ITER, fusion, and the conceptual design of a fusion power plant

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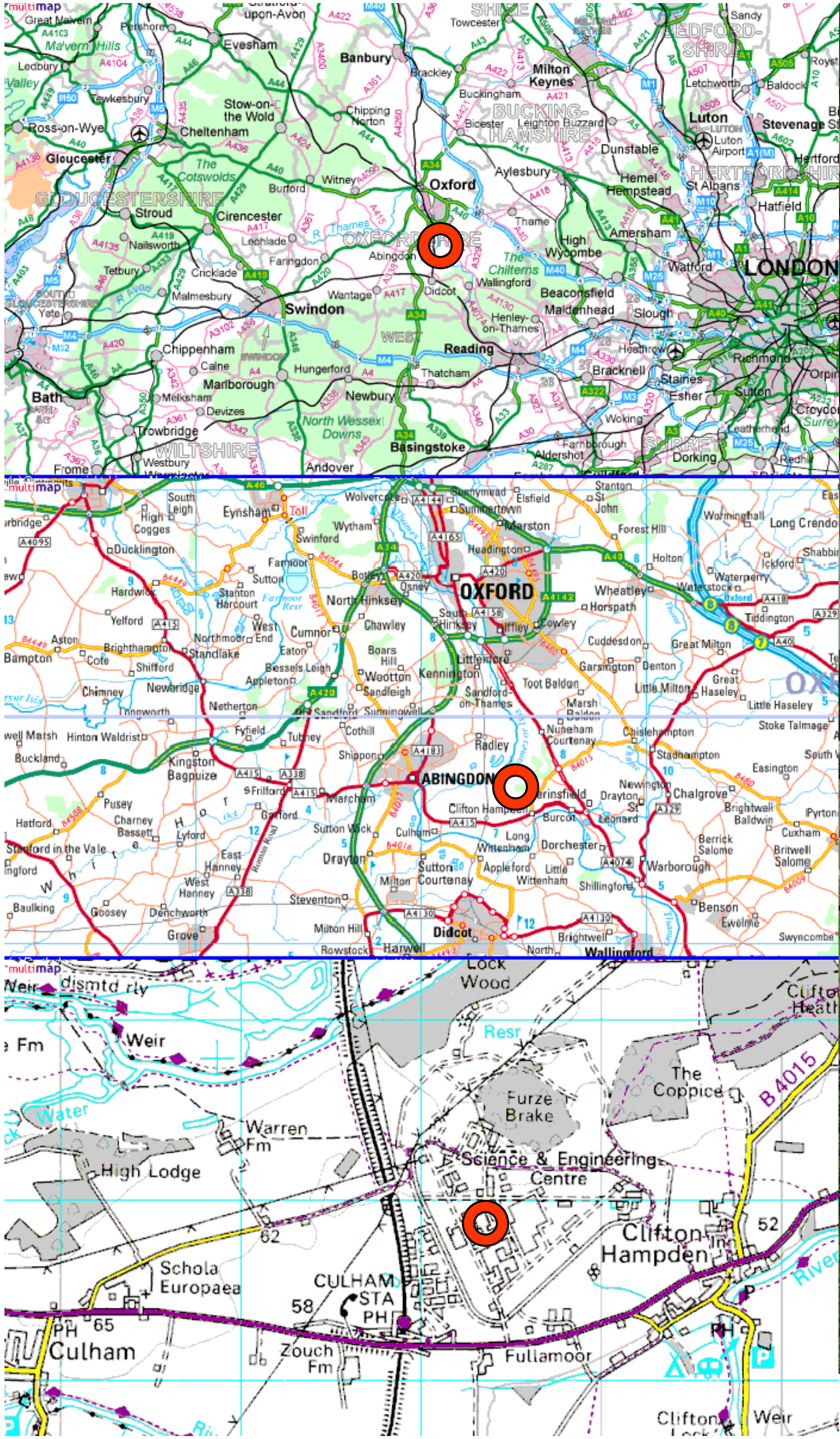
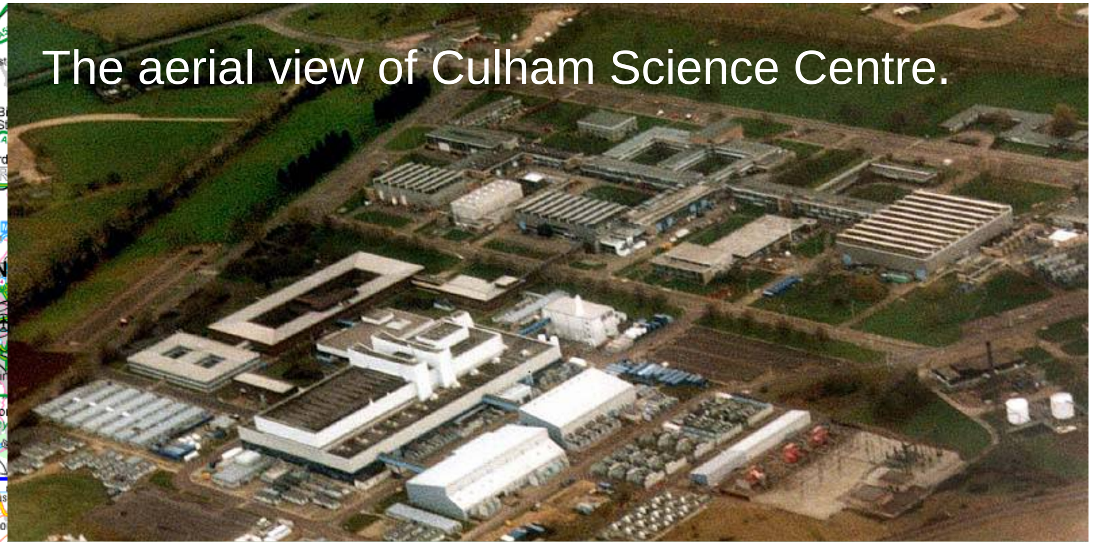
17th November 2008

UKAEA Fusion Working in Europe





The aerial view of Culham Science Centre.

The aerial view of JET building.

fusion, and fusion power plant design

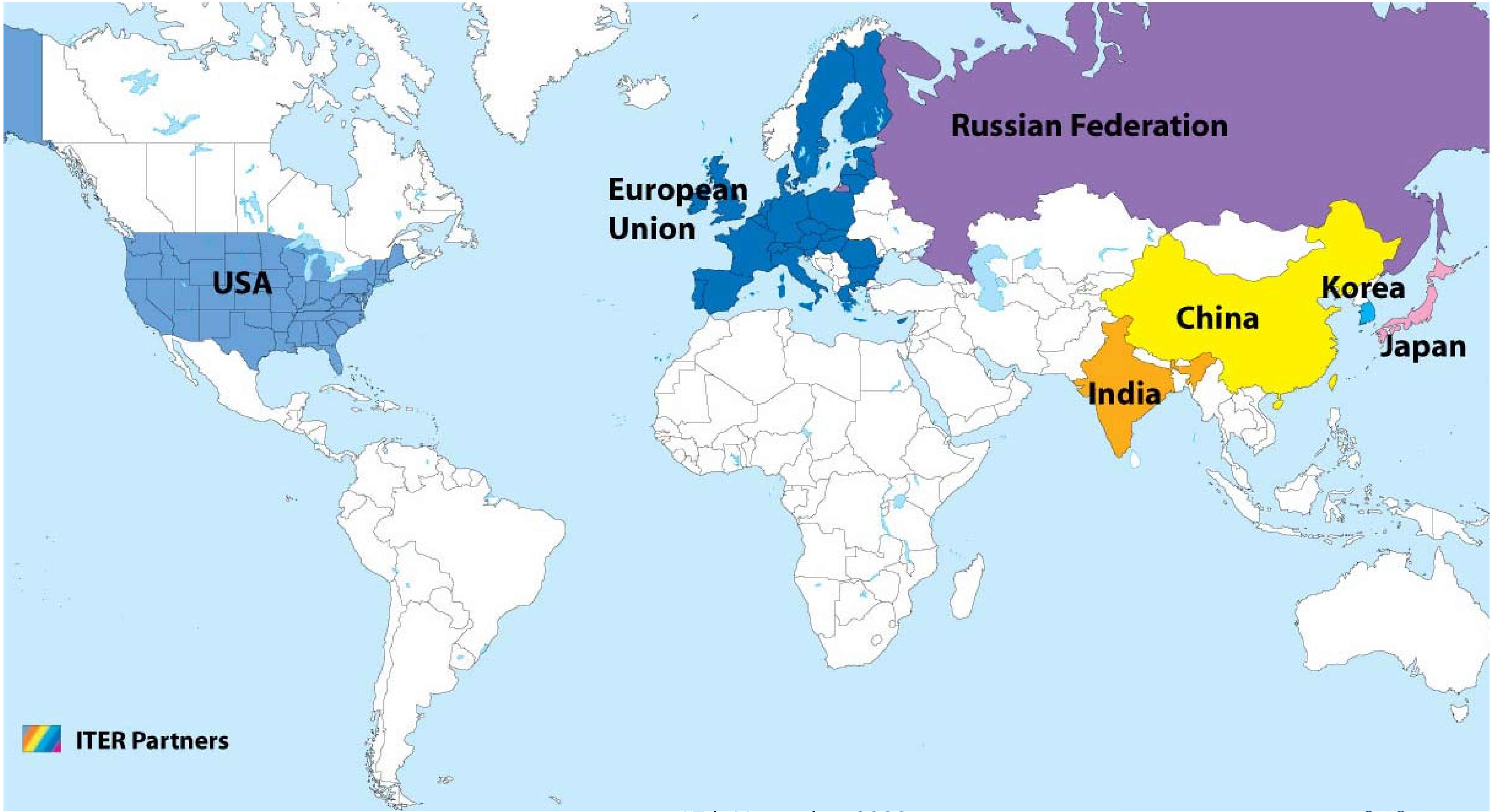
Reykjavik 1986

ITER – the history

- An agreement on International Thermonuclear Experimental Reactor was signed by M. Gorbachev and R. Reagan in Reykjavik in 1986.
- 1992: the US, the USSR, the EU and Japan began a 6-year period of Engineering and Design ITER studies.
- 1998: the US withdraws from the ITER project under Congressional direction. Other parties carry on with the work.
- 2001: studies show that all the above issues can be successfully resolved with a smaller tokamak design. China and Korea express interest, joining in 2002. India joins in 2004. In 2003 the US re-joins ITER negotiations.

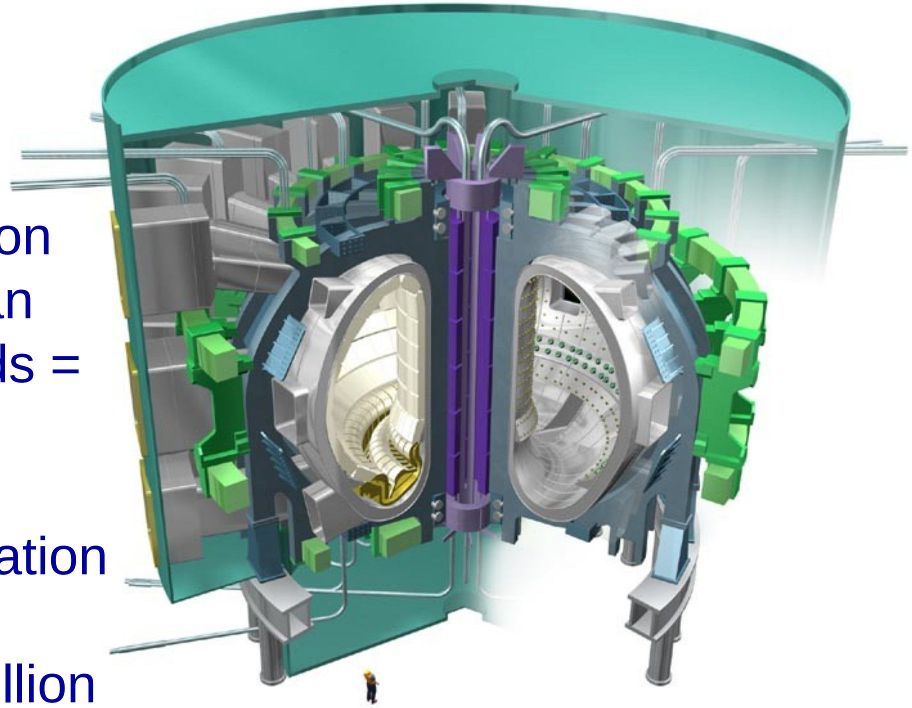
Seven parties involved in the construction of ITER

(ITER: International Thermonuclear Experimental Reactor)

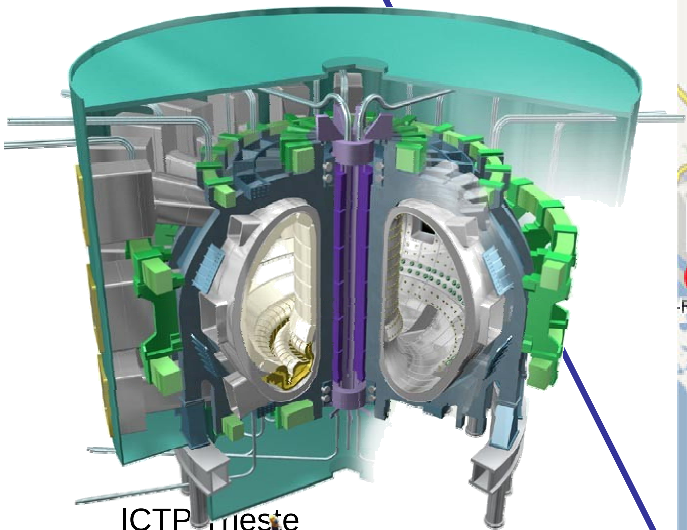


ITER – Key facts

- Objective: to demonstrate the scientific and technological feasibility of fusion power
- Designed to produce 500 MW of fusion power (tenfold the energy input) for an extended period of time ~500 seconds = 5 to 10 minutes at a time
- 10 years construction, 20 years operation
- Initial construction cost estimate: 5 billion Euros for construction, and 5 billion for operation and decommissioning



Location: Cadarache (near an existing CEA site)



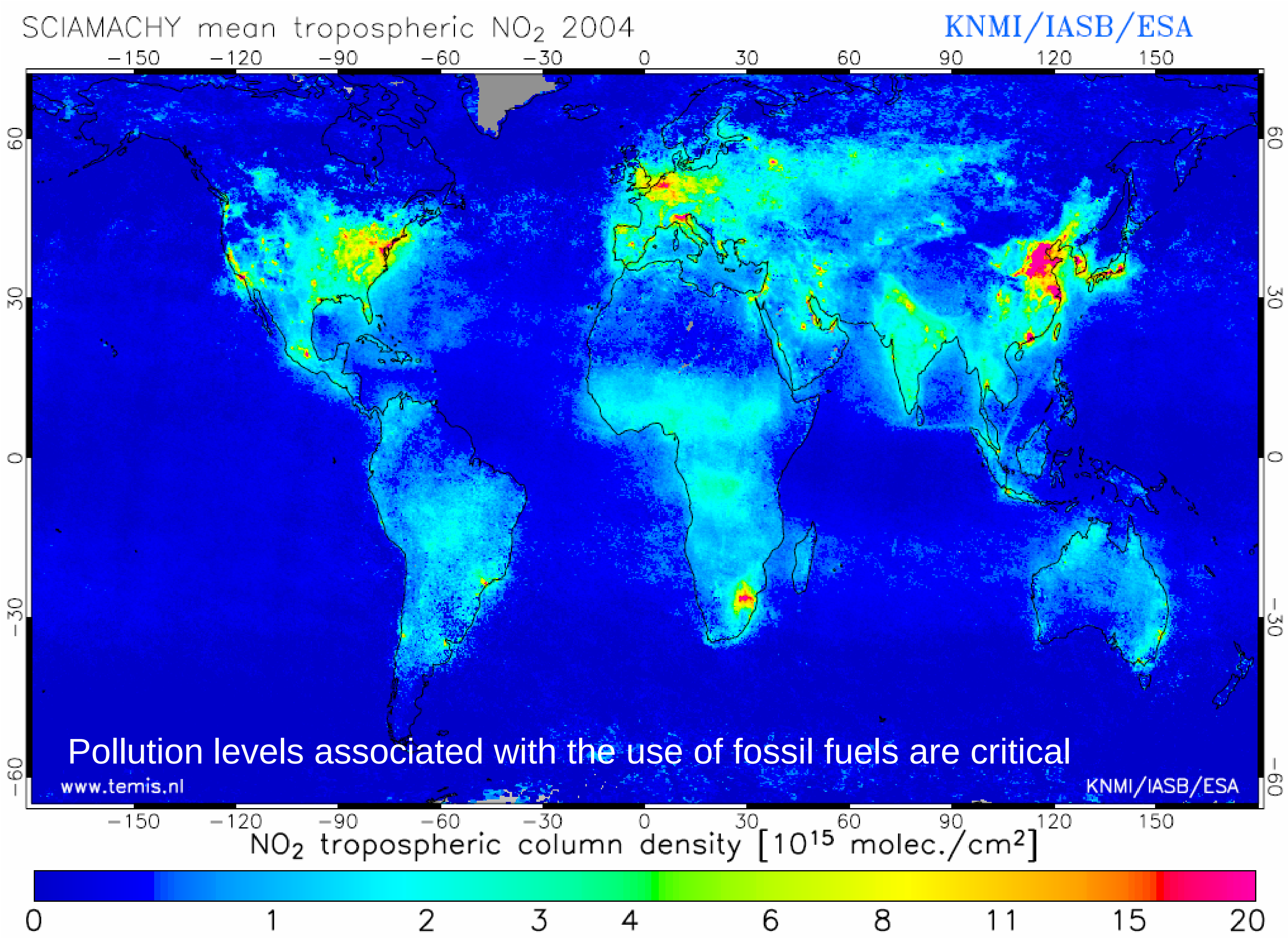
= Route for ITER components

Aerial view of the ITER site

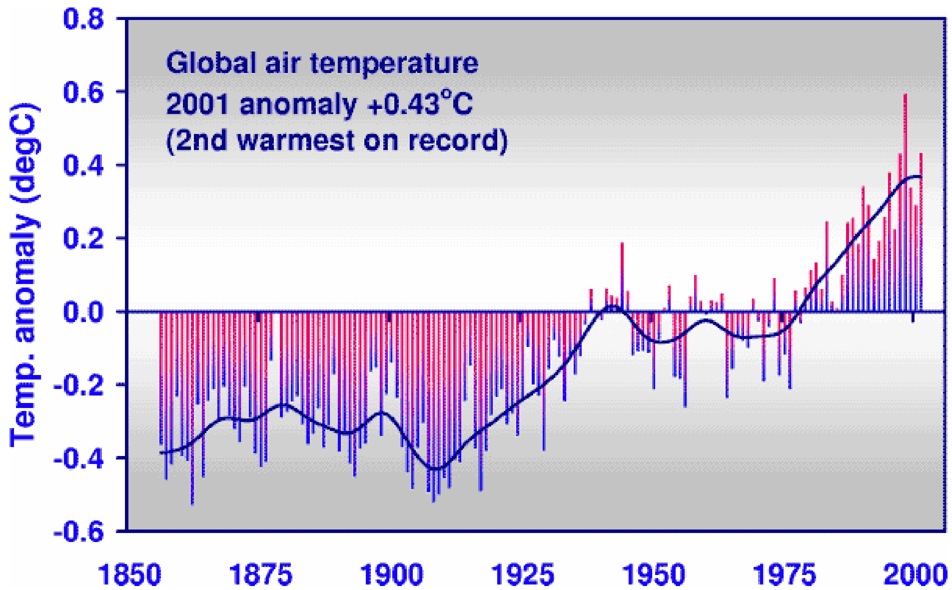
The current ITER office

Why do we need ITER and what is fusion?

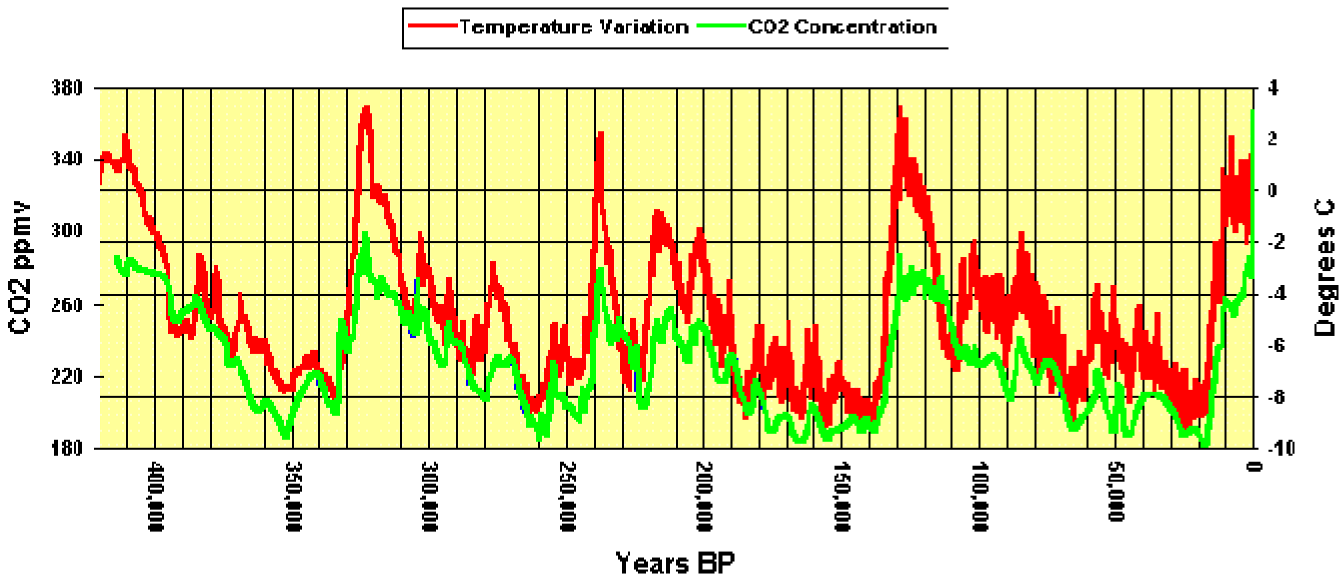
Why do we need ITER?



Why do we need ITER?



There is a correlation between the amount of CO_2 emitted into the atmosphere, due to the use of fossil fuels, and the average global temperature. Global warming requires developing power generating technologies not relying on fossil fuels.



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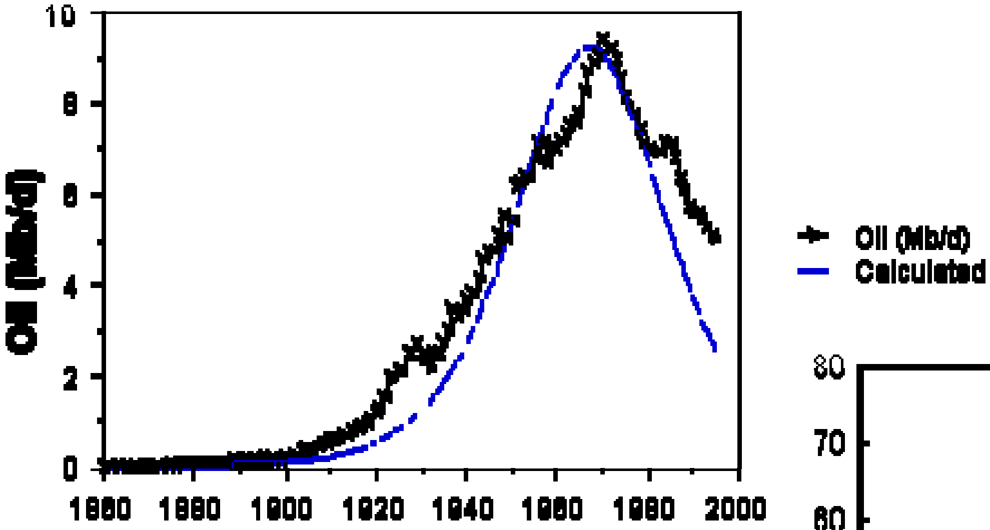
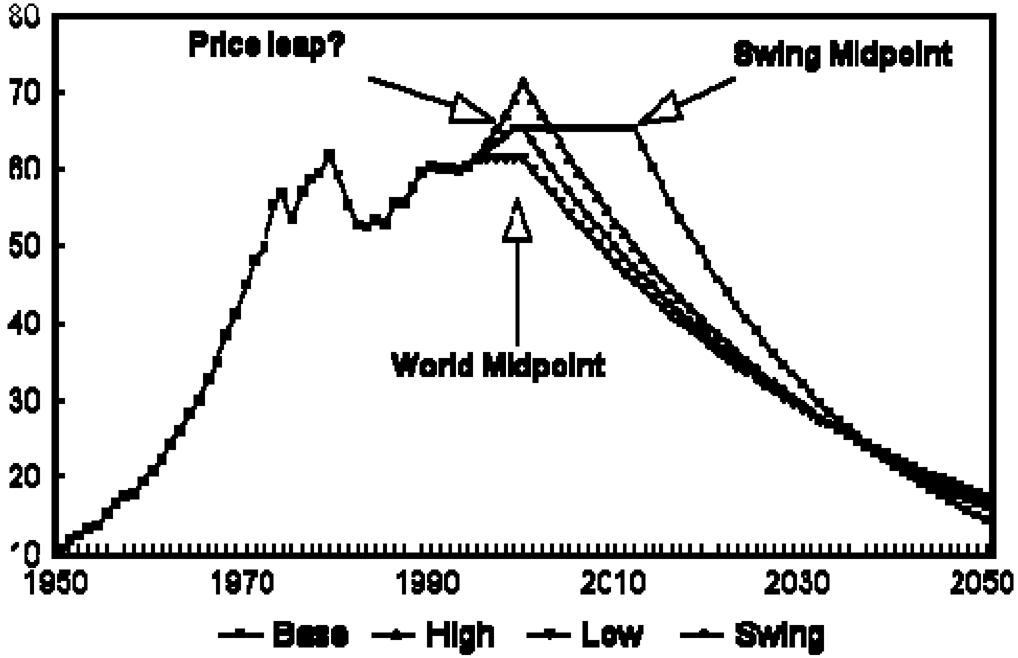
Fusion Working in Europe

The end of oil? (and other fossil fuel resources)



In 1956 M.K. Hubert of Shell correctly predicted that the US oil production would peak at around 1970.



World rate of oil production (in thousands of kbarrels per day). The Swing Case assumes a price leap when Middle East production reaches 30% of world total. This model analysis was performed and published in 1999. Note the question mark after “Price leap”.

Alternative energy sources: nuclear fission

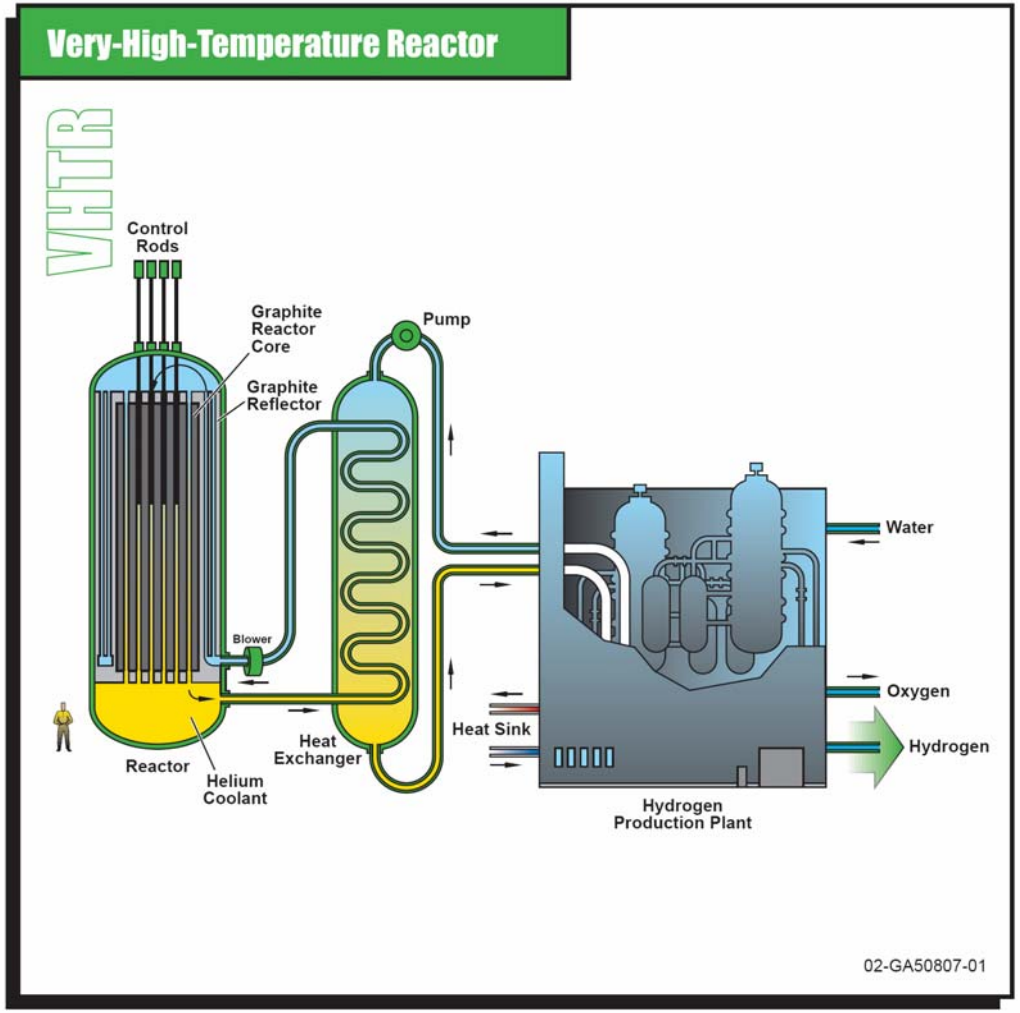
Nuclear fission is a proven alternative but has its own issues.

- **Public concerns on safety.**
- **Long lived radioactive waste products (many thousands of years) that require transportation and re-processing.**

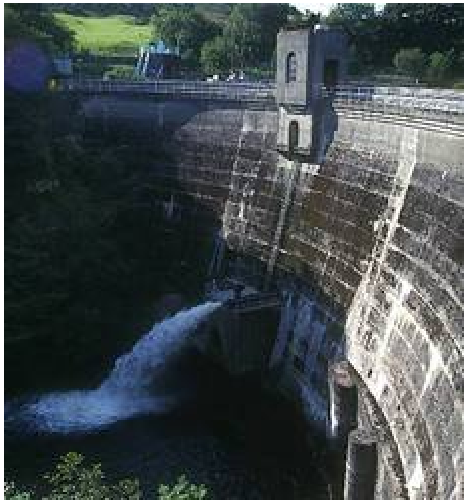
China has vowed to increase the nuclear content of its power generation mix to 4 per cent by 2020 from the current 2 per cent, which can be translated into some 30 nuclear plants totalling 40 gigawatts of installed capacity.

Alternative energy sources: nuclear fission

The VHTR concept addresses two of the issues: power generation and technology for producing hydrogen that could be used as fuel for ground transportation



Wind, wave, solar, hydro



Renewable energy sources are attractive options at present and offer long term, clean energy reserves.

<u>However</u> :

Low energy density

•Fluctuations in time require storage systems, reducing efficiency and increasing costs

•Only solar power generation has the potential needed for making global impact.

1. Germany - 20,622MW
2. Spain - 11,615MW
3. USA - 11,603MW
4. India - 6,270MW
5. Denmark - 3,136MW
6. China - 2,604MW
7. Italy - 2,123MW
8. UK - 2,034MW
9. Portugal - 1,716MW
10. France - 1,567MW
(Source: BWEA, 2007)

Fusion as a Long Term Alternative

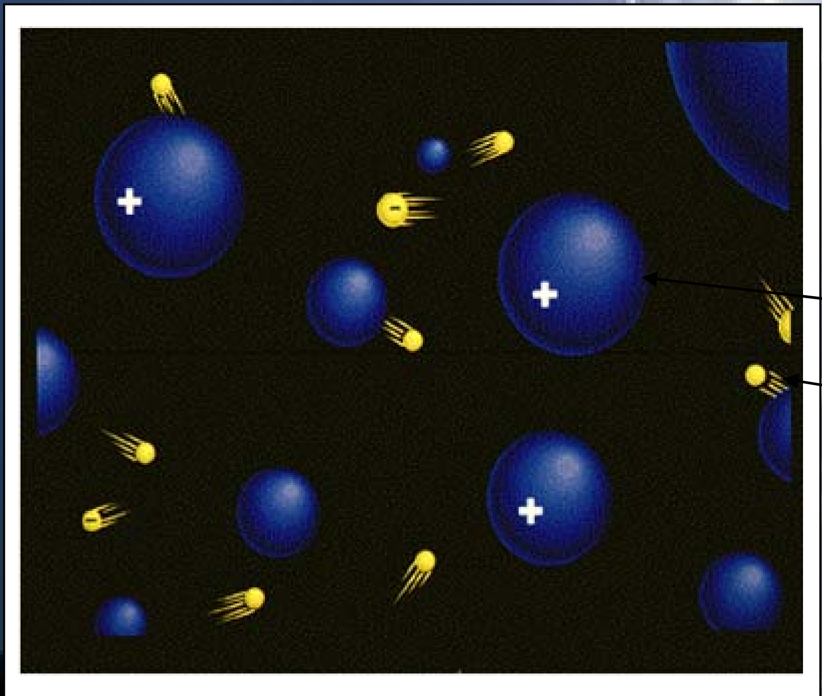
Can we control it and use it?

- The fusion process releases vast amounts of energy from the sun and stars (confirming that it is a feasible way of power generation).
- The energy released per kilogram of fuel is 10 million times more than that released by burning a kilogram of coal.
- But: we need to *control* the fusion process and the energy it releases. This requires an approach different to conventional burning of fuel.

- We have to create very hot *plasma* →
- We have to develop suitable materials →

➢What is plasma?

Plasma is the fourth state of matter, the others being solid, liquid and gas. Most of the Universe is in the plasma state.



If a gas is heated to temperatures above 10000 ^0K the atoms split into

ions (+) and

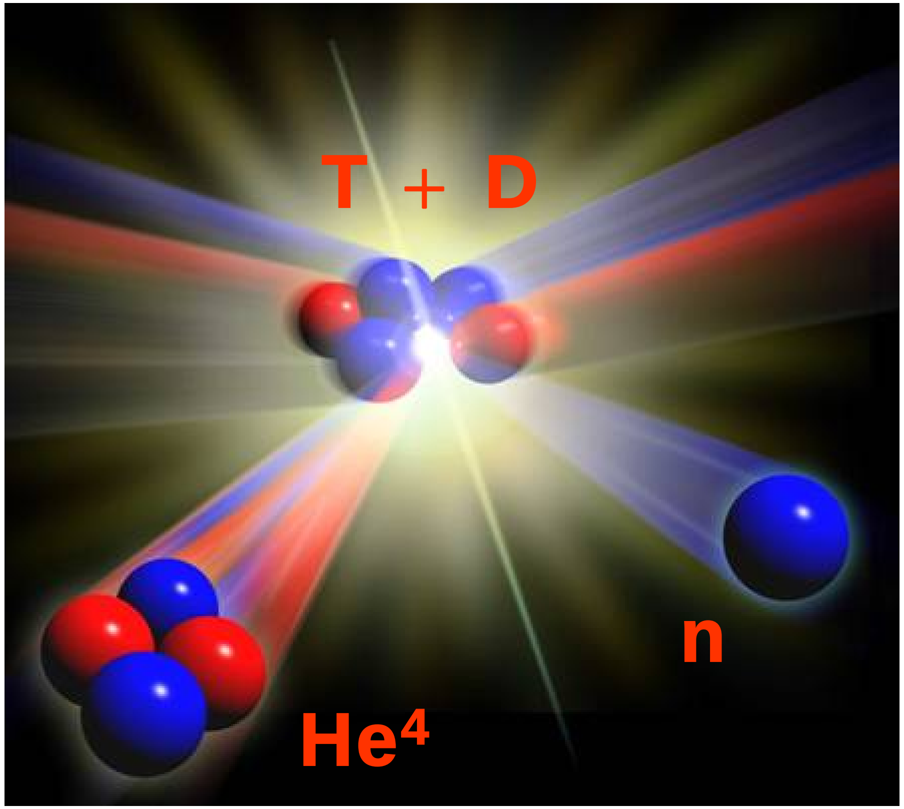
electrons (-)

to form a plasma.

UKAEA Fusion Working with Europe

The fusion process in plasma

Fusion occurs in a plasma when two light nuclei (D+T)* are forced together, producing a larger nucleus (He^4) + a neutron (n).



The combined mass of the two small nuclei is greater than the mass of the nucleus they produce.

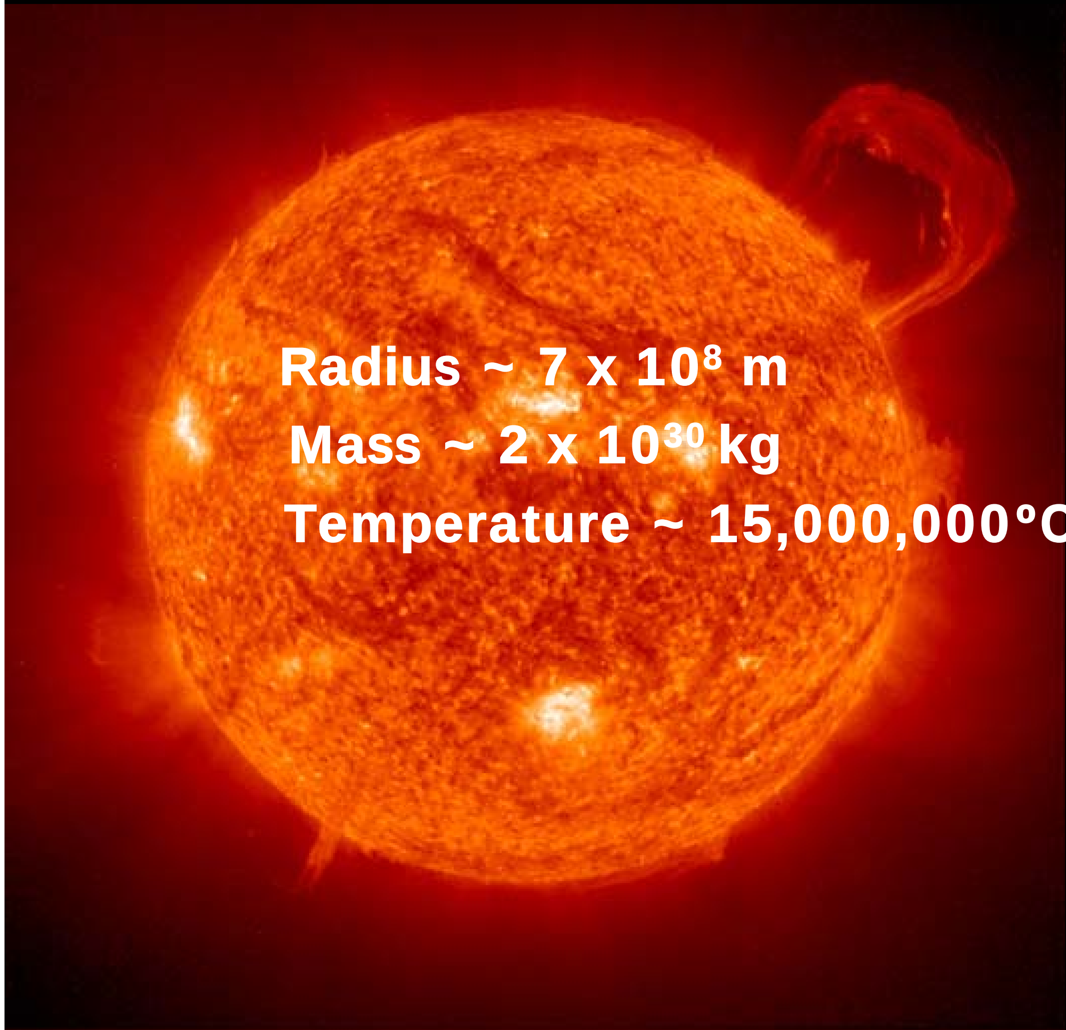
The lost mass Δm (0.4%) is changed into energy.

We can calculate the energy released using Einstein's famous equation:

$$E = \Delta m\, c^2$$

*** Deuterium & Tritium are hydrogen isotopes**

Fusion is the process powering the Sun...



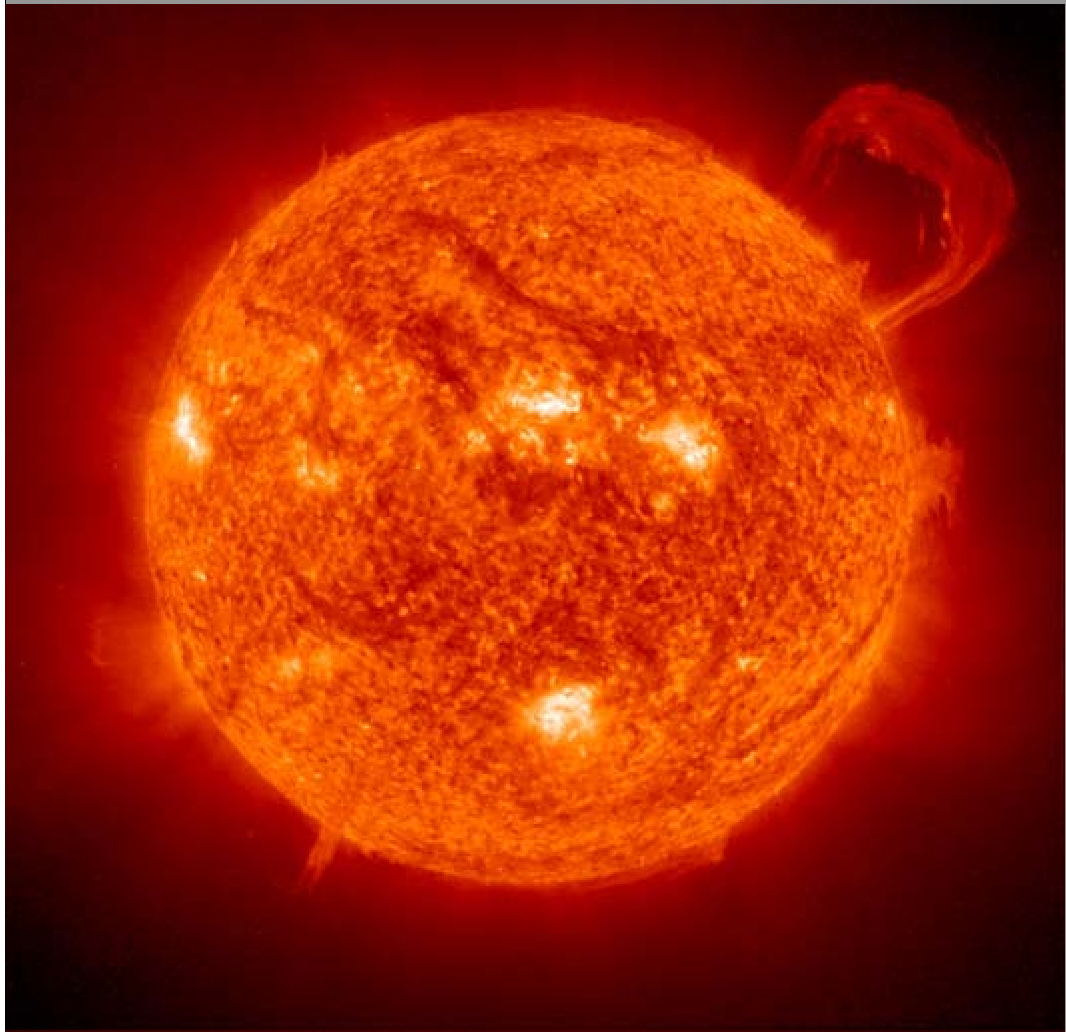
Radius ~ 7 x 10^8 m

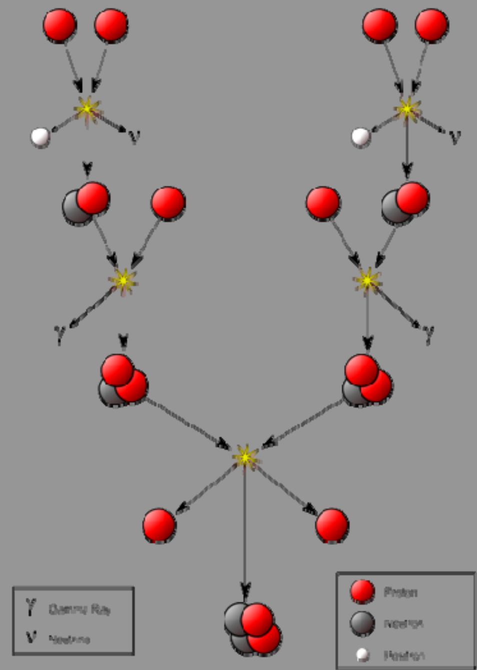
Mass ~ 2 x 10^{30} kg

Temperature ~ 15,000,000°C

Gravity confines the plasma in the Sun. The fusion process burns up the hydrogen and the energy is radiated away.

Fusion is the process powering the Sun...





NOTE: the type of fusion reaction that powers the Sun is *different* from the one that is going to be used in ITER and in fusion power plants. D-T reaction has lower threshold.

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Fusion Working with Europe

Magnetic fusion research

The three main conditions for starting the fusion process in a plasma are:

1. The plasma density needs to be ***below*** a threshold value (otherwise plasma develops instabilities). Vacuum pumps are required for this.
2. The plasma temperature needs to be ***above*** a threshold value. Additional plasma heating is required.
3. The plasma needs to be contained for times ***longer*** than a threshold value. The magnetic field is required to ensure plasma confinement.

Magnetic fusion research

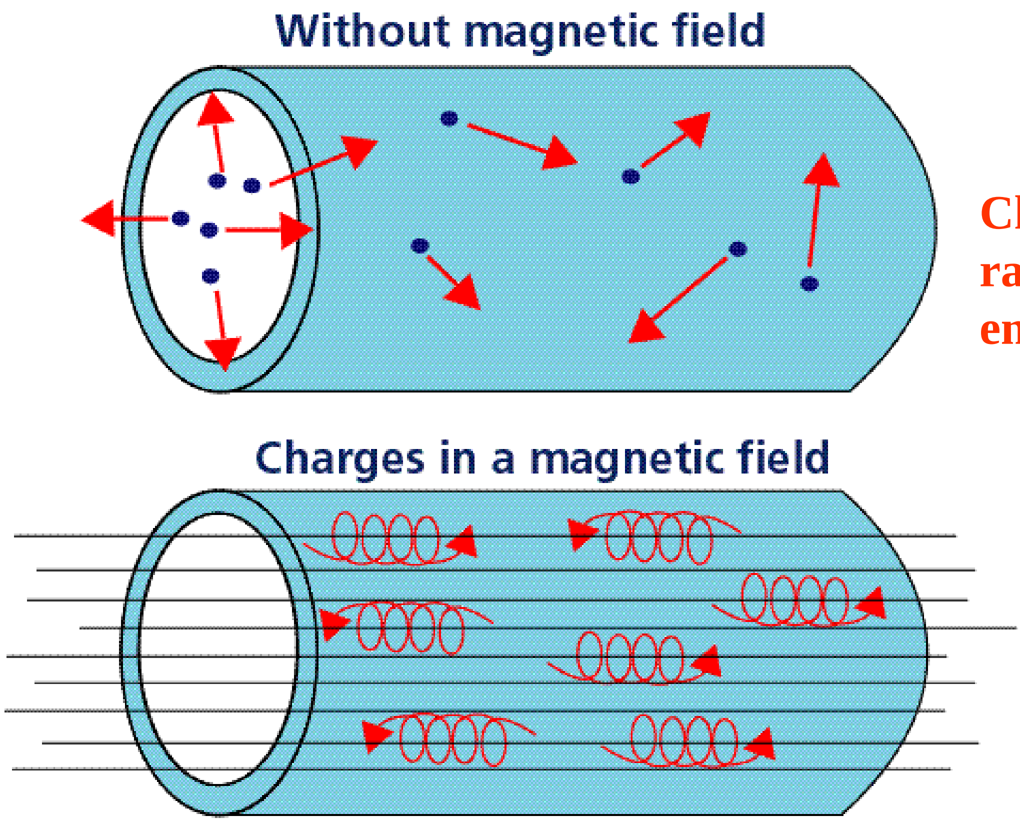
$$P = nk_B T$$

$$n \sim 10^{-6} \times \text{atmospheric density}; T \sim 10^{6} \times \text{ambient temperature}$$

$$P \sim 1\,\text{bar}$$

Although even the largest tokamaks contain in total no more than 0.01 g of hydrogen mixture at any one time, the very high temperature of the plasma means that plasma pressure may reach 1 bar = atmospheric pressure. Plasma has to be confined and held together by super-strong magnetic fields, created by (superconducting) magnets.

Magnetic field is required to confine the plasma

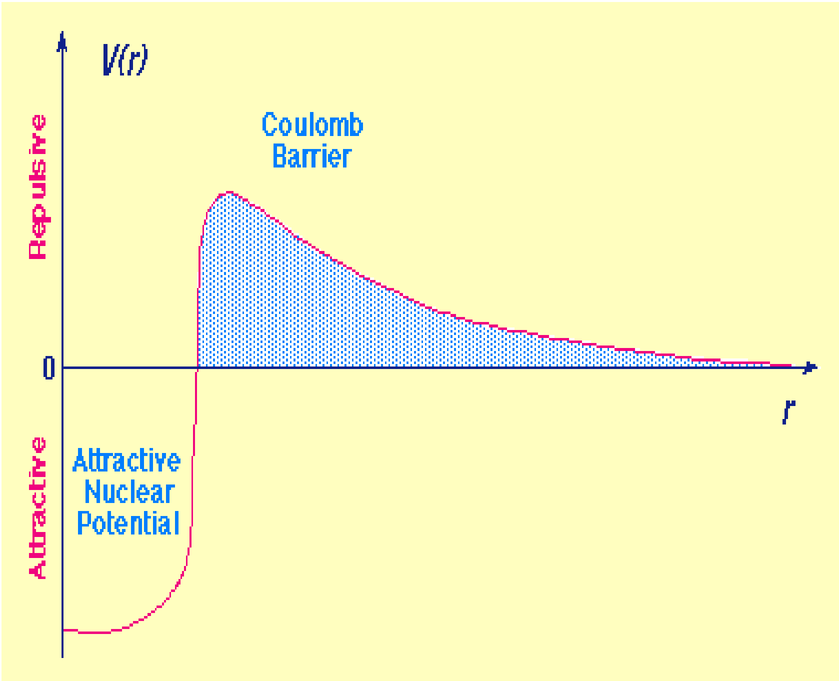


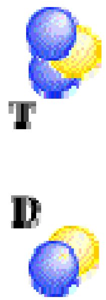
Chaotic motion, rapid loss of energy

Gyro motion + collisons

Heating The Plasma

It is not enough to merely confine the plasma - it must be heated so there is sufficient energy for the fusion reaction to take place

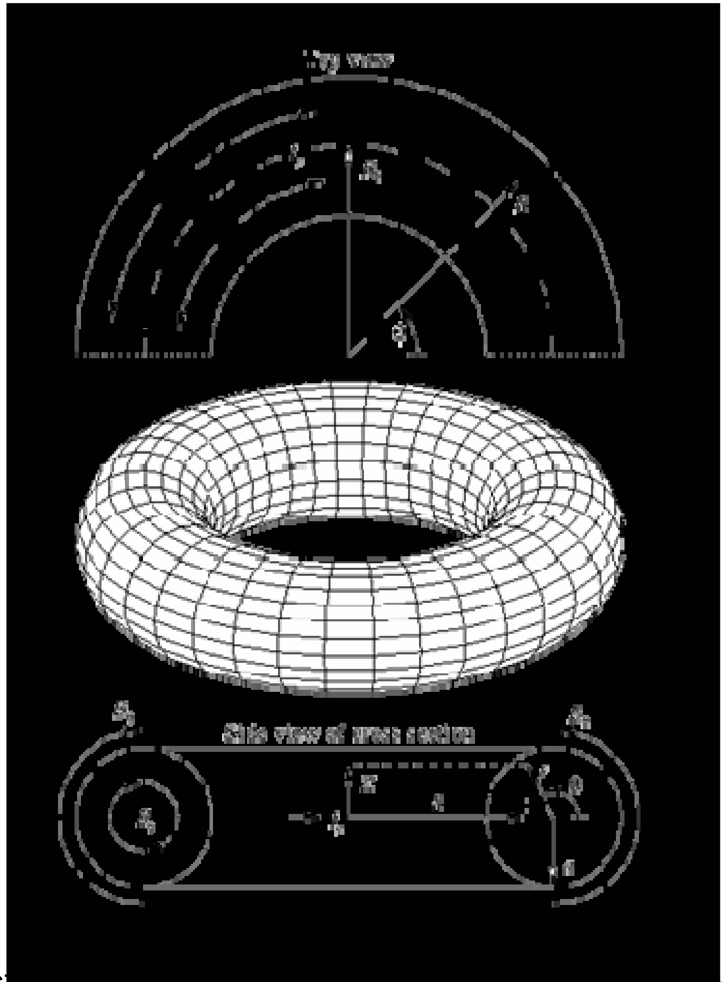




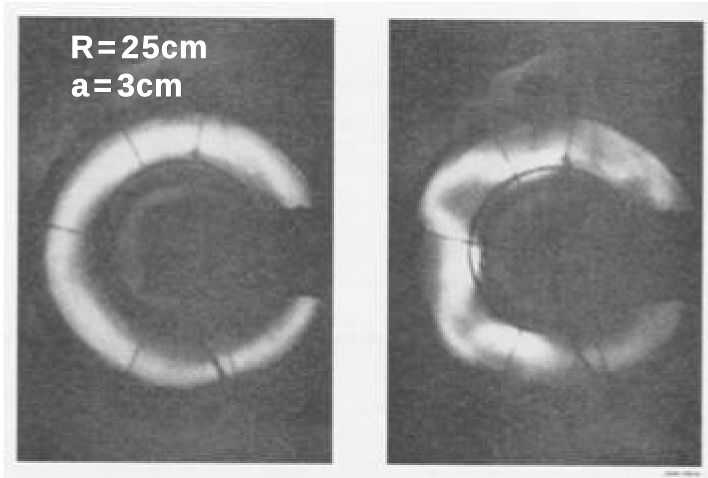
Nuclei in the plasma must overcome the repulsive Coulomb force in order to get close enough to react

The Pinch Effect - 1940's

Peter Thonemann and Sir George Thomson's idea

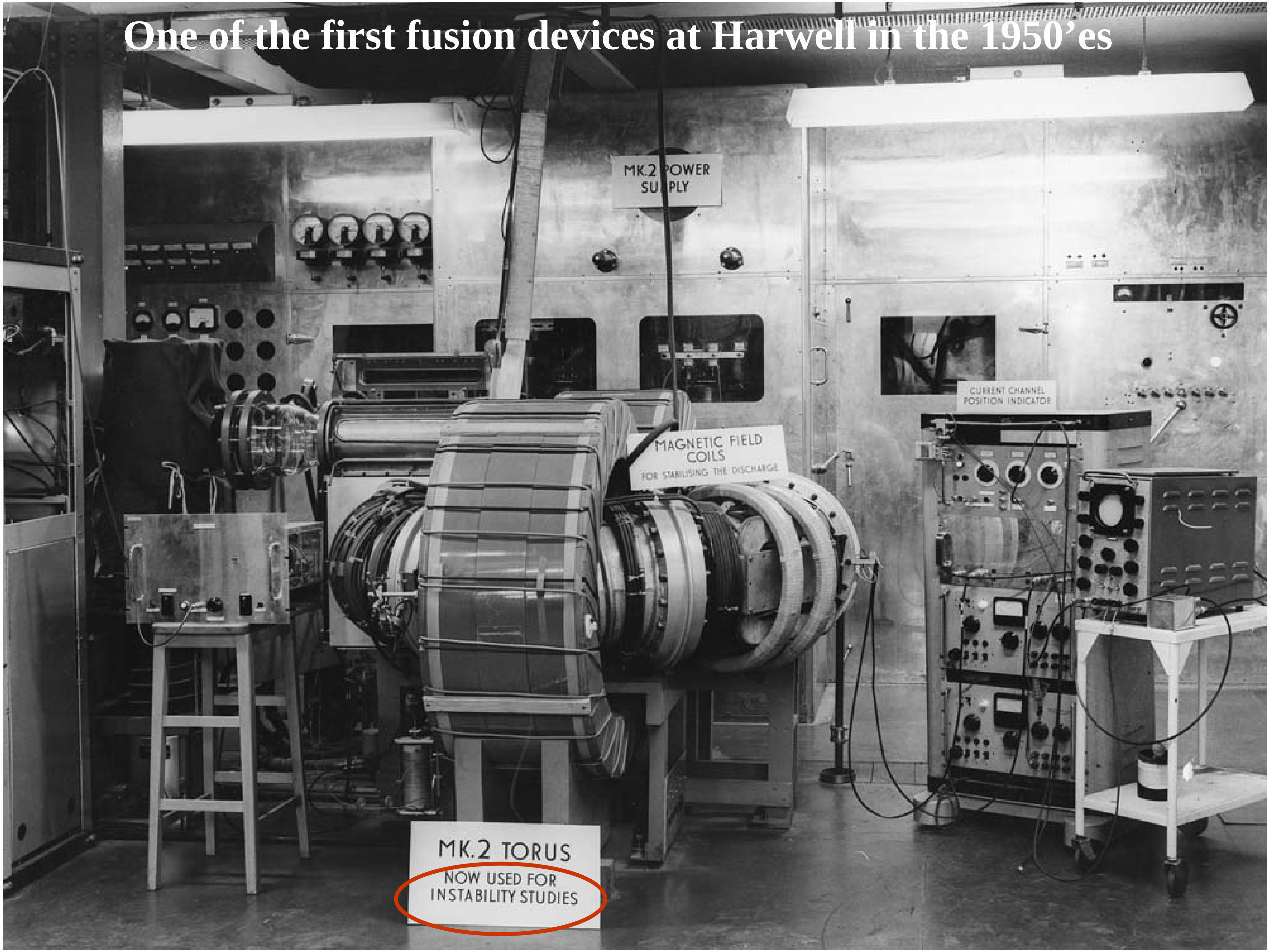


Alan Ware and Sir George Thomson at Imperial College.



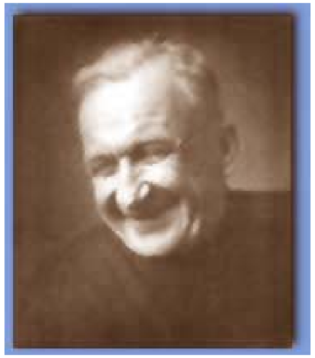
Plasma ring unstable

One of the first fusion devices at Harwell in the 1950'es

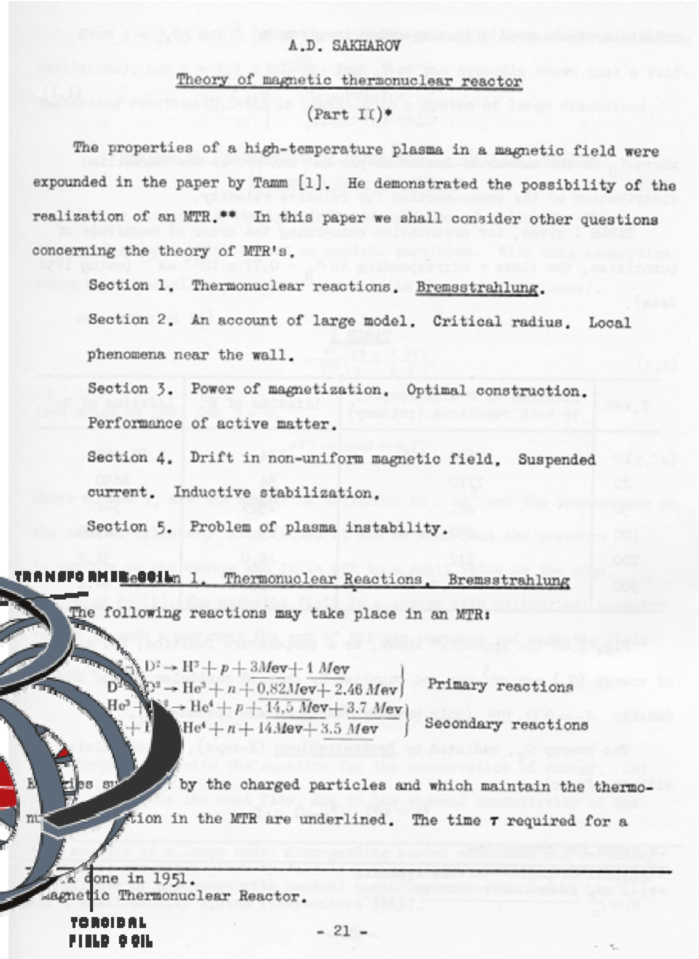


The tokamak revolution

A. D. Sakharov



I. Tamm



A.D. SAKHAROV

Theory of magnetic thermonuclear reactor

(Part II)*

The properties of a high-temperature plasma in a magnetic field were expounded in the paper by Tamm [1]. He demonstrated the possibility of the realization of an MTR.** In this paper we shall consider other questions concerning the theory of MTR's.

Section 1. Thermonuclear reactions. Bremsstrahlung.

Section 2. An account of large model. Critical radius. Local phenomena near the wall.

Section 3. Power of magnetization. Optimal construction. Performance of active matter.

Section 4. Drift in non-uniform magnetic field. Suspended current. Inductive stabilization.

Section 5. Problem of plasma instability.

Section 1. Thermonuclear Reactions. Bremsstrahlung

The following reactions may take place in an MTR:

$D^2 \to H^3 + p + 3 Mev + 1 Mev$ / $D^2 \to He^3 + n + 0.82 Mev + 2.46 Mev$ — Primary reactions

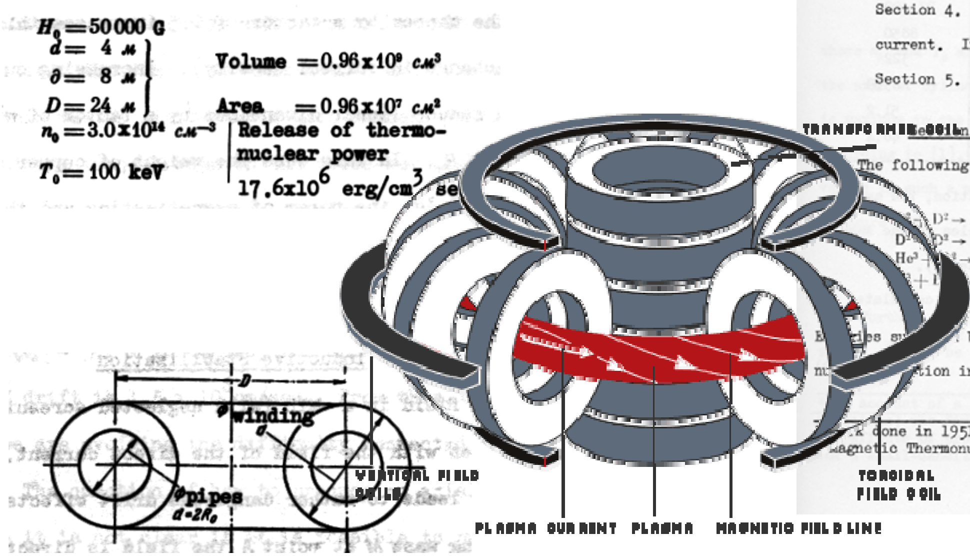
$He^3 \to He^4 + p + 14.5 Mev + 3.7 Mev$ / $He^4 + n + 14 Mev + 3.5 Mev$ — Secondary reactions

... by the charged particles and which maintain the thermo- ... tion in the MTR are underlined. The time τ required for a

... done in 1951.

... Magnetic Thermonuclear Reactor.

- 21 -



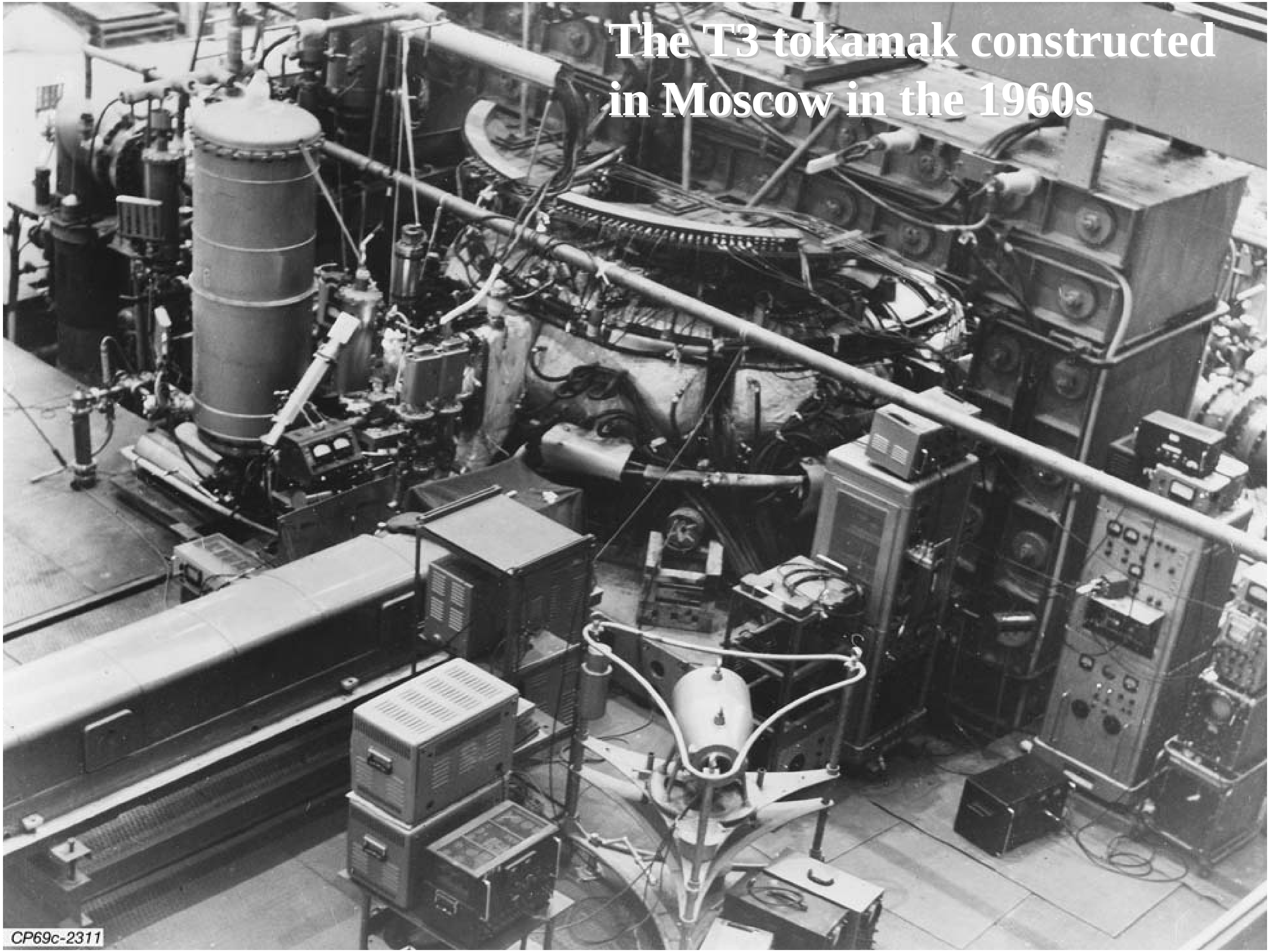
Tokamak as a theoretical concept was proposed in 1951.

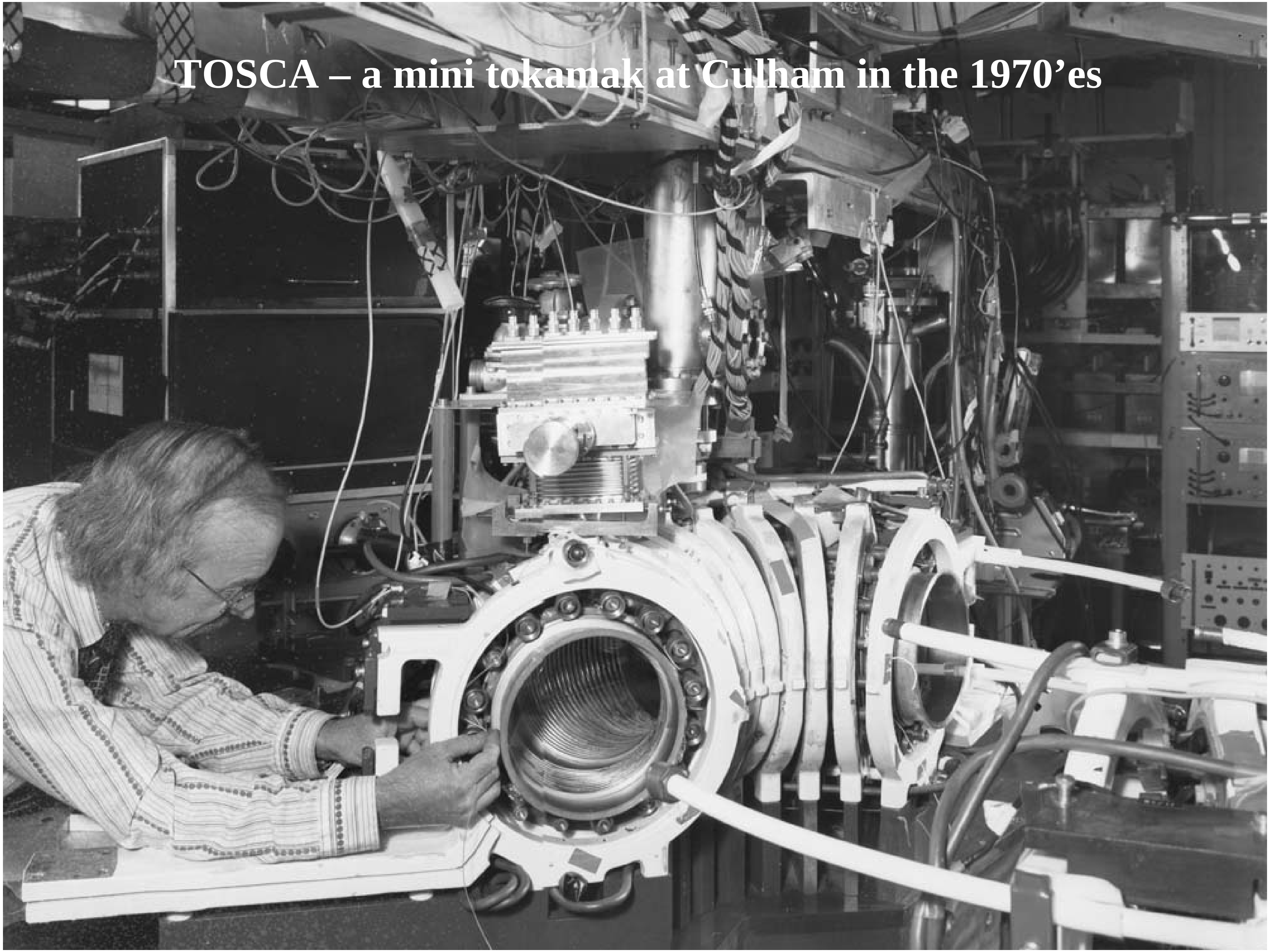
The tokamak* revolution

- Fusion research began in Britain in the 1940's.
- In the 1950's it was secret (cold war) until 1956, when Kurchatov gave a talk at Harwell in the UK. 1958: the first international conference on fusion.
- The 1960's saw the development of the "Perhaps-trons" at Culham (UK), Kurchatov (USSR), Los Alamos, Livermore, Princeton (USA) and elsewhere. Russian claimed that they achieved temperatures 10 times higher than elsewhere (10 million degrees).
- In 1969 British scientists were sent to Kurchatov Institute (Moscow) to make measurements on the T3 tokamak. Russian claims, i.e. T~10 million degrees, were confirmed.
- After 1969 many tokamaks were built.

* to-ka-ma-k [Russian] means toroidal chamber with magnetic coils

The T3 tokamak constructed in Moscow in the 1960s




TOSCA – a mini tokamak at Culham in the 1970’es

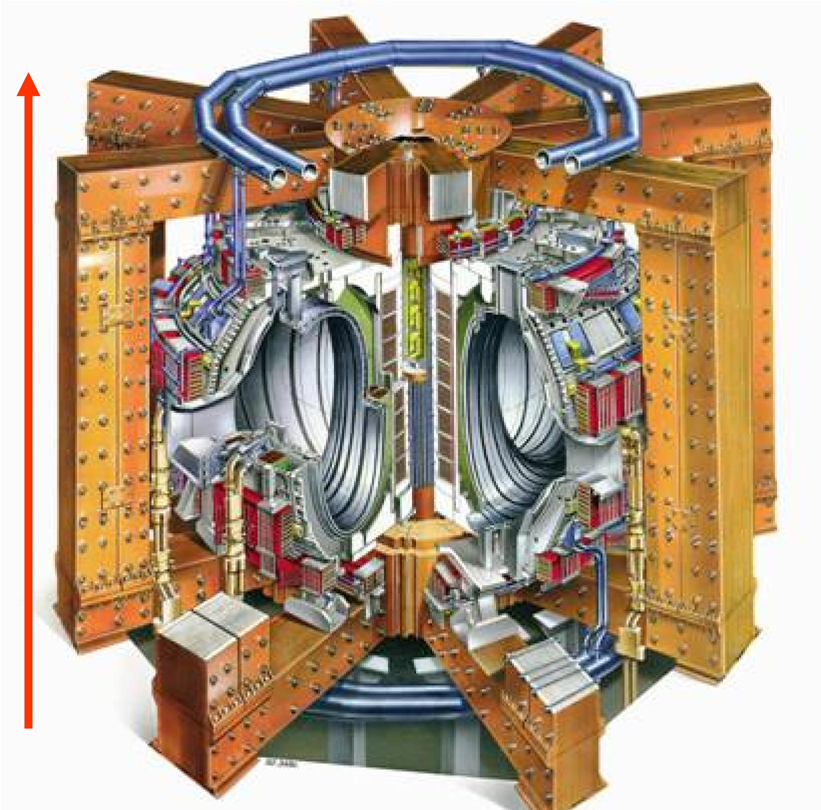
The oil crisis & large tokamaks

- The oil crisis of 1973-74 produced a turnaround for the funding of energy research.
- Fusion experiments indicated that a very large tokamak (as large as JET!) would reach break-even conditions.
- 1973-1978 large tokamaks designed: EU JET, USA TFTR, Japan JT-60 and Soviet Union T-20.
- These devices were completed in 1983, except T-20 (later downgraded to T-15 that never really operated).
- 1983-1990: the “tokamak race”.

The JET building at Culham Science Centre

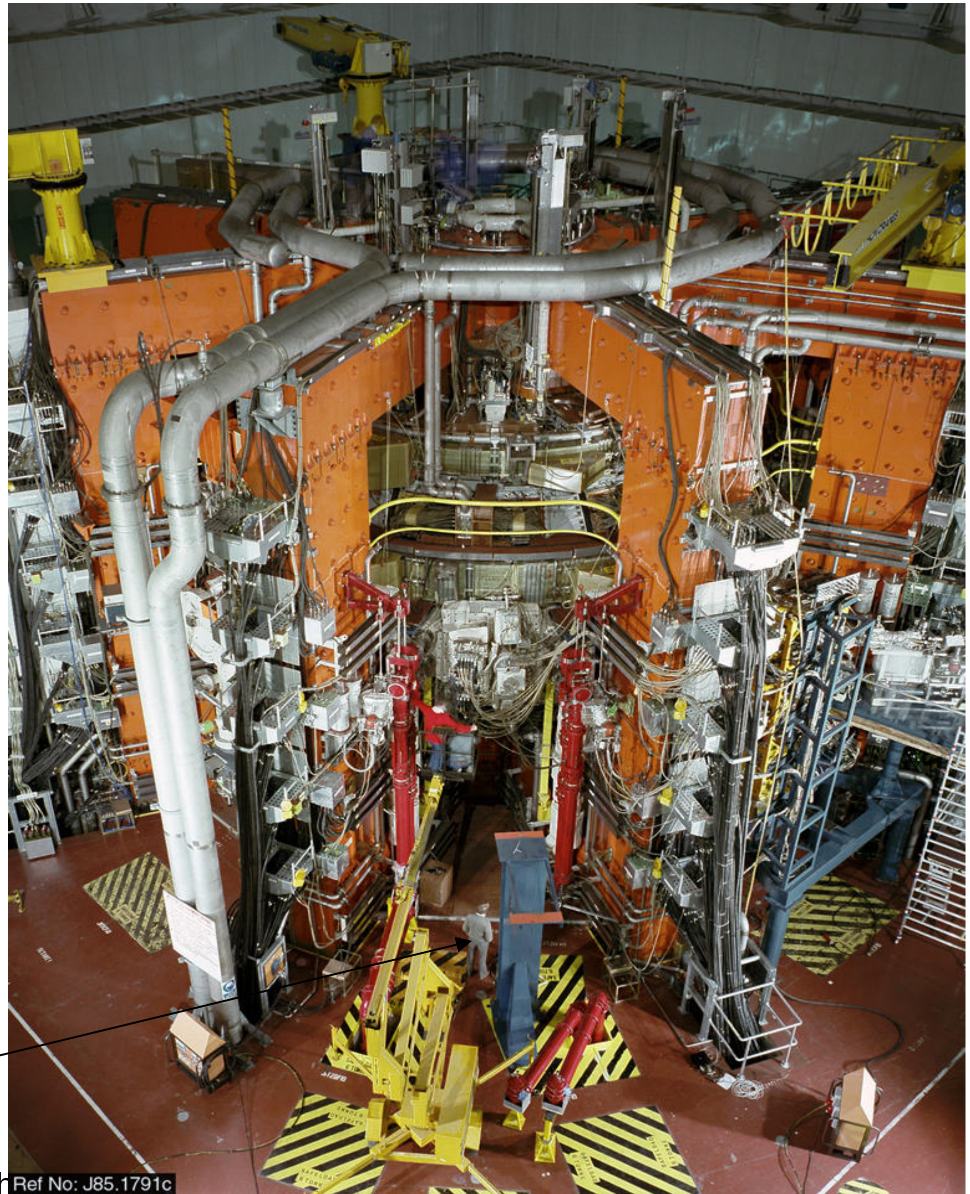
The JET Tokamak*

Volume ~100 m³ Power 40 MW



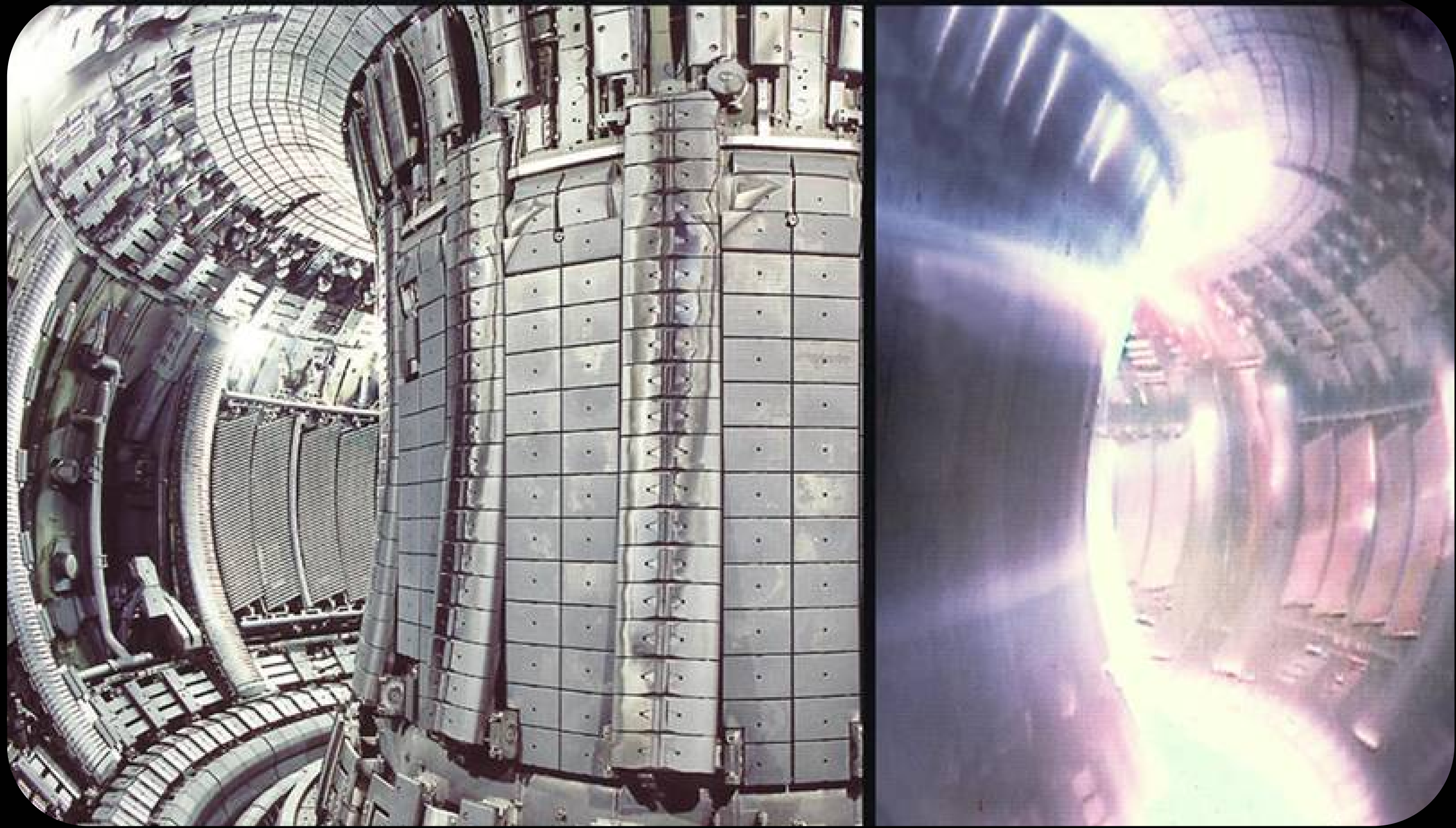
Height 13 m

Man



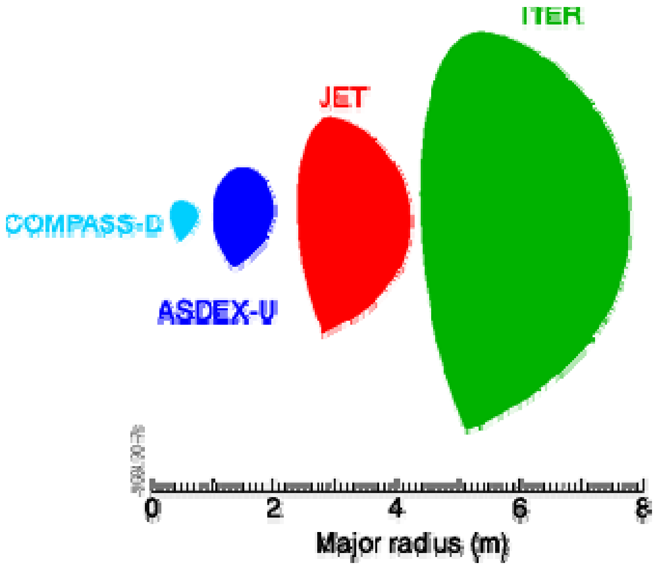
*Operated since 2000 under European Fusion Development Agreeement (EFDA)

20 years later: plasma in a complex JET vessel

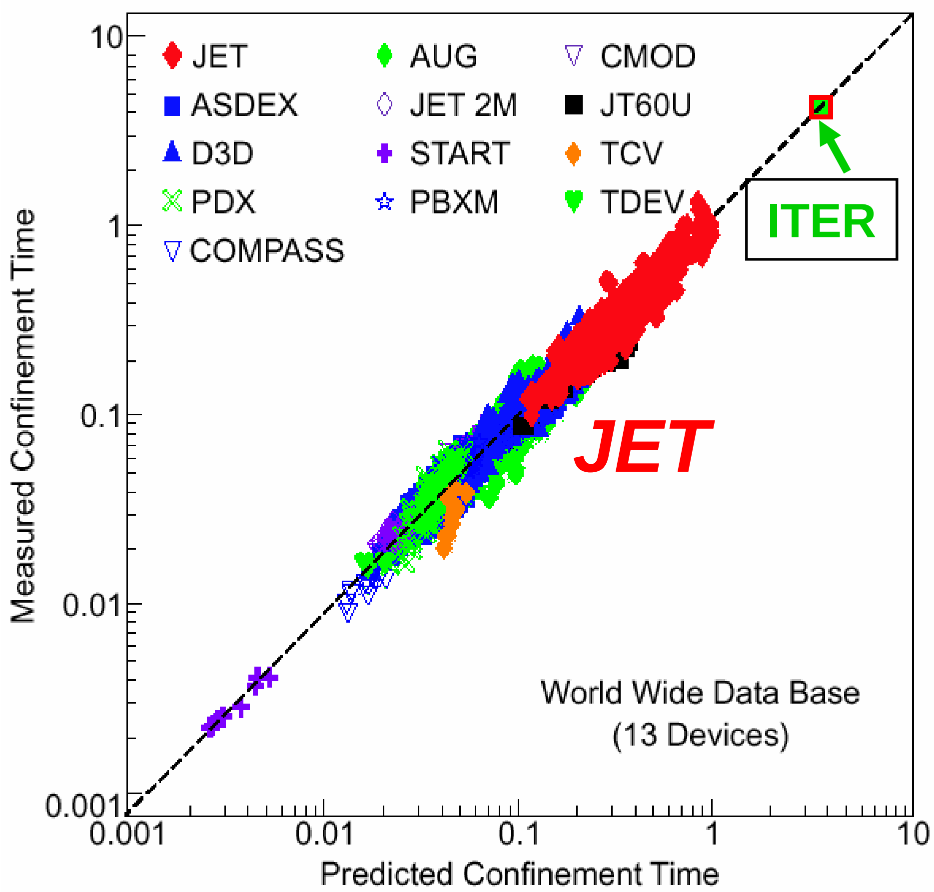


Heating with 20 MW → Temperature up to 200,000,000 ºK

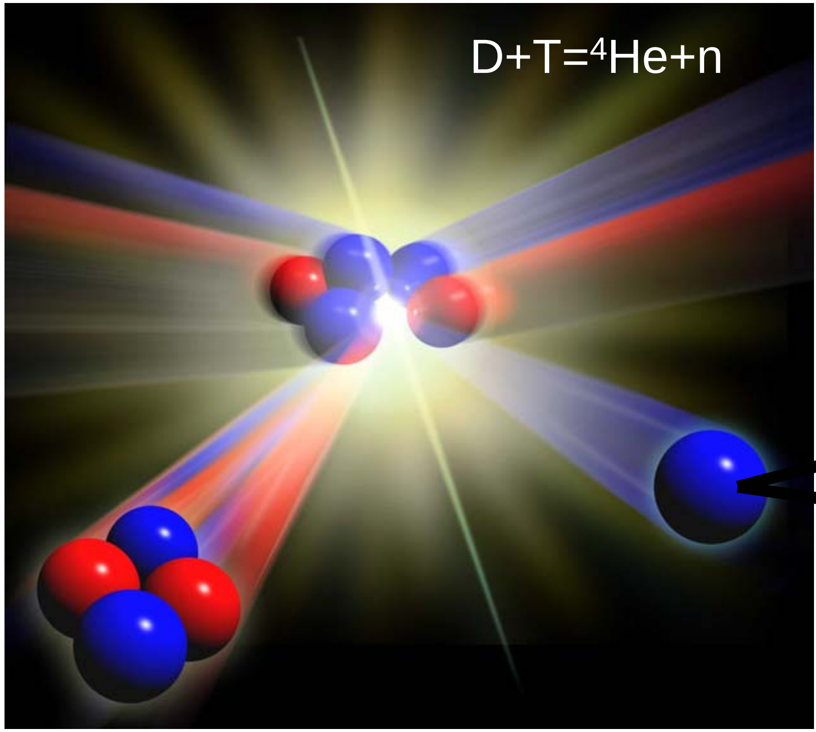
JET has provided key design data for ITER

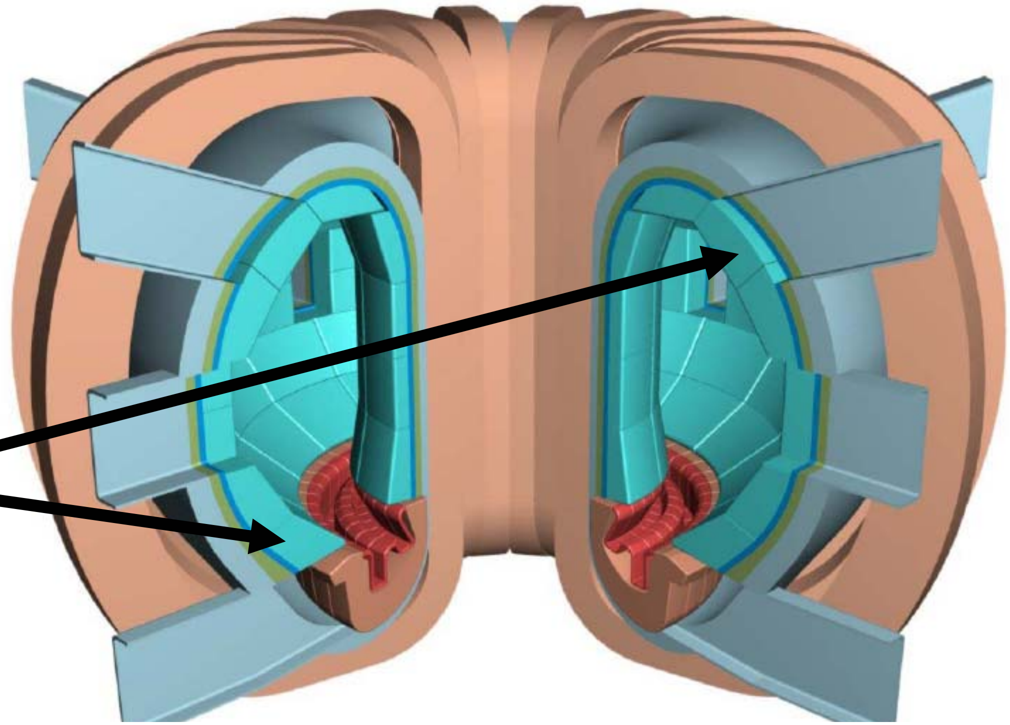


Cross section of present EU D-shape tokamaks compared to the ITER project



Conceptual design of a fusion power plant

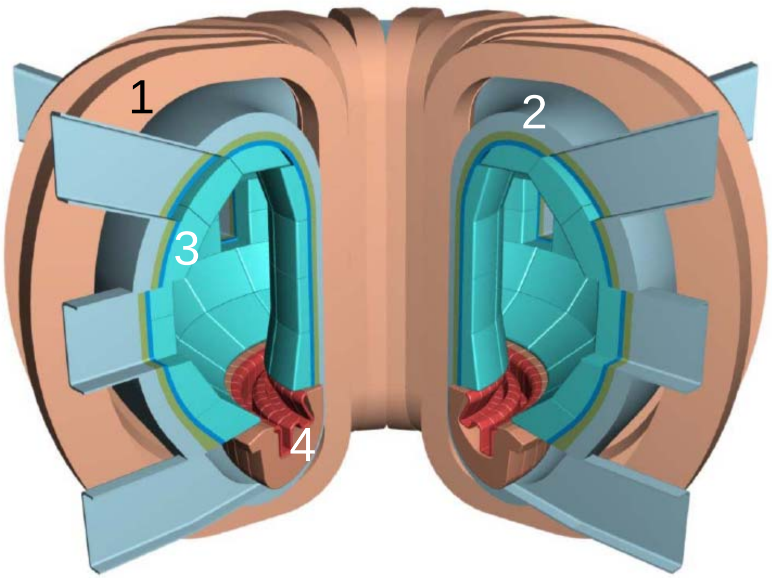




DEMO: radiation damage from 14.1 MeV neutrons is expected to reach 100 dpa in the first wall materials over 10 full power years. DPA = displacement per atom.

Schematic view of a fusion power plant, total height approximately 20m. The items for which material performance is particularly crucial are the blanket, shown in blue, and the divertor, red. The vacuum vessel, grey, has access ports for maintenance which pass between the magnets, brown. [D. Ward, S. L. Dudarev, Materials Today, 2008, in press]

Conceptual design of a fusion power plant



The main elements of a fusion power plant are:

- the magnets - which confine the plasma and partially insulate it against heat loss, allowing the energy-carrying neutrons to escape;
- the vacuum vessel – which prevents the deuterium-tritium fuel from being contaminated by other gases;
- the blanket – which absorbs the high-energy neutrons produced in the fusion reactions in the plasma, and extracts their energy through collisions with atoms in the blanket materials, whilst at the same time producing, by reaction between the neutrons and lithium compounds, the tritium that is subsequently burnt in the plasma;
- the divertor – like the exhaust on a car, this part of the fusion power station extracts the burnt fuel (helium), hence maintaining the purity of the deuterium-tritium mixture.

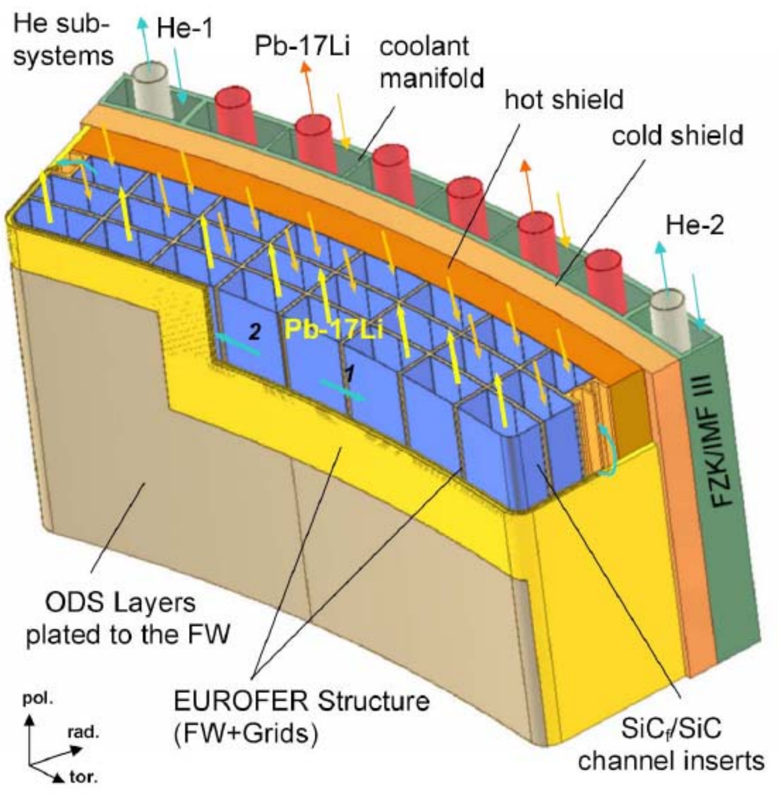
Conceptual design of a fusion power plant

The vacuum vessel is required because the density of plasma is very low (there is an upper *empirical* limit on plasma density, above which it tends to develop instabilities). The 100 m^3 JET tokamak contains only ~0.01 grams of D-T fuel at any one point in time.

The shielding efficiency of the blanket + the vacuum vessel should satisfy limits imposed by the fact that the superconducting magnets must not generate too much heat from nuclear reactions induced by the tiny flux of neutrons still penetrating through the structure. Also the dose rate outside the vessel should remain within safety limits for the maintainence of the power plant. Fusion neutrons have much higher energy (~14 MeV) than fission neutrons (~1 MeV maximum).

The neutron wall load *in ITER* is expected to vary between 0.59 MW/m^2 maximum for the inboard facing parts of the first wall (area ~200 m^2), and 0.78 MW/m^2 maximum for the outboard facing parts of the first wall (area ~470 m^2). The total neutron power is ~300 MW, which is ~4/5 of the total power generated by the plasma. *In a fusion power plant* the neutron wall load it is expected to reach ~2 MW/m^2, giving the total output power approaching 2 GW.

Conceptual design of a fusion power plant

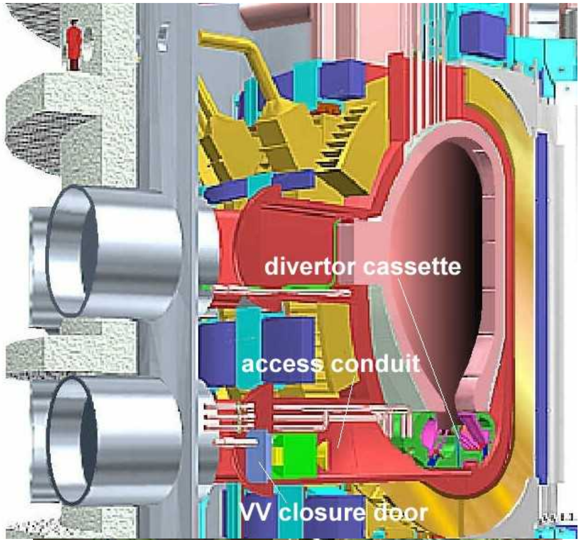


<u>The tritium breeding blanket</u>, shown schematically in this figure, is required to produce tritium, which is one of the two isotopes of hydrogen required for sustaining fusion reactions in the plasma. Deuterium is going to be extracted from ocean water, whereas tritium is going to be generated using the fusion neutrons via the reaction

$$n + {}^{6}Li \rightarrow T + {}^{4}He + 4.78 MeV.$$

A part (but no all) of the 14 MeV energy of neutrons coming out of plasma will hence be spent on tritium re-generation. Tritium will be released from the lithium compound by the flow of helium used as coolant.

Conceptual design of a fusion power plant



The divertor, which is potentially one of the most technologicaly challenging part of a fusion power plant, will be subjected to direct impact of particles coming from plasma. Surface erosion, neutron bombarment, and extremely high power load, leading to high temperature of operation, are the three major challenges that will need to be addressed in the power plant design. This poses the problem of *compatibility* of materials since temperature variations during periods of “cold” maintainence and “hot” operation will impose severe limits on the range of thermal expansion coefficients for materials used for constructing the divertor.

Main Irradiation Conditions

	ITER	DEMO	*Reactor*
Fusion Power	0.5 GW	2-2.5 GW	*3-4 GW*
Heat Flux (First Wall)	0.1-0.3 MW/m^2	0.5 MW/m^2	*0.5 MW/m^2*
Neutron Wall Load (First Wall)	0.78 MW/m^2	< 2 MW/m^2	*~2 MW/m^2*
Integrated wall load (First Wall)	0.07 MW/m^2 (3 yrs inductive operation)	5-8 $MW.year/m^2$	*10-15 $MW.year/m^2$*
Displacement per atom	<3 dpa	50-80 dpa	*100-150 dpa*
Transmutation product rates (First Wall)	~10 appm He/dpa ~45 appm H/dpa	FM steels: ~10 appm He/dpa FM steels: ~45 appm H/dpa	

Fission Reactors: 0.2 to 0.3 appm He/dpa

Increasing Challenge

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