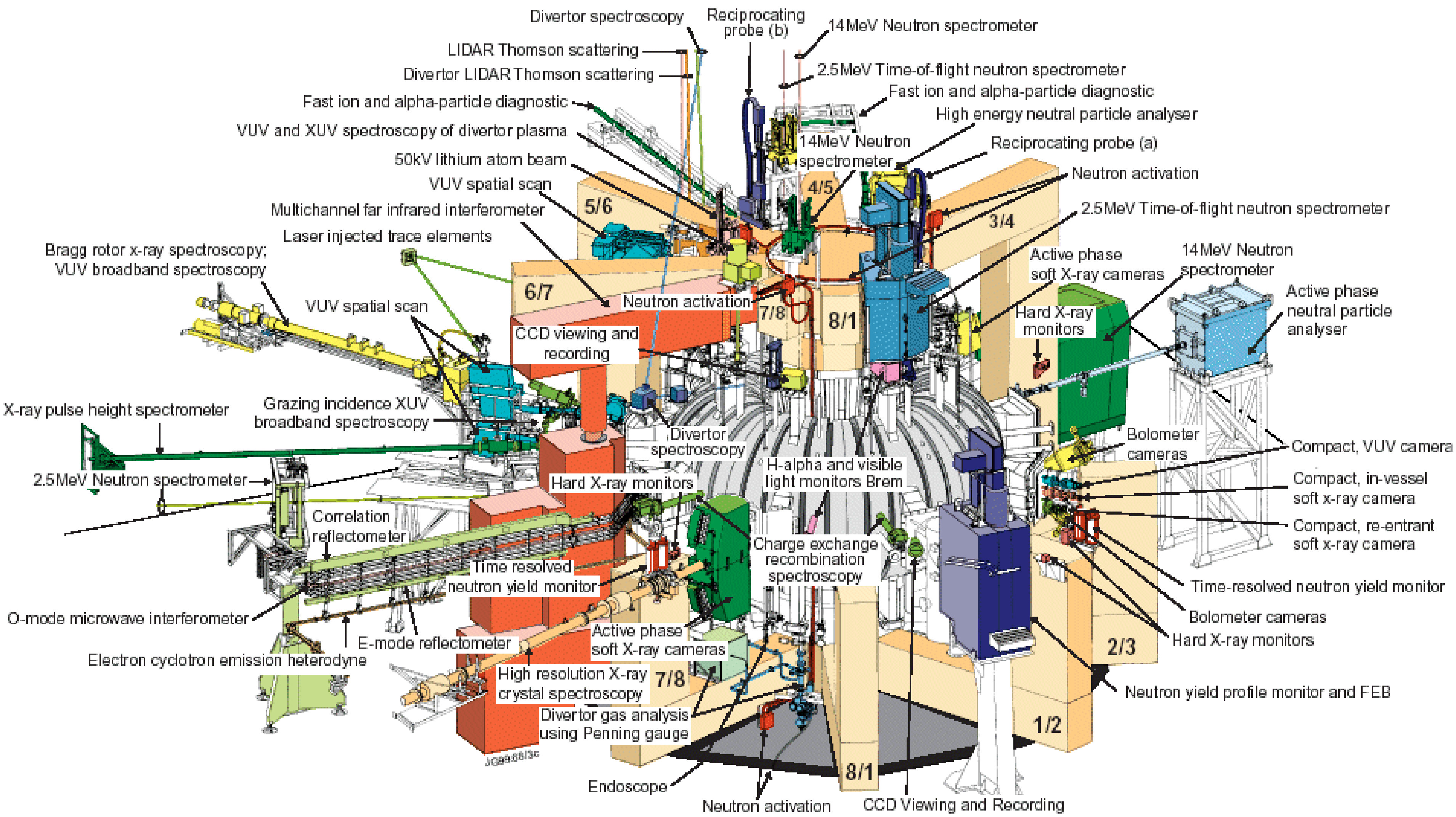
JOINT EUROPEAN TORUS (JET)

- JET is a tokamak – the most developed and promising system
- Currently the world's best fusion research facility
- Operated by UKAEA at Culham as a facility for European scientists





JET is surrounded by instrumentation, heating and other systems



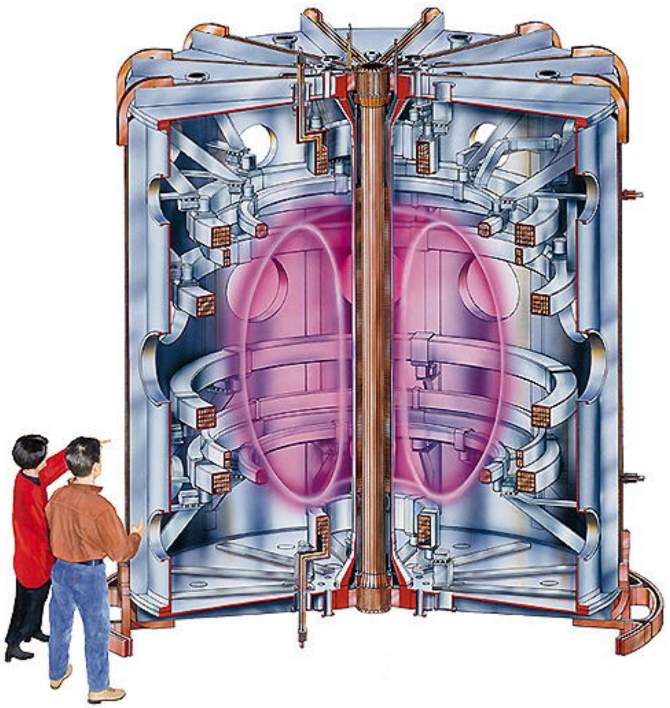
Mega Amp Spherical Tokamak (MAST) - centrepiece of the UK's own programme

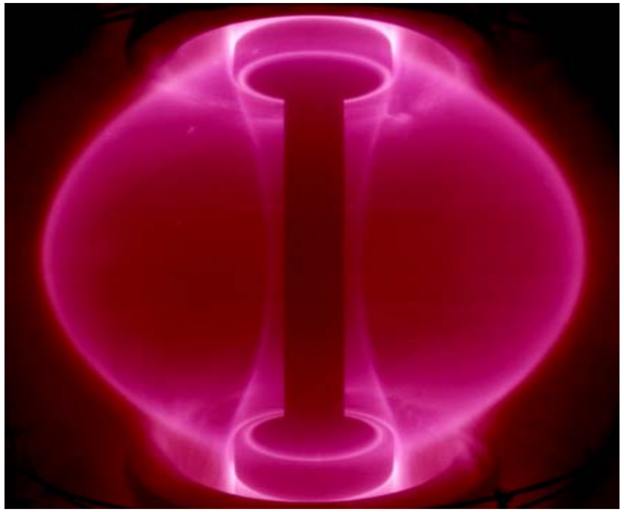
Based on a promising more compact, but less developed, configuration than JET. The UK has pioneered this spherical tokamak approach

⇒ interesting new information, expanding fusion databases

⇒ could play vital role as a "Component Test Facility"

⇒ could, in long-run, be basis for smaller and simpler power stations





UKAEA Fusion Working in Europe

How does a tokamak work and what do we study?

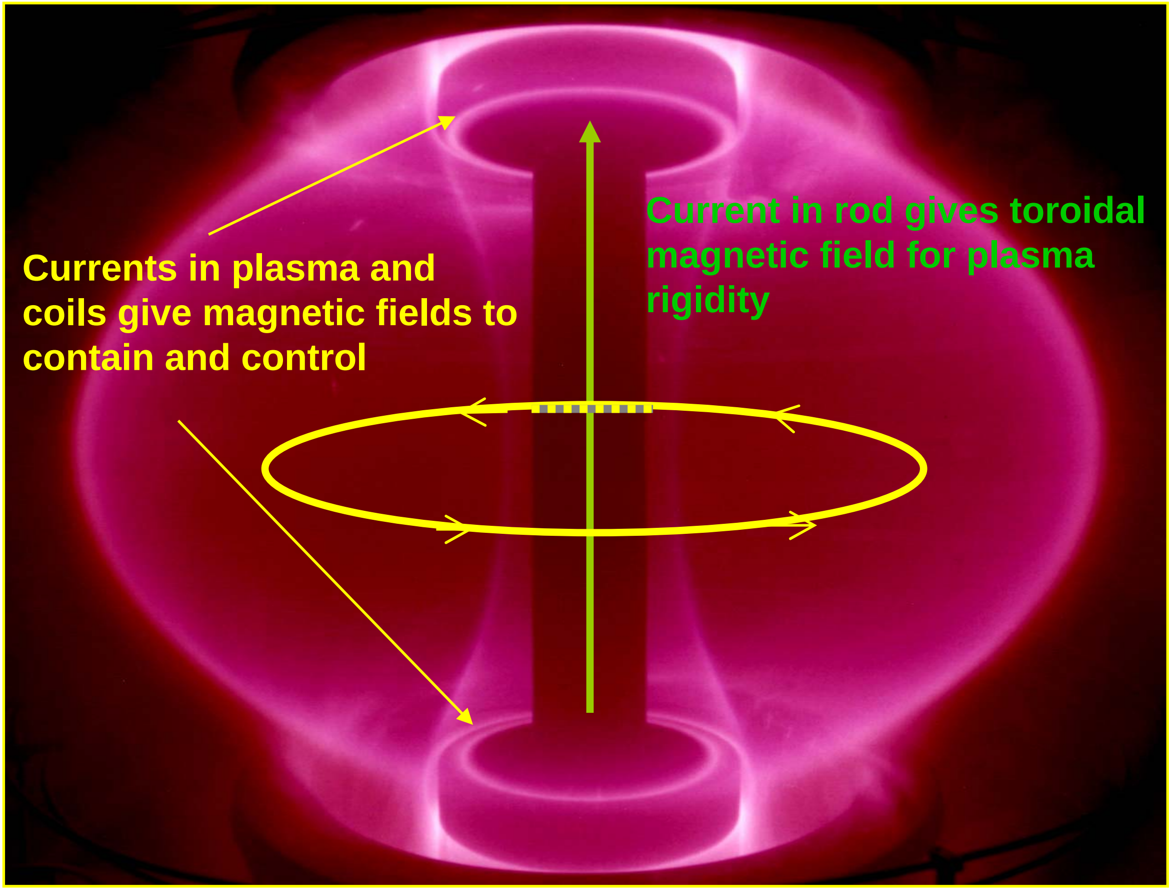
Research Areas:

⇒ Energy losses from the hot plasma - turbulence, etc.

⇒ Plasma stability, control

⇒ Plasma kinetics - heating, current drive, waves, fast particles

⇒ exhaust - edge flows, interplay with atomic and surface physics



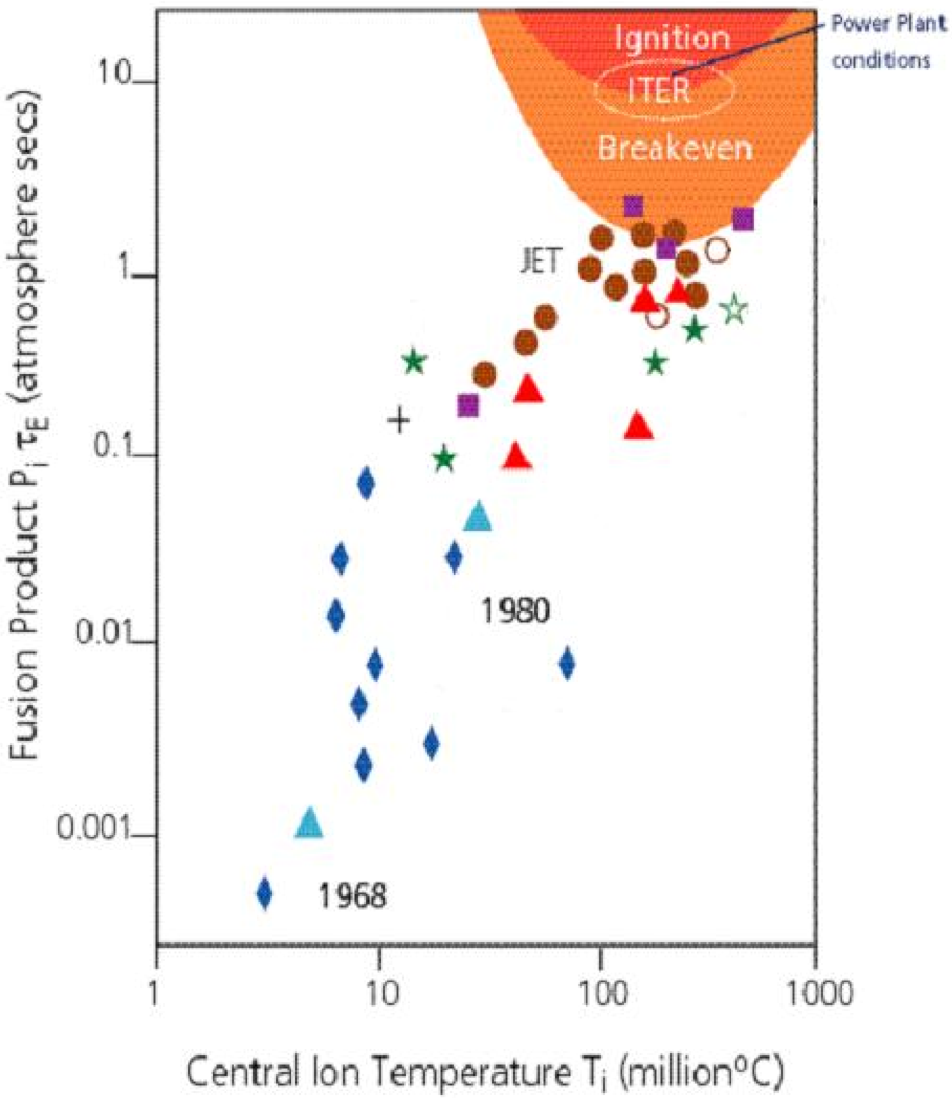
Plasma in spherical tokamak at Culham. Temperature is ~ 10 million ^{o}C

This research needs a wide range of instrumentation plus beam and microwave heating systems to get the plasma hotter than the sun

UKAEA Fusion Working in Europe

Major progress in recent years

- Huge strides in physics, engineering, technology
- **JET**: 16 MW of fusion power ~ equal to heating power. 21 MJ of fusion energy in one pulse
- Ready to build **ITER** - the next generation, Giga Watt-scale tokamak
- Scaling laws that fit data from existing tokamaks give great confidence that ITER/power stations will achieve desired plasma performance



NEXT STEPS FOR FUSION

- Construct **ITER**, then operate it to demonstrate:

  ⇒ energy out = 10× energy in, "burning" plasma
  ⇒ integration of the plasma with power station technologies – superconducting coils, test blanket modules

  While ITER is built (10 years) operate JET to improve ITER operation and continue configuration optimisation (MAST, . . .)

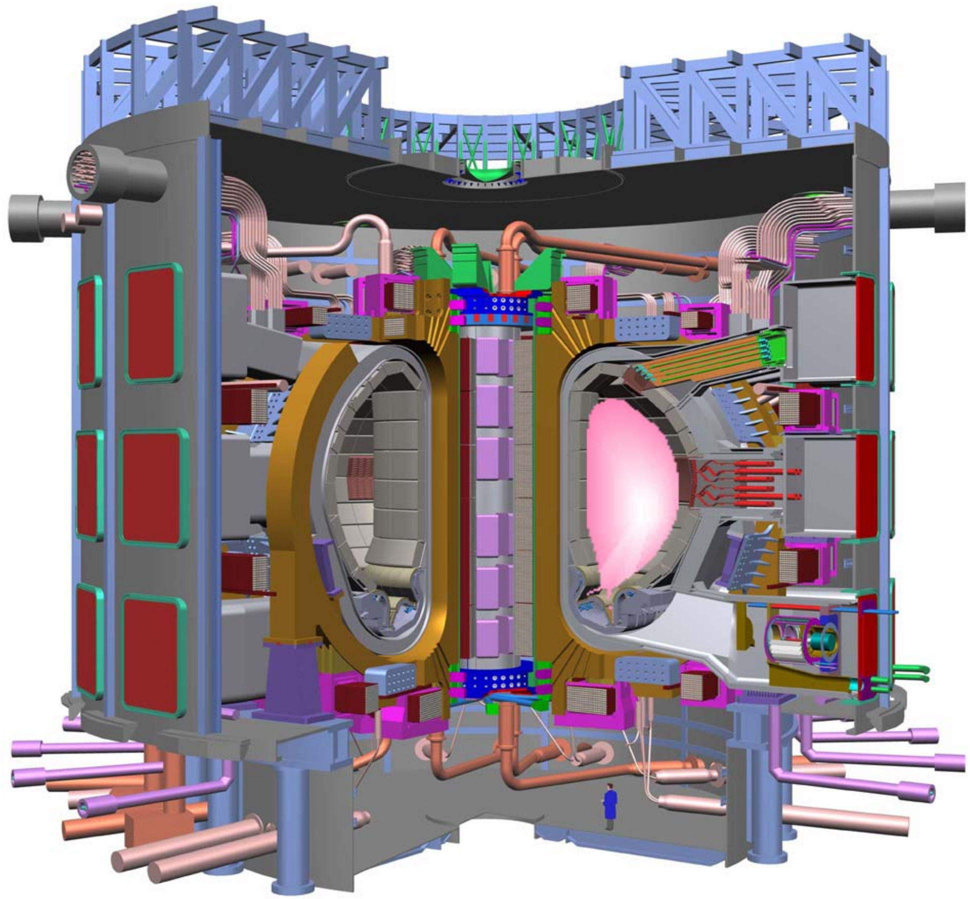
- Intensify R&D on materials for plasma-facing and structural components and test at the proposed International Fusion Materials Irradiation Facility (IFMIF)

- There is increasing support world-wide for proceeding with ITER and IFMIF in parallel – the "Fast Track" to fusion power – which could be followed by prototype power stations within 30 years.

UKAEA Fusion Working in Europe

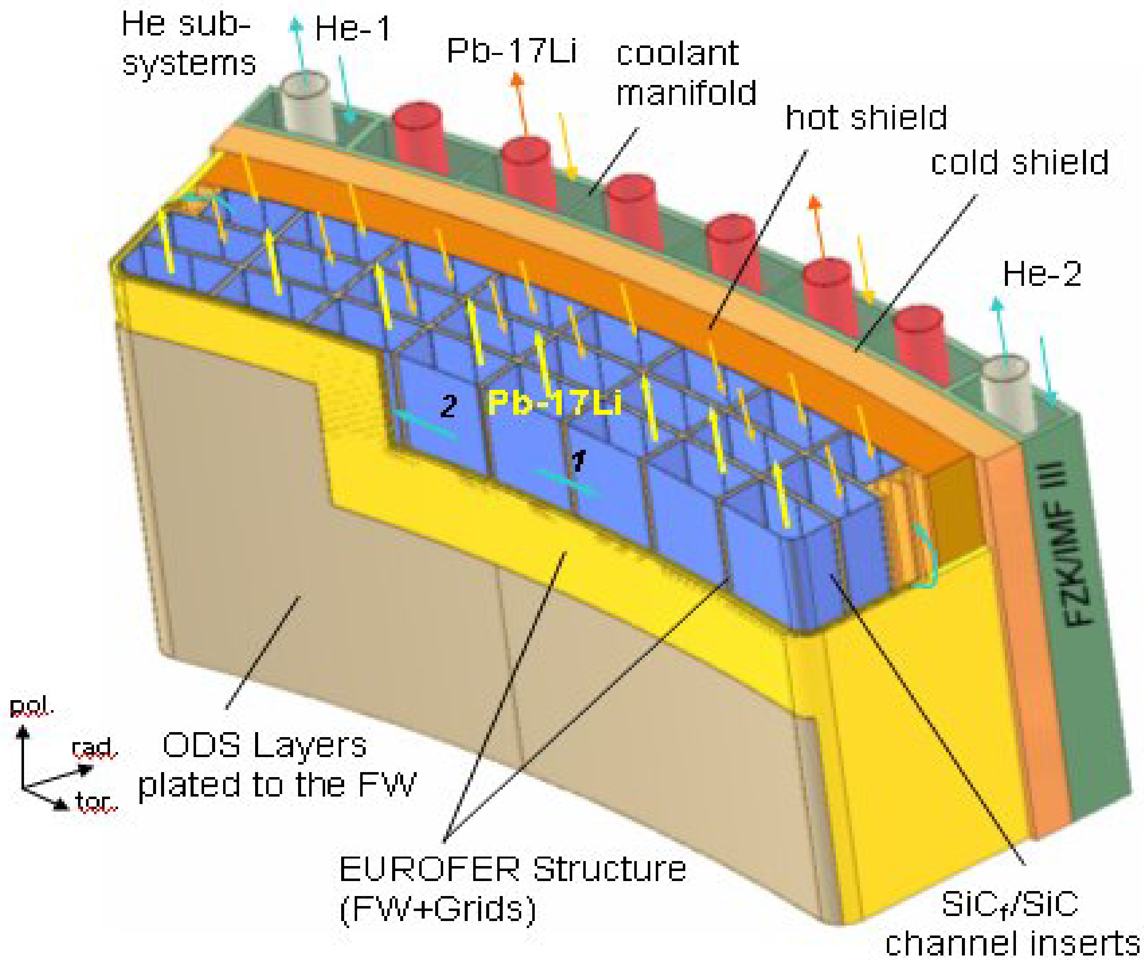
ITER - International Tokamak Experimental Reactor

- Aim is to demonstrate integrated physics and engineering on the scale of a power station
- Key ITER components already prototyped and tested by industry
- 5 Billion Euro construction cost
- Partnership between Europe, Japan, Russia, US, China, South Korea. India has asked to join.
- 18 month siting deadlock (Europe vs. Japan) ended in June – ITER will be built at Cadarache in France with other joint EU-J projects in Japan



One blanket design that could be tested on ITER

– neutrons would heat the blanket (→ electricity in a power station) and generate tritium through reactions with lithium



UKAEA Fusion
Working in Europe

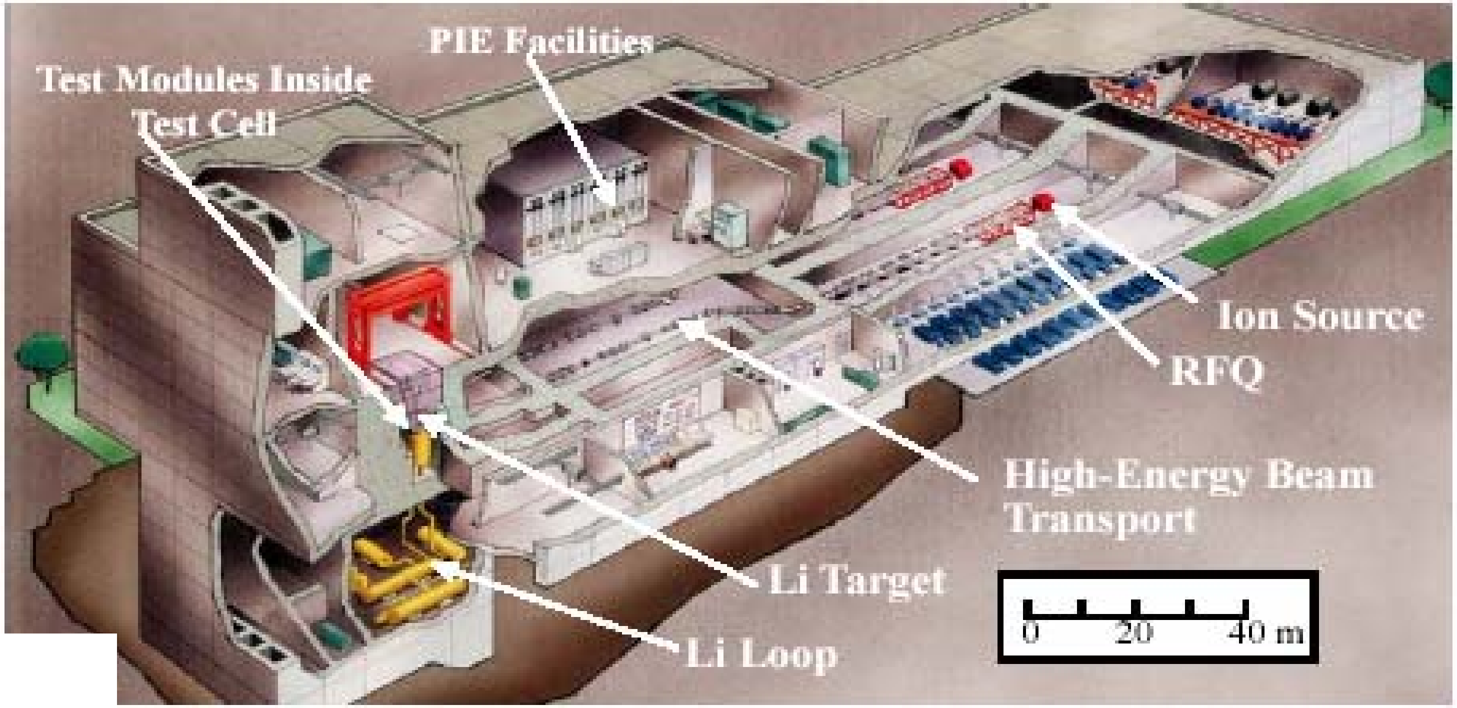
Performance of Materials is key to reliability of fusion power stations and hence cost of electricity

- ITER won't give the day-in day-out continual operation of a power station.
- Structural materials will be bombarded by 2 MW/m^2 of 14 MeV neutrons for many years $\Rightarrow$ 20 displacements per atom per year

  (14 MeV fusion neutrons $\Rightarrow$ much bigger cascades than in fission + new effects as helium is generated in material)
- Various materials have been considered, and there are good candidates which survive similar doses of lower energy neutrons, BUT further modelling and experiments are essential:
- Only a dedicated (€800M) accelerator-based test facility - IFMIF - can reproduce reactor conditions: results from IFMIF will be needed before a prototype commercial reactor can be licensed and built

IFMIF - International Fusion Materials Irradiation Facility

(may be taken forward as part of the ITER deal with Japan)



. Overview of the IFMIF design, with major subsystems identified. The lithium target and all test modules are located in a common test cell. Post-Irradiation Examination (PIE) facilities are provided to examine irradiated specimens on site. Maximum availability is achieved by using two independent accelerators. The ion source, RFQ and HEBT of one deuteron beam line are indicated.

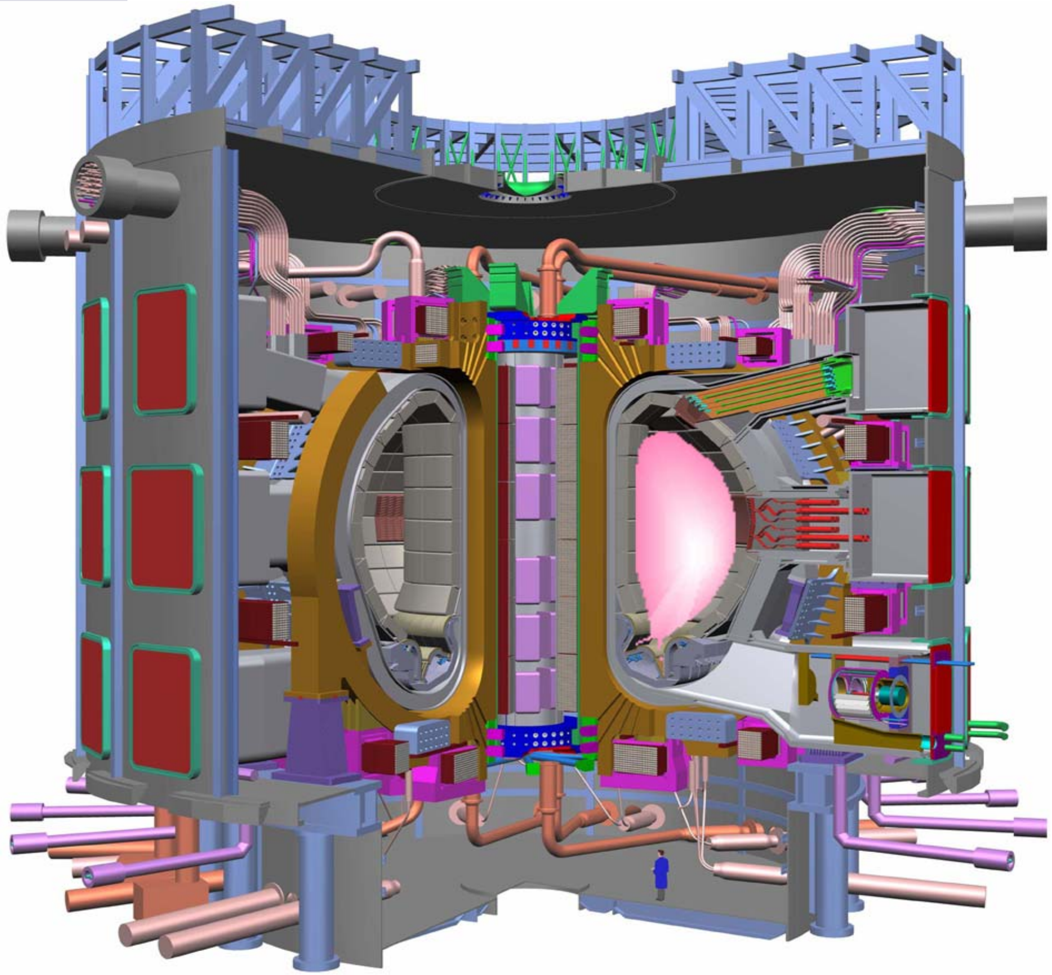
Back to ITER ….. what happens now?

- Site has been chosen in France so now negotiations can be completed (a key meeting is today)
- Hope to initial international agreement early 2006, then parliaments etc. have to ratify.
- Then international and partners' own ITER organisations established
- Procurement will be mainly "in kind" – the six partners own organisations will provide the components. Europe will provide ~ 40%
- ~ 90% of procurement will be direct from industry but specialist components including instrumentation need further R&D by labs like Culham

A very short description of ITER's instrumentation needs

- from a non-expert !

ITER Measurement needs - wide range



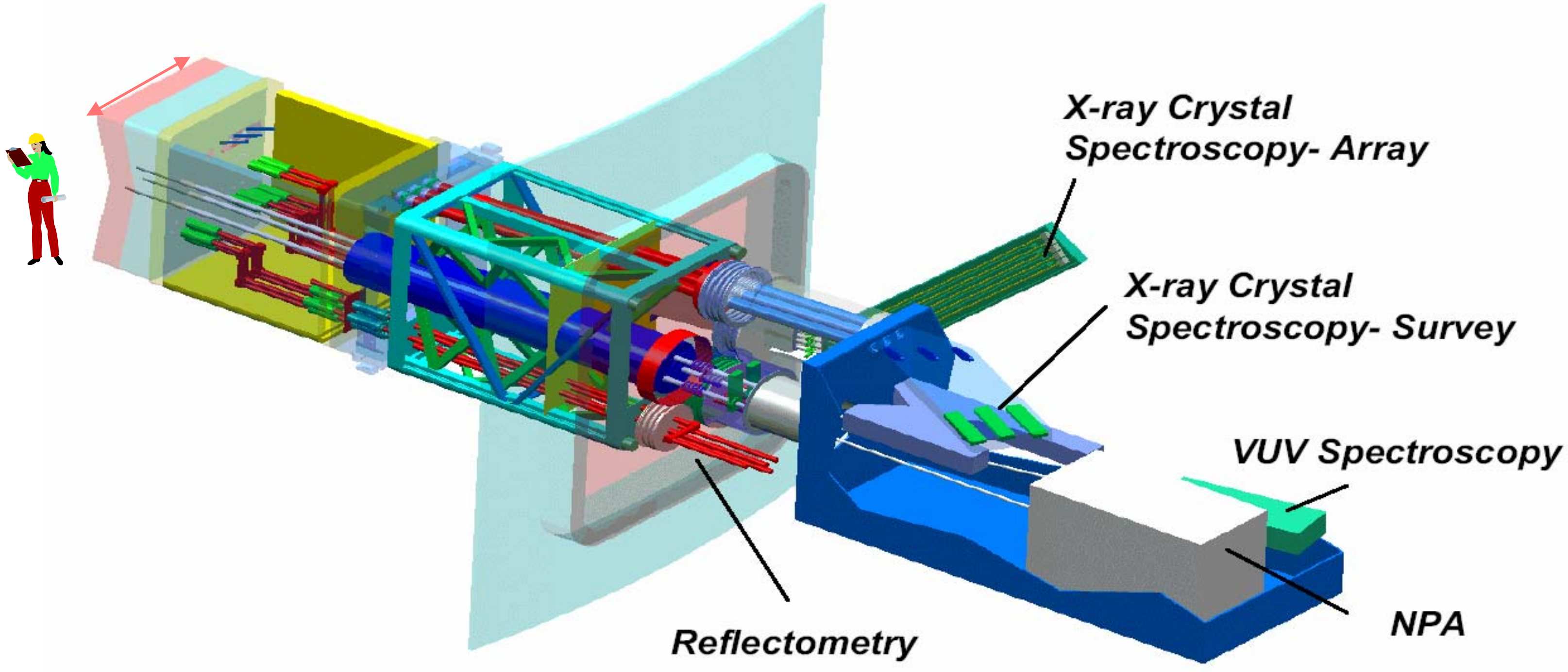
- Particles (keV to >14MeV): neutrons, neutrals, fast ions, edge plasma Langmuir probes, deposition probes
- X-rays: line spectra (Doppler + survey), UV: line spectra
- Visible/IR: Doppler (charge exchange from beams), impurity, Thomson scattering (laser - LIDAR), thermal imaging
- Far infra-red: interferometry, polarimetry (lasers)
- Microwaves: interferometry, reflectometry, collective scattering
- Bolometry (radiative losses)
- Magnetic fields: pick-up coils, etc.
- Engineering

Measurements: General issues

The techniques for ITER are used on existing tokamaks including JET but ITER will pose many challenges both in the range of parameters to be measured and in its harsher environment.

- Real-time multi-variable control of the plasma → requires high accuracy and reliability
- Long plasma pulse length → requires high stability
- Mixing high accuracy and reliability with hostile environment - engineering extremes (thermo-mechanical loads, electromagnetic stresses, etc.)
- Scale and cost: ITER port plugs will be very large
- Nuclear environment - materials issues, labyrinths, reliability, automatic/remote calibration, alignment to consider, as well as neutronics (not allowed to let many out)
- Data volume – not as big as LHC but still challenging
- Administratively complex: multi-party, contractual interfaces, QA …..

ITER diagnostics will be arranged in "Port Plugs" - responsibility for these will be allocated to the ITER partners



- Within Europe, responsibilities will be allocated to consortia of fusion labs.
- UK wants to lead one or more diagnostics and a port plug. We're positioned for laser scattering (electron temperature, density) and charge exchange recombination spectroscopy (ion temperature and rotation) plus smaller roles in other diagnostics

CONCLUSIONS

- **The cocktail of energy sources that we need must include large-scale sources of base load electricity – fusion is one of very few options**
- **A Prototype power station could be putting fusion power into the grid in under 30 years if ITER and IFMIF proceed in parallel and there are no major surprises**
- **There is still a lot of work to be done for experiments like JET and labs like Culham – including developing the instrumentation for ITER**

For more information please visit

www.fusion.org.uk, www.jet.efda.org, www.iter.org