The Fast Track to Fusion Power

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THE LOOMING ENERGY CRISIS

- **World Energy use expected to double by 2045**

  (~ economic growth ⇒ growing energy use in China and India)

- **Currently 80% of primary energy supply from burning fossil fuels**

  ⇒ serious air pollution

  ⇒ CO_2 ⇒ climate change

  which are running out (oil [→ 95% of transport] first)

  [+ 11% from burning wood, waste etc, also ⇒ CO_2, unless wood replanted]

- **Today: only viable alternative able → large fraction of global need is nuclear, which only → electricity (~ $^1/_3$ of primary energy use)**

Now - remarks on climate change

- when will fossil fuels run out? [NB: the more is left, the more CO_2]

- how can we address the problem?

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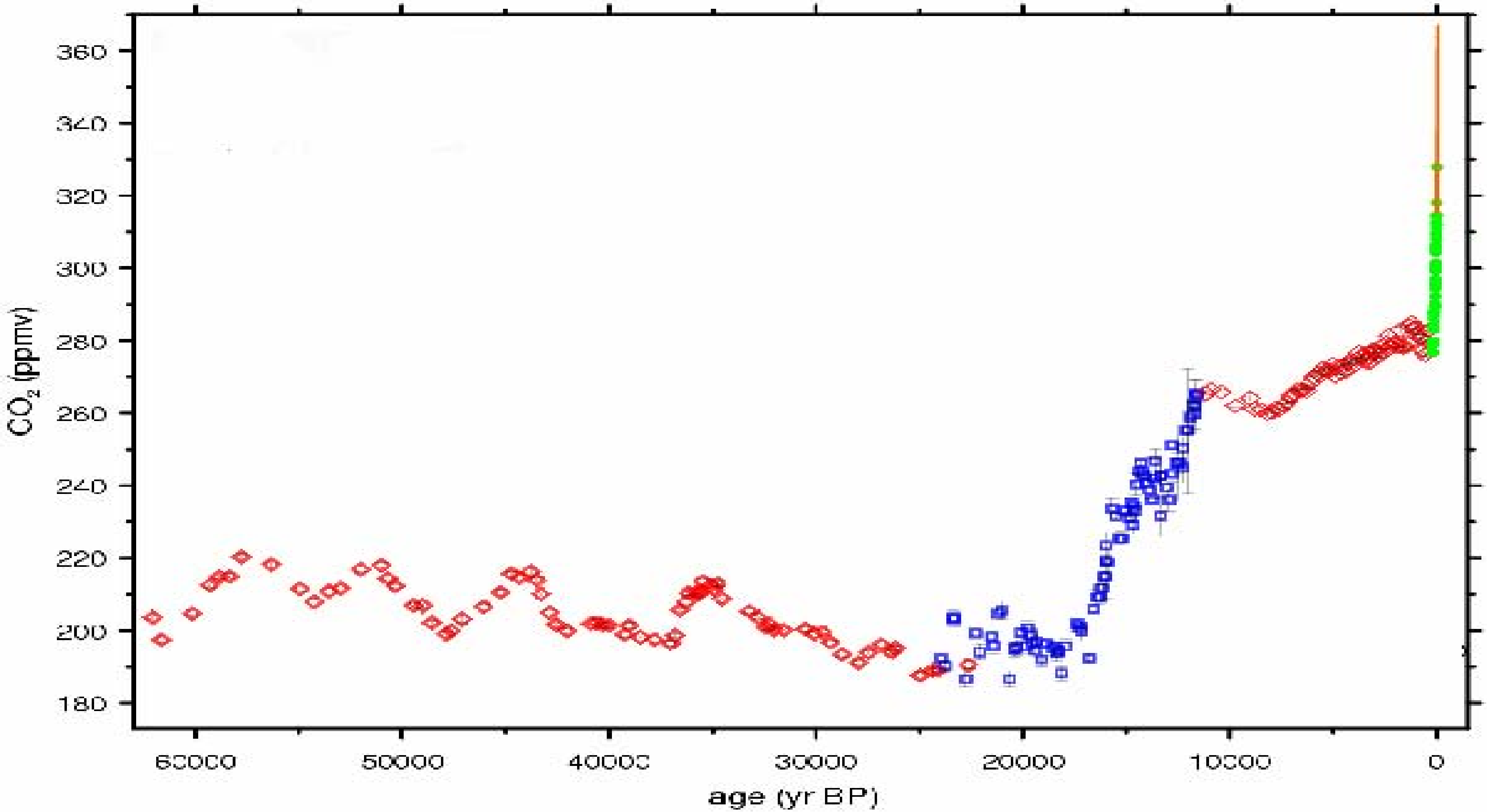
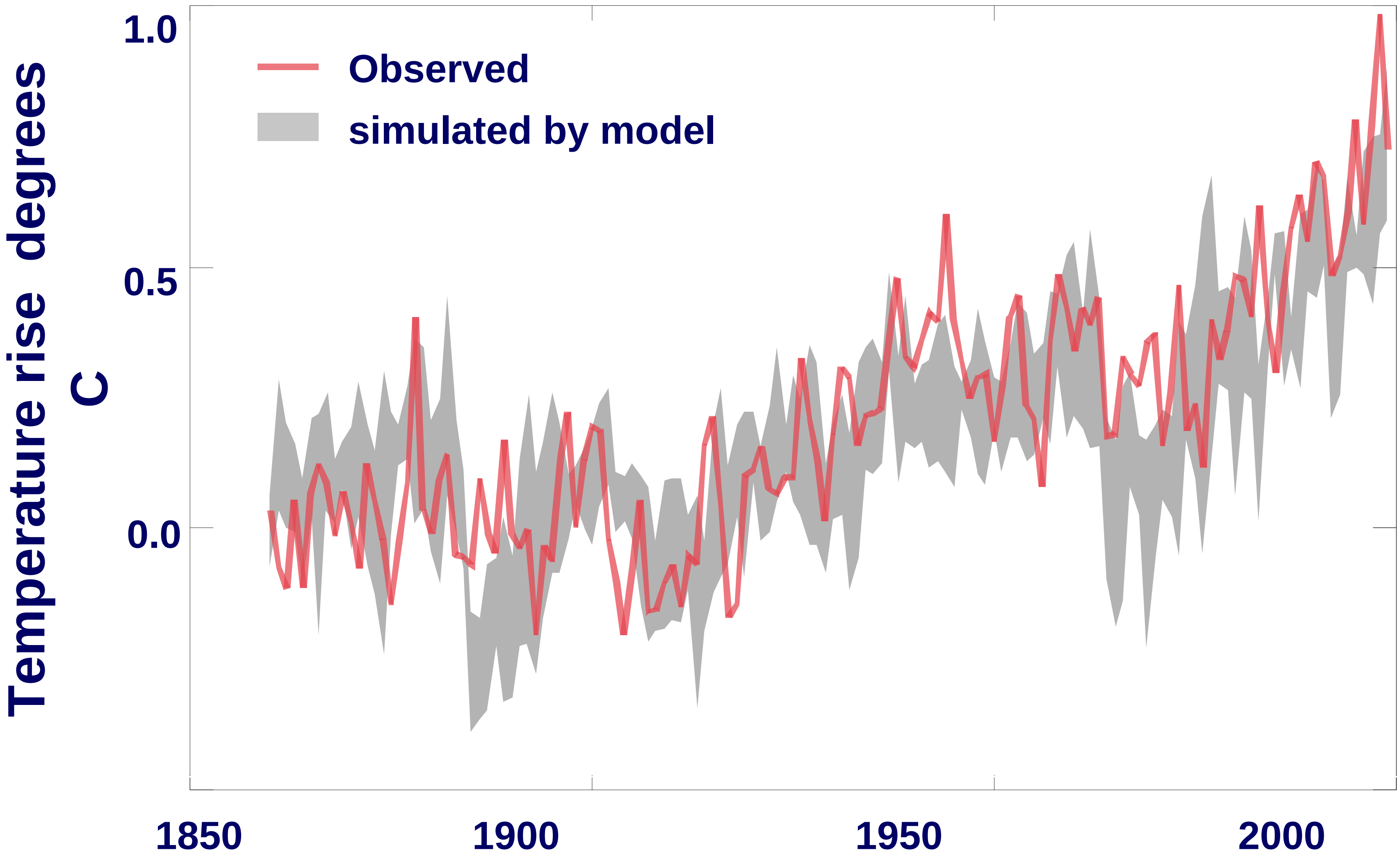
Carbon dioxide levels over the last 60,000 years



Source University of Berne and National Oceanic, and Atmospheric Administration

Modelling global warming



Source: Hadley Centre

Climate Change Is Happening

from "Rhone-Glacier and its Ice Grotto" M. Carlen & Fotohaus Geiger

View of the Rhone Glacier from the 1930s when it had already retreated to the end of the valley

In this 2001photograph the ice is barely visible in the saddle below the peaks

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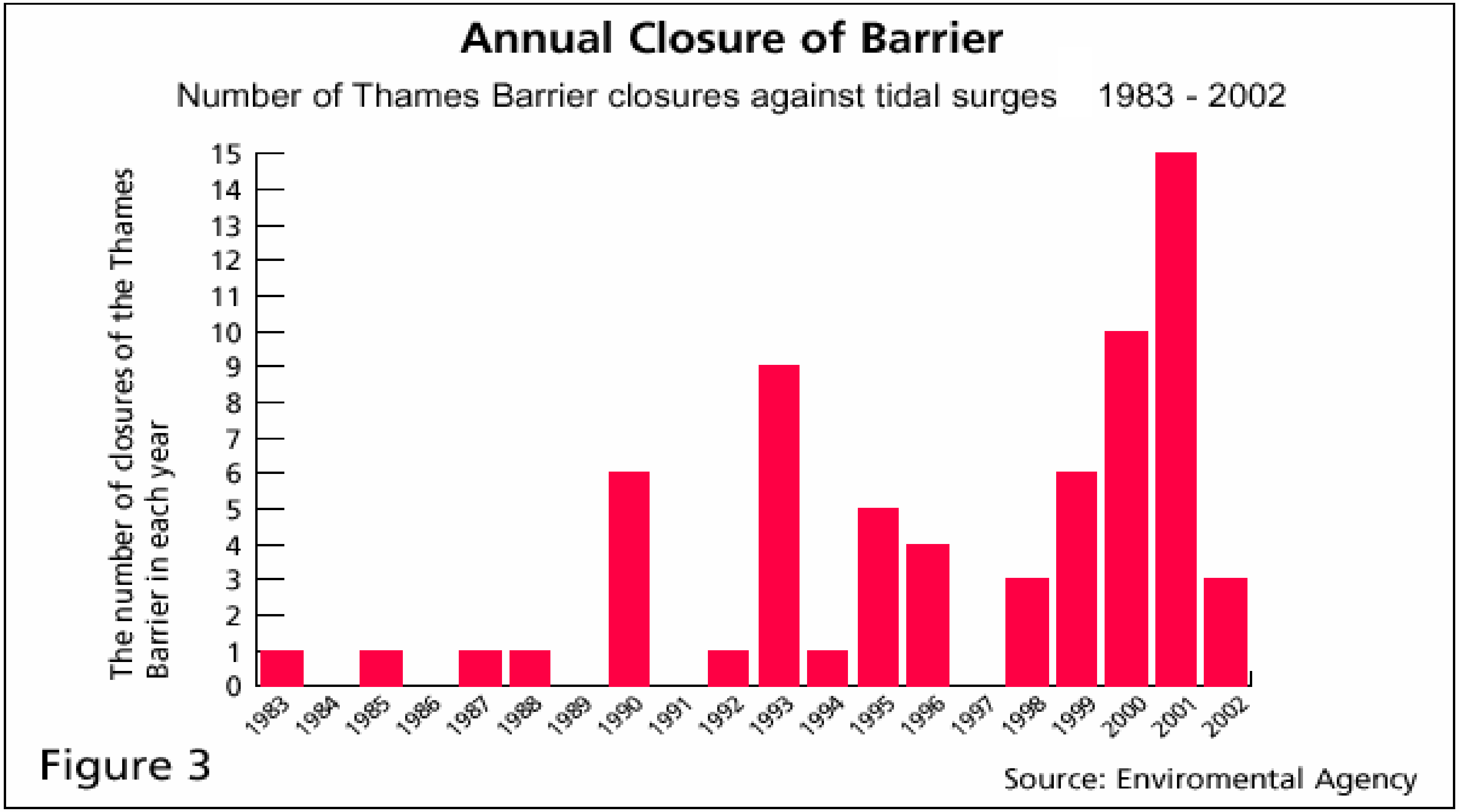
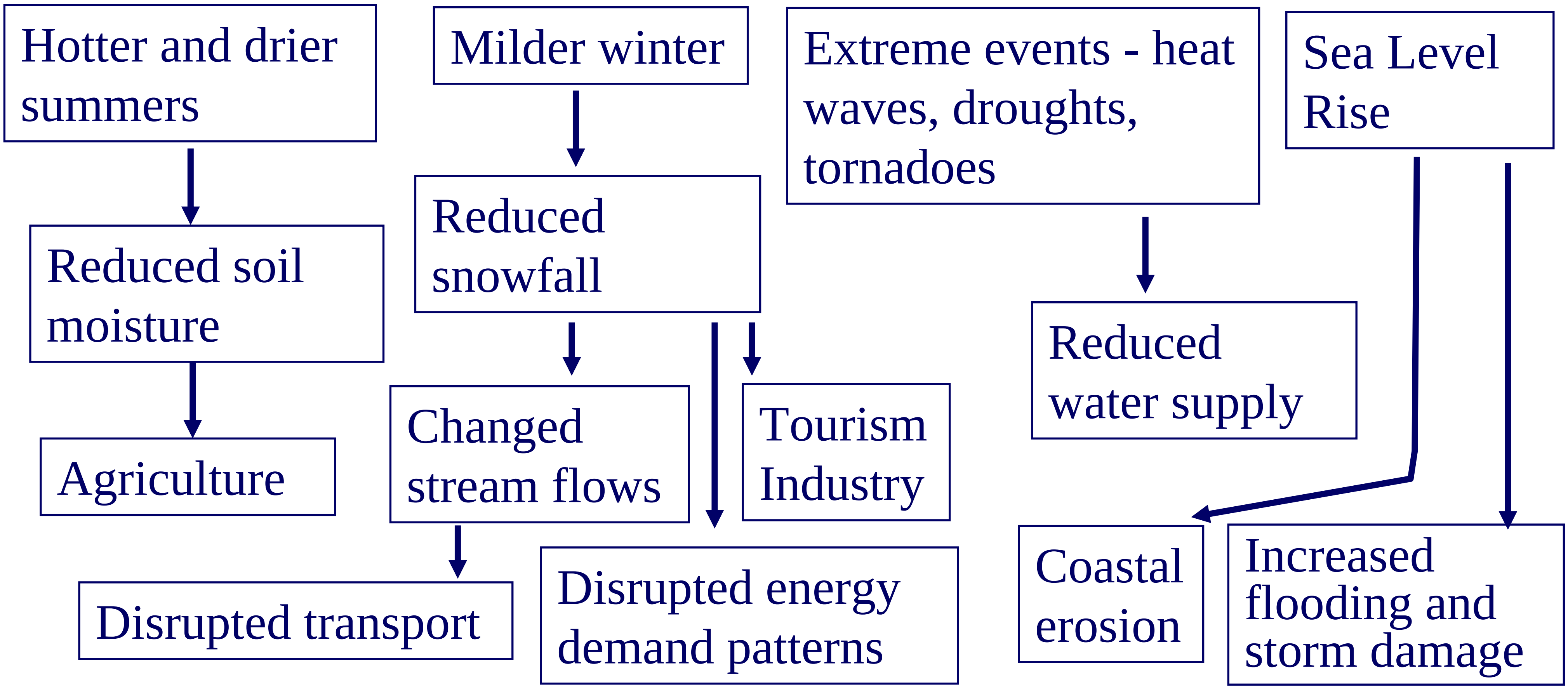
Thames Barrier Now Closed Frequently to Counteract Increasing Flood Risk



The Effects Of Climate Change



Ambitious goal for 2050 (when total world power market predicted to be 30TW)

- limit CO_2 to twice pre-industrial level

Will need 20 TW of CO_2-free power (compared to today's world total of 13 TW)

US DoE "The technology to generate this amount of emission-free power does not exist"

Saudi saying "My father rode a camel. I drive a car. My son flies a plane. His son will ride a camel". Is this true?

- **US Geological Survey - estimates remaining oil will last 60 years*** ***with current use*** **⇒ 40 years* if use doubles in forty years**

*ignoring price↑ ⇒ consumption↓ as end approaches

- **One view** **- situation actually worse**
  - conventional oil production ⇒ peak in 5-10 years, then fall ~ 3% pa (⇒ "prices up, inflation, recession, international tension")
- **Another view** **- don't cry wolf, estimates wrong in past**
  - lots of unconventional oil (yes, but big costs/challenges → useable form)

Part of the problem is disagreement on whether 40 years is a long time

Conclusion - need study (~IPCC WGI) ⇒ balanced assessment

Estimates for

gas → 200 years
coal → 200+ years

} But with current consumption (and no allowance for growth to replace oil)

I believe (~ climate change + finite fossil fuels: US DoE "These coupled challenges cannot be met with existing technology") **that we must act now to avert crisis**

Club of Rome's wrong (1970) predictions of catastrophes? Caution?

- Certainly - "Prediction difficult, especially when it involves the future"
- Club of Rome estimated world's total oil endowment ~ today's estimates, but then used only the (**much** smaller) known reserves + 7% growth ⇒ oil would soon be exhausted
- Predicted failure to feed rising populations avoided ~ **"green revolution"**

We need to seek revolutions ⇒ ample clean energy

US DoE: *"Major scientific breakthroughs will be required to provide reliable, economical solutions"*

WHAT MUST BE DONE?

- **Recognise the problem, and that**
  - only new/improved technology can → solution (although fiscal measures ⇒ change behaviour of consumers + stimulate work by industry also essential)
  - increased investment in energy research essential*. Note: energy market ~ $3 trillion p.a., so 10% cost increase → $300 bn p.a.
  - global co-ordination and collaboration (→ necessary funding and expertise; prevent duplication) and co-operation essential: results should be openly available (as far as practical)
- **Barriers**
  - seriousness of problem not recognised by enough governments
  - we don't know what is being done world-wide

    ⇒ this needs study

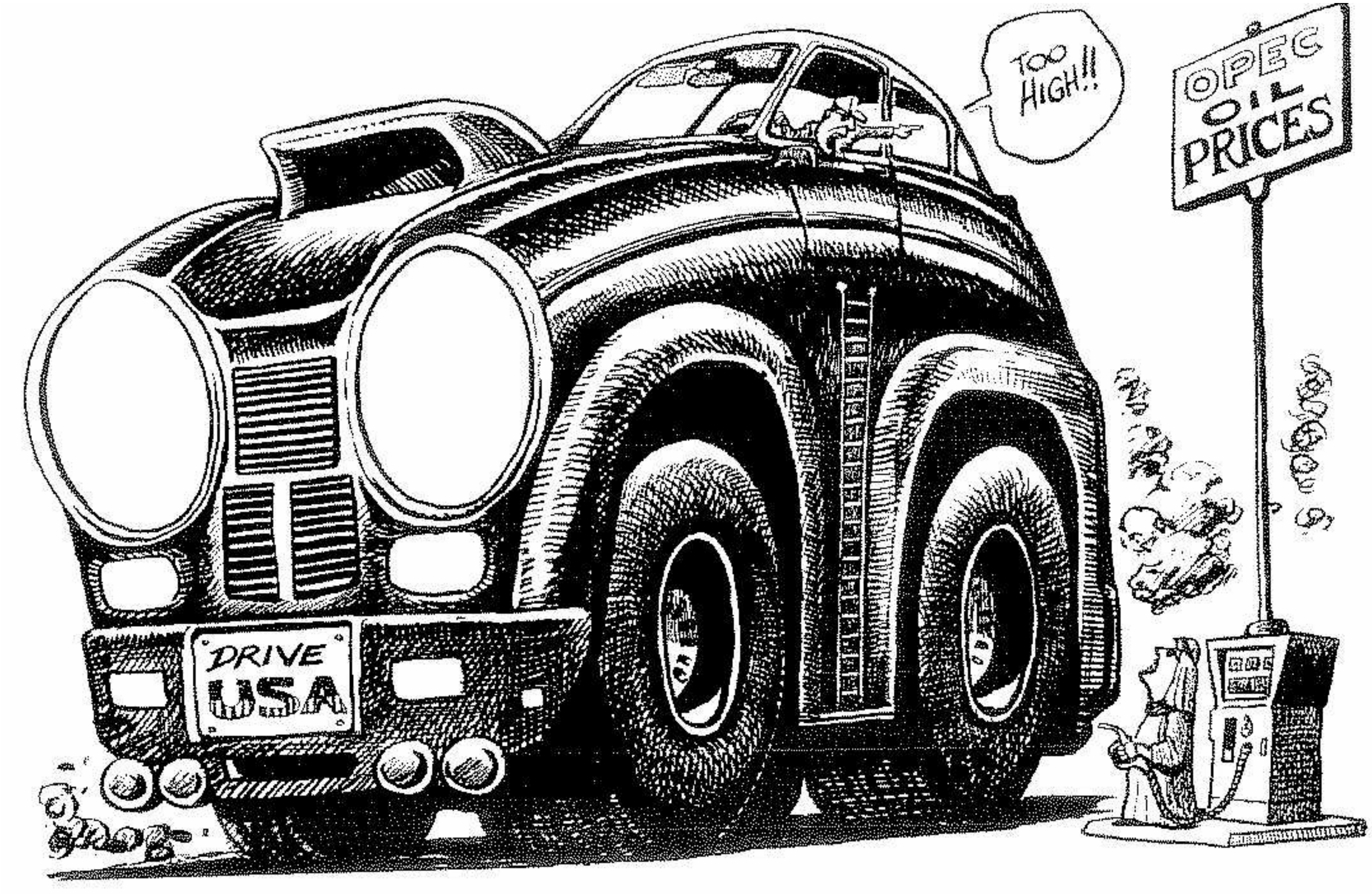
** public funding down 50% globally since 1980 in real terms; private funding also down, by (e.g.) 67% in USA in 1985-98*

FOCUS FOR RESEARCH

Must explore all avenues (solution = cocktail). Note - highly interdisciplinary: social, biological and physical sciences

- **Energy efficiency - yes** (will ameliorate but not solve problem)
- **CO_2 capture and sequestration - yes** (but big challenges & uncertainties, and will add costs)
- **Renewables - yes** (but, apart from solar, do not have potential to meet large fraction of global demand)
- **Solar - yes** (enough in principle, but currently very expensive and mostly not where needed; don't know how to store and transport). Need breakthrough - reflectors in space?
- **Energy storage* - yes** (essential for large scale use of intermittent sources)

*** energy storage/retrieval inevitably ⇒ significant losses**



The Economist 29/5/04

- **Biomass -** **yes** (but cannot meet large fraction of global demand)
- **Alternatives for transport -** **yes: hydrogen?** (note: a carrier, **not** a source, of energy; huge technical challenges); **bioethanols** ($\rightarrow$ aircraft fuel?); **miracle battery breakthrough?**
- **Nuclear -** **yes** (currently 16% of world's electricity; no CO_2; huge improvements in reliability, cost, safety), **but uranium will eventually run out/become very expensive which will trigger a move to fast breeder reactors (**use plutonium: hope we can avoid this); **yes to studying accelerator driven transmutation of nuclear waste**

***Note** - **Generation IV Nuclear Consortium** (governments + industry in 10 countries + Euratom) developing (25 year time horizon) "highly economical, enhanced safety, minimum waste, proliferation resistant" reactors [4of 6 models being studied are fast breeders]*

Parenthesis on nuclear power + accelerator driven systems:

- **(Non-political) constraints on the growth of nuclear power:**

- waste storage space
- exhaustion of lower cost U

} breeders*, incinerators*, reprocessing
*possibly accelerator driven

- **Breeding** ^{238}U + n → ^{239}U → ^{239}Np (2d) → ^{239}Pu (3/6 Gen IV reactors)
  ^{232}Th + n → ^{233}Th → ^{233}Pa (27d) → ^{233}U (1/6 Gen IV reactors)
  Fertile **Fissile**

- **U/Pu cycle:** large Pu inventory, slow ramp up *
- **Th/U cycle:** need Pu or highly enriched U core ⇒ large number of neutrons
  ⇒ reasonable ramp up
  or accelerator driven spallation neutrons

* N (LWRs) ⇒ N(LWRs + FBRs) ~ 40 years

Accelerator Driven Systems (ADS)

- **Spallation neutrons**

⇒ **drive 'energy amplifier':** promoted in context of Th/U cycle, which works with critical thermal reactors (with Pu or HEU core to ramp up) - nuclear community asks: *why pay over-cost of accelerator?* and focus

⇒ **burn minor actinides** (+ produce energy as by-product to help cover cost)**:**

Accelerators:

- **European Technical Working Group Roadmap:**

- eXperimental ADS: 5-10 mA @ 600MeV

- industrial ADS: 15-40 mA @ 1 GeV

- **DoE Roadmap: 40 mA @ 1.5 GeV**

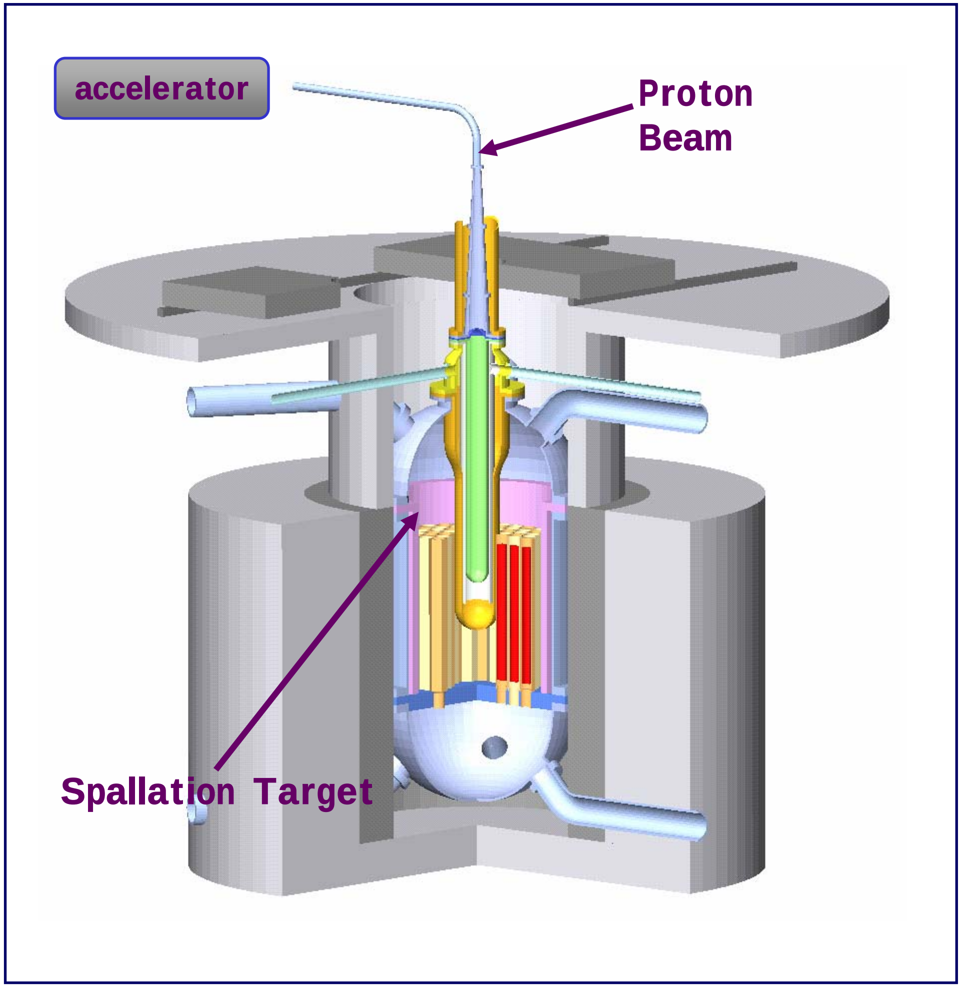
Simple concept, but realisation looks complex ☞

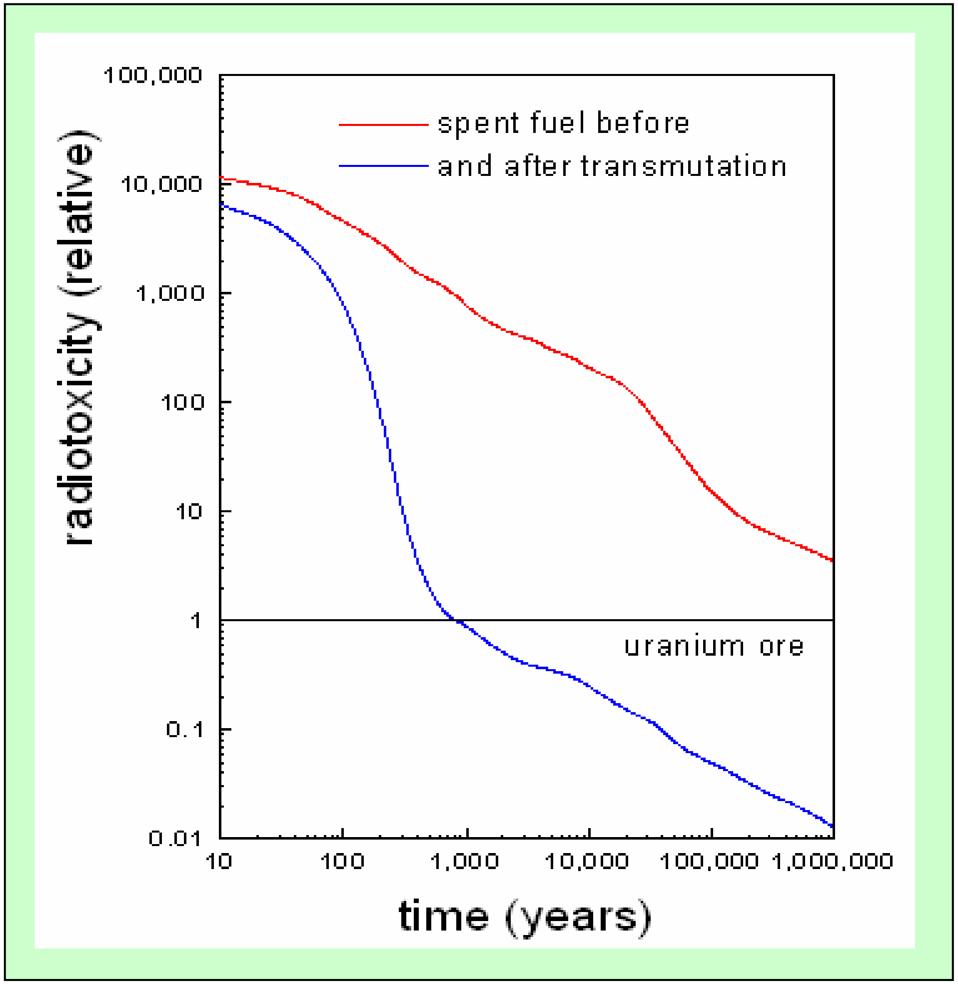
ADS: Accelerator Driven (subcritical) System for transmutation

Both critical reactors and sub-critical Accelerator Driven Systems (ADS) are potential candidates as dedicated transmutation systems.

Critical reactors, however, loaded with fuel containing large amounts of MA pose safety problems caused by unfavourable reactivity coefficients and small delayed neutron fraction.

ADS operates flexible and safe at high transmutation rate (sub-criticality not virtue but necessity!)

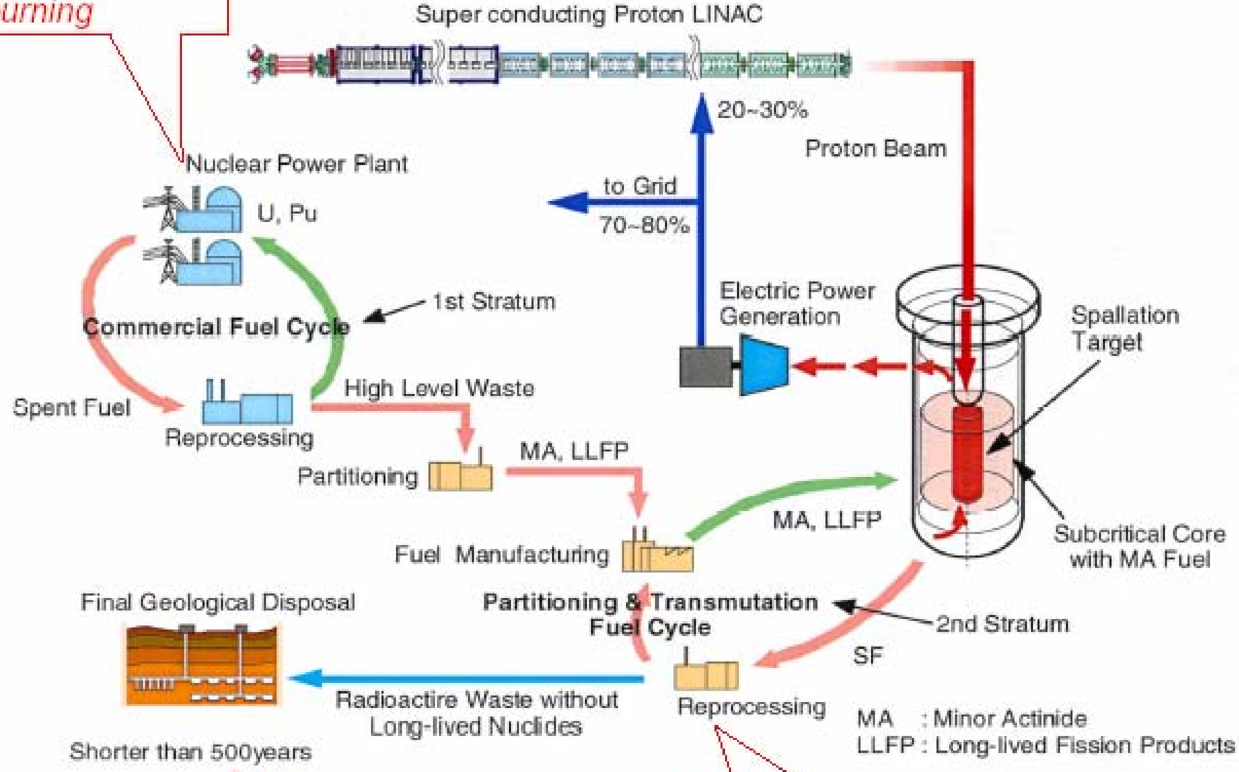




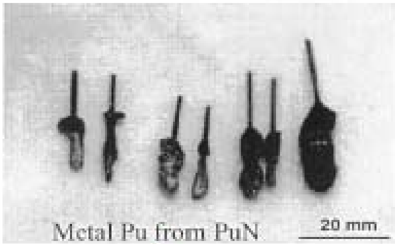
Courtesy Alex C Mueller

Japanese Proposal (JAERI/KEK)

Nuclear System with MOX Pu burning



- ***Nitride fuel***
  - Thermochemical stability
  - Good thermal property
  - High heavy-metal density
- ***Pyroprocess***
  - Compact facility with minimum envelope
  - Easy recovery of **N-15** (to avoid C-14 from N-14)



Nitride Fuel and Pyro processing

Incineration of Minor Actinides and Long Lived FF

Disposal for ∼ 500 years

Courtesy C Rubbia

■ Fusion - yes

Apart from fossil fuels (as long as they last), **solar** (not [yet?] viable/economical except for niche uses) **and nuclear** ($\rightarrow$ fast breeders in the future), ***fusion is the only known technology capable in principle of producing a large fraction of world's electricity***

With so few options, I believe we must develop fusion as fast as possible - although success is not certain

The Joint European Torus (JET) at Culham in the UK has produced 16 MW and shown that fusion can work

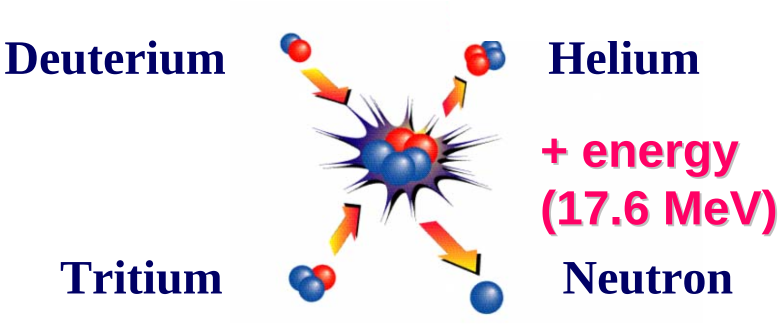
The big question is whether/when we can develop the technology $\rightarrow$ robust, reliable ($\Rightarrow$ economic) fusion power stations

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 :



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

Compare burning fossil fuel (oil, coal, wood or gas)

Hydrocarbon + Oxygen + Energy (electron volts - eV)

→ Ash + Carbon Dioxide + Water + More Energy (eV)

1 GW **for one day needs** 10,000 tons of fossil fuel **= 10 train loads of coal**

With burning deuterium and tritium

Deuteron + Tritium + Energy (~10 keV)

→ Helium ('ash') + neutron + energy (17 MeV)

1 GW for one day needs **1 kg of deuterium* + tritium****

***** extracted from (sea) water (deuterium/hydrogen = 1/6700)

****** bred by: neutron + lithium (very abundant) → tritium + helium

Lithium in one laptop battery + half a bath-full of water = 40 tonnes of coal ⇒ 200,000 kW-hours = UK per capita electricity production for 30 years

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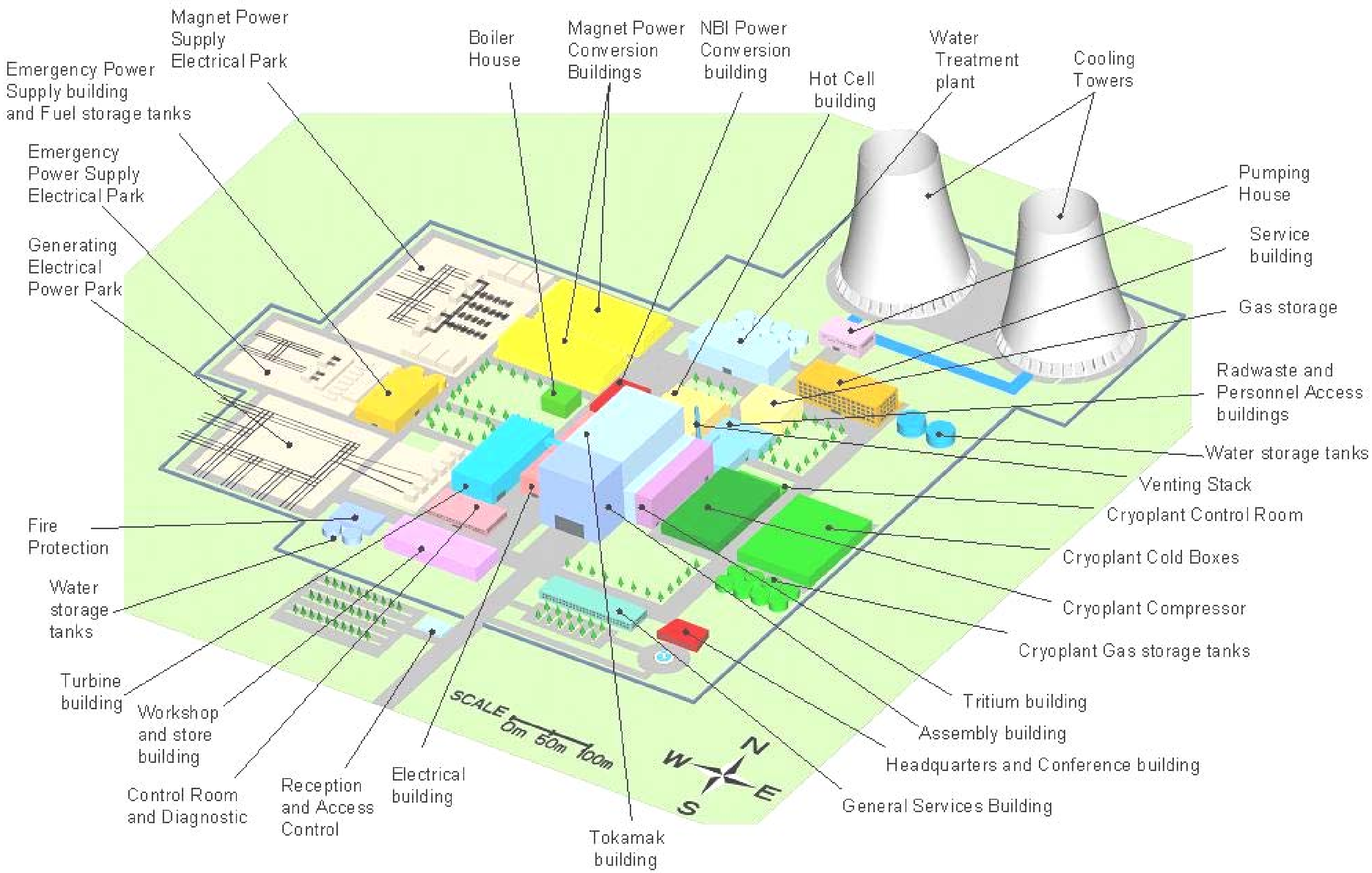
Layout of Conceptual Power Plant



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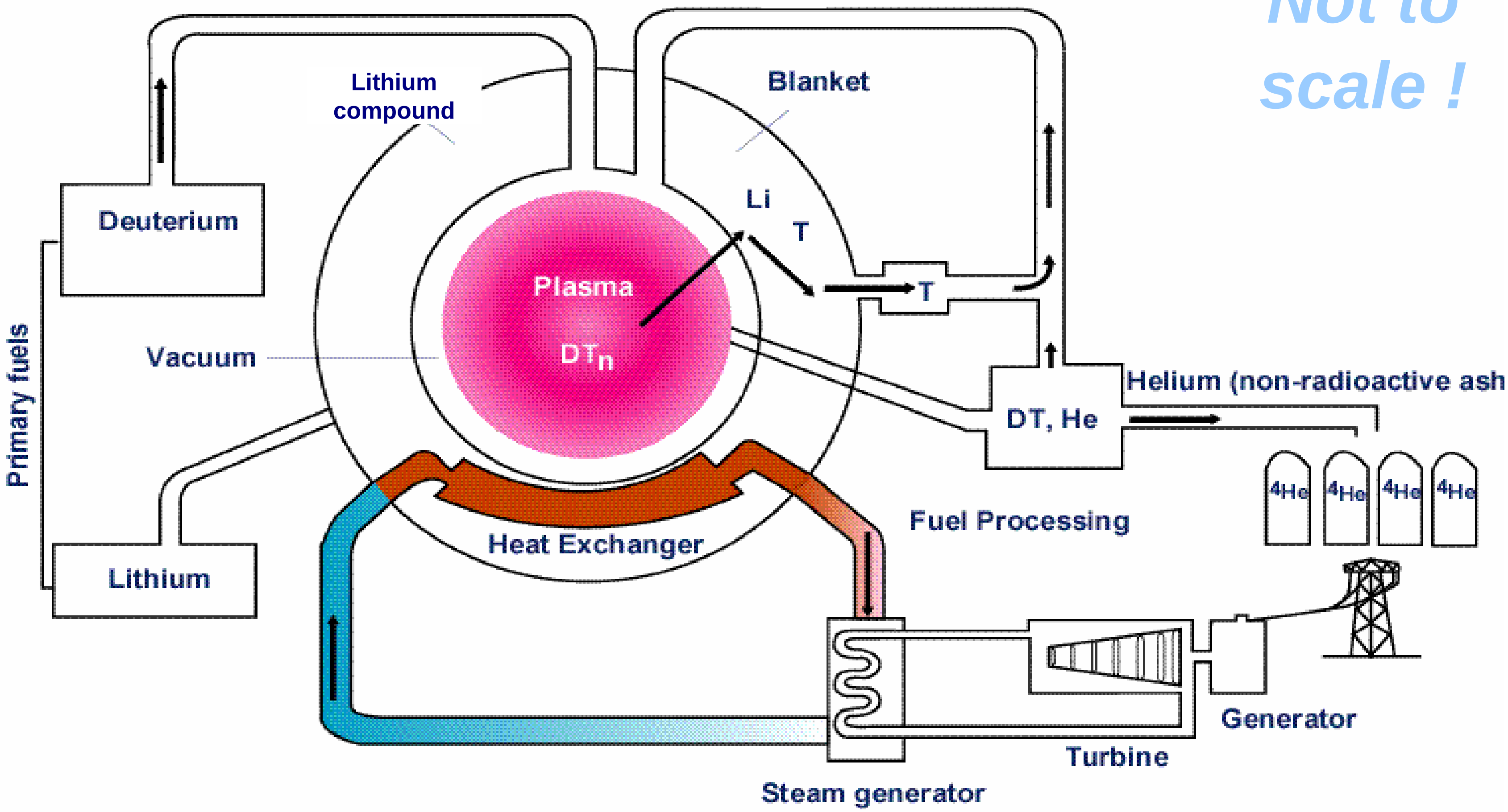
A Fusion power plant would be like a conventional one, but with different fuel and furnace

Not to scale !



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FUSION ADVANTAGES

– unlimited fuel

– no CO_2 or air pollution

– major accidents impossible*

– no radioactive "ash" and no long-lived radioactive waste

– potentially (depending on reliability) competitive "internal" cost, and essentially zero "external" cost [impact on health, climate]

* 100 tonne core of uranium, plutonium etc in nuclear reactor replaced by 1/10 gram of deuterium and tritium

DISADVANTAGES

– Development not complete or certain

– Container ⇒ radioactive: but not long-lived - could recycle after 100 years

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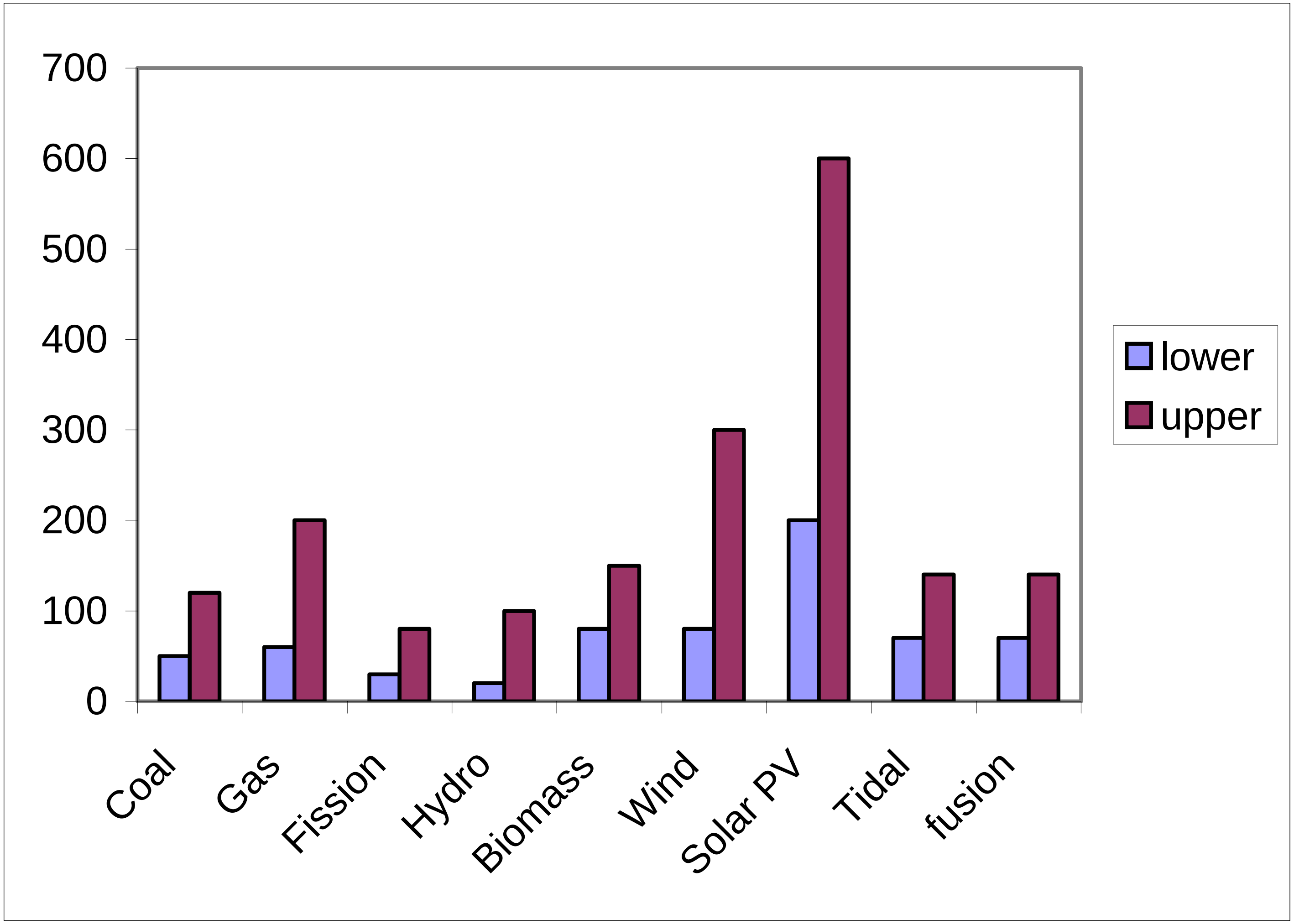

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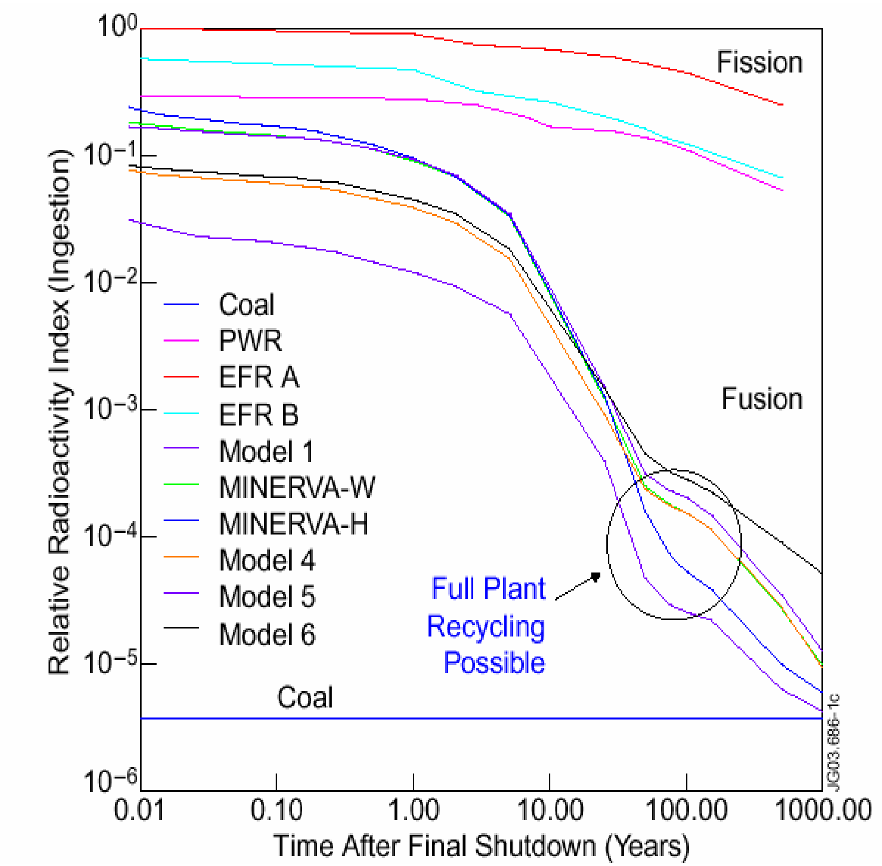
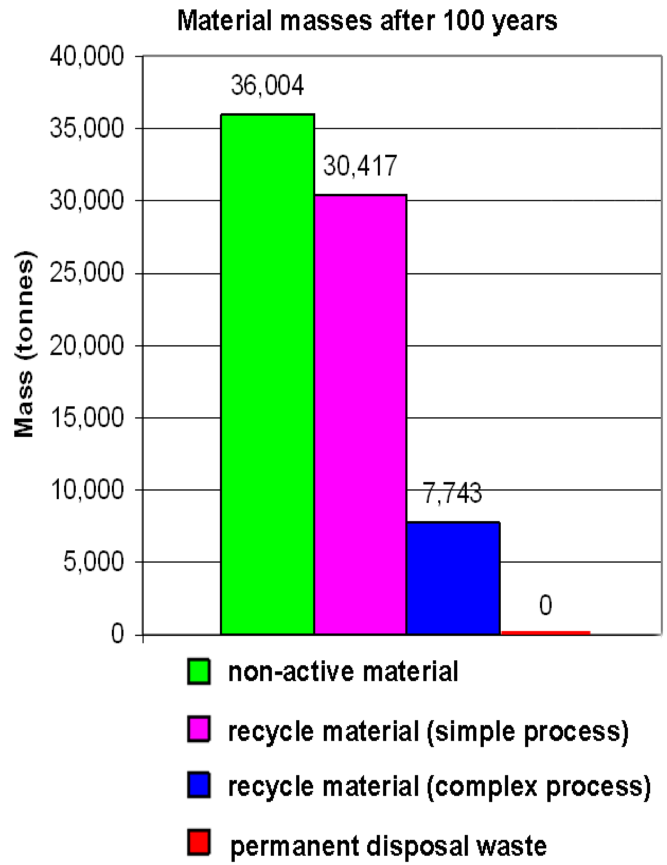
RADIOACTIVITY

No equivalent of core of fission reactor + no actinides (long-lifetimes)





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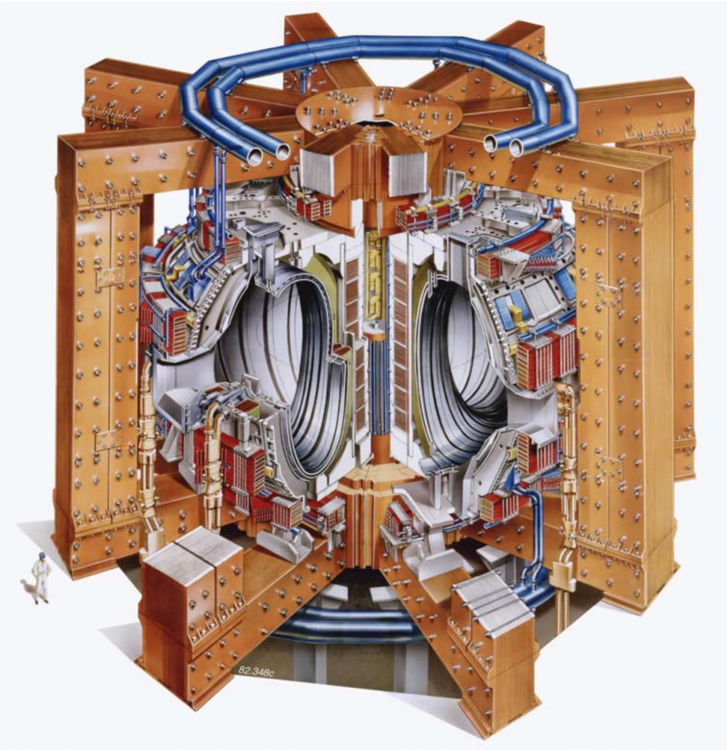
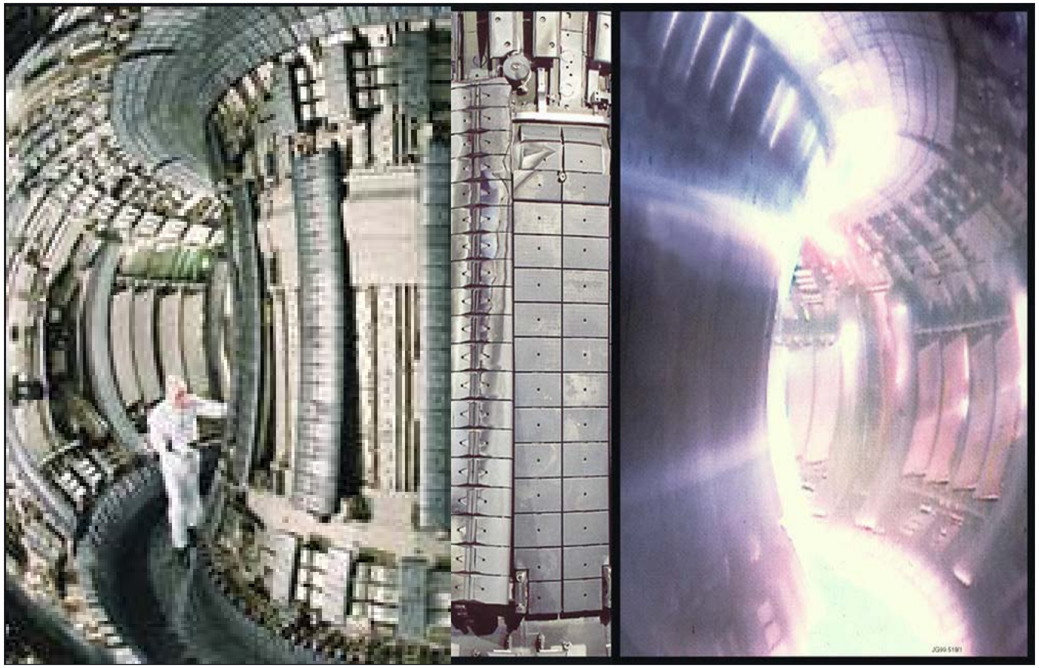
JOINT EUROPEAN TORUS (JET)

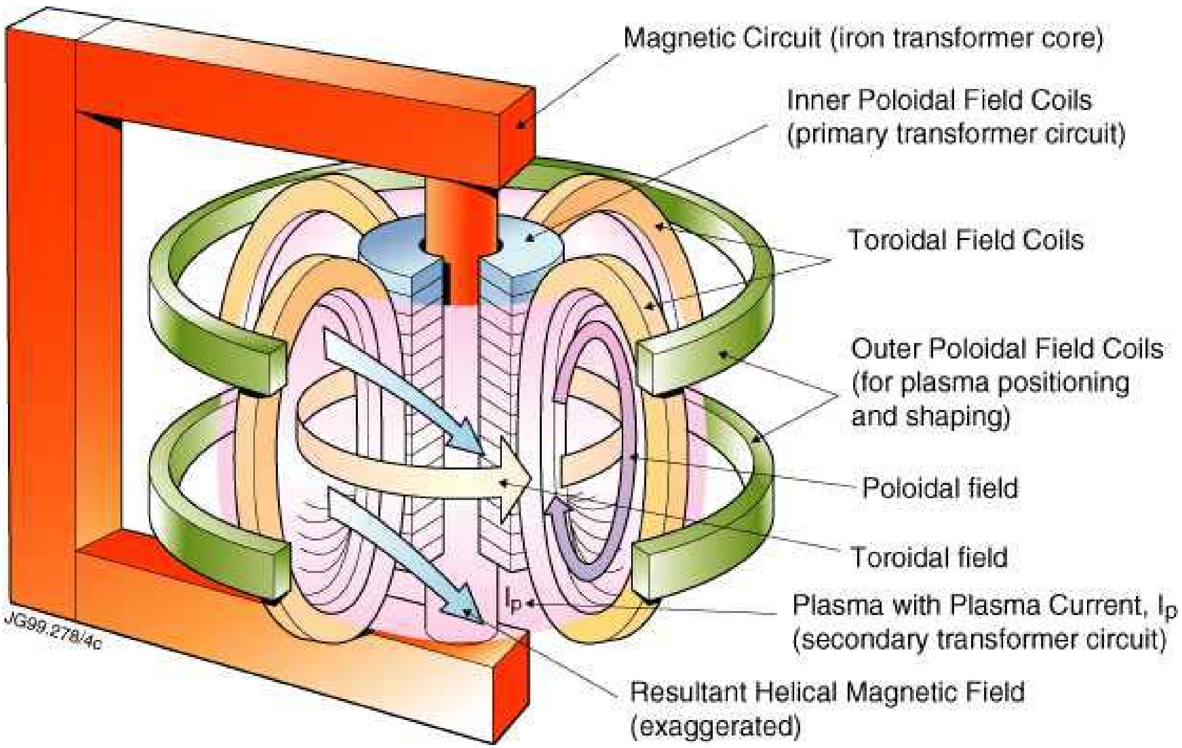
Currently the world's best fusion research facility

Operated by UKAEA as a facility for European scientists





Heating Systems for Tokamaks

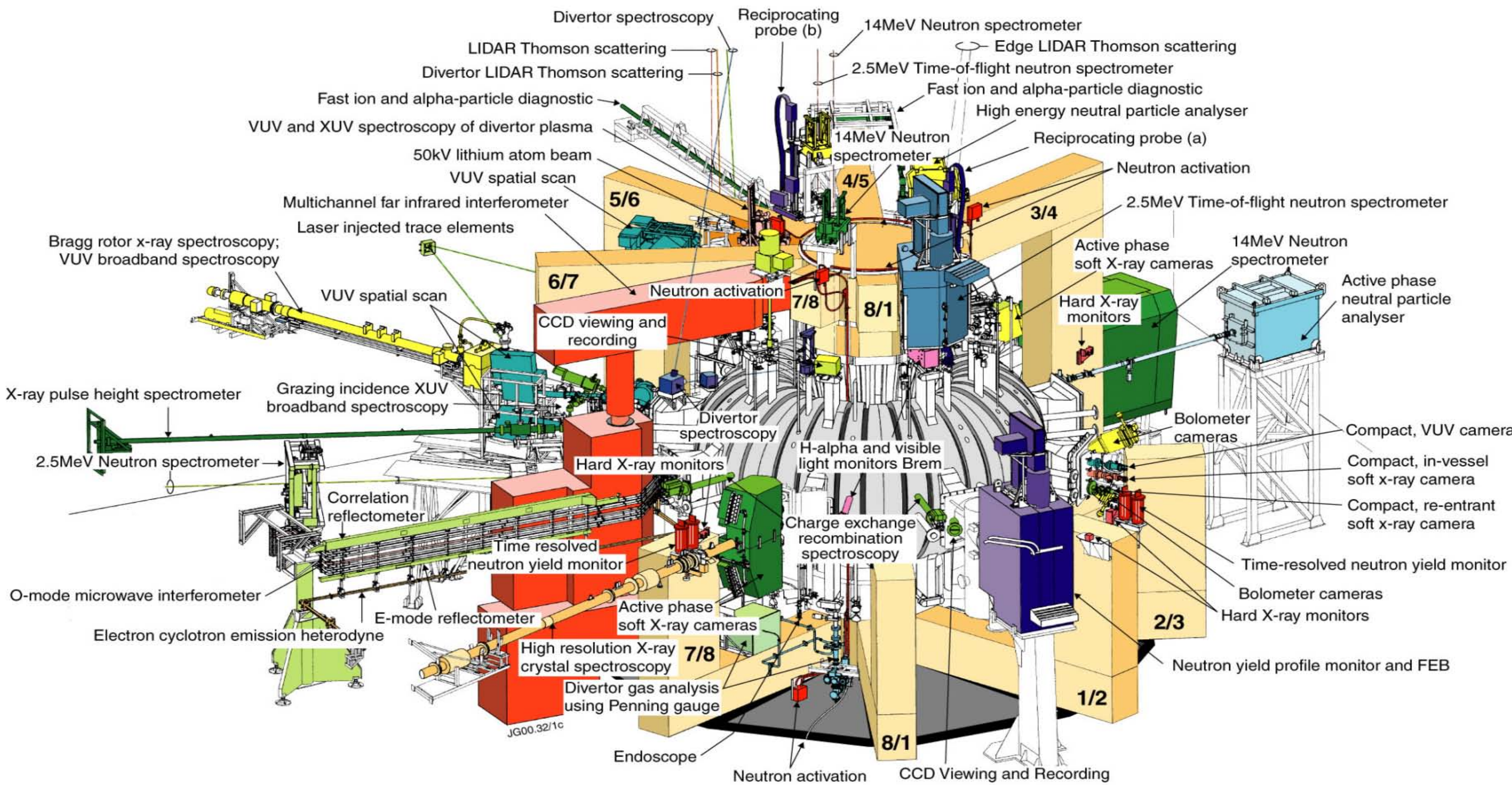


- **Tokamak plasmas are generated by transformer action, and heated by the passage of current.**
- Plasma resistivity varies as ~ $1/(T_e)^{1.5}$, this limits achievable plasma temperature by these means (~ 3.5 keV in large Tokamak such as JET).
- **Fusion reaction requires ~ 20 keV temperature for maximum reactivity of DT reaction.**

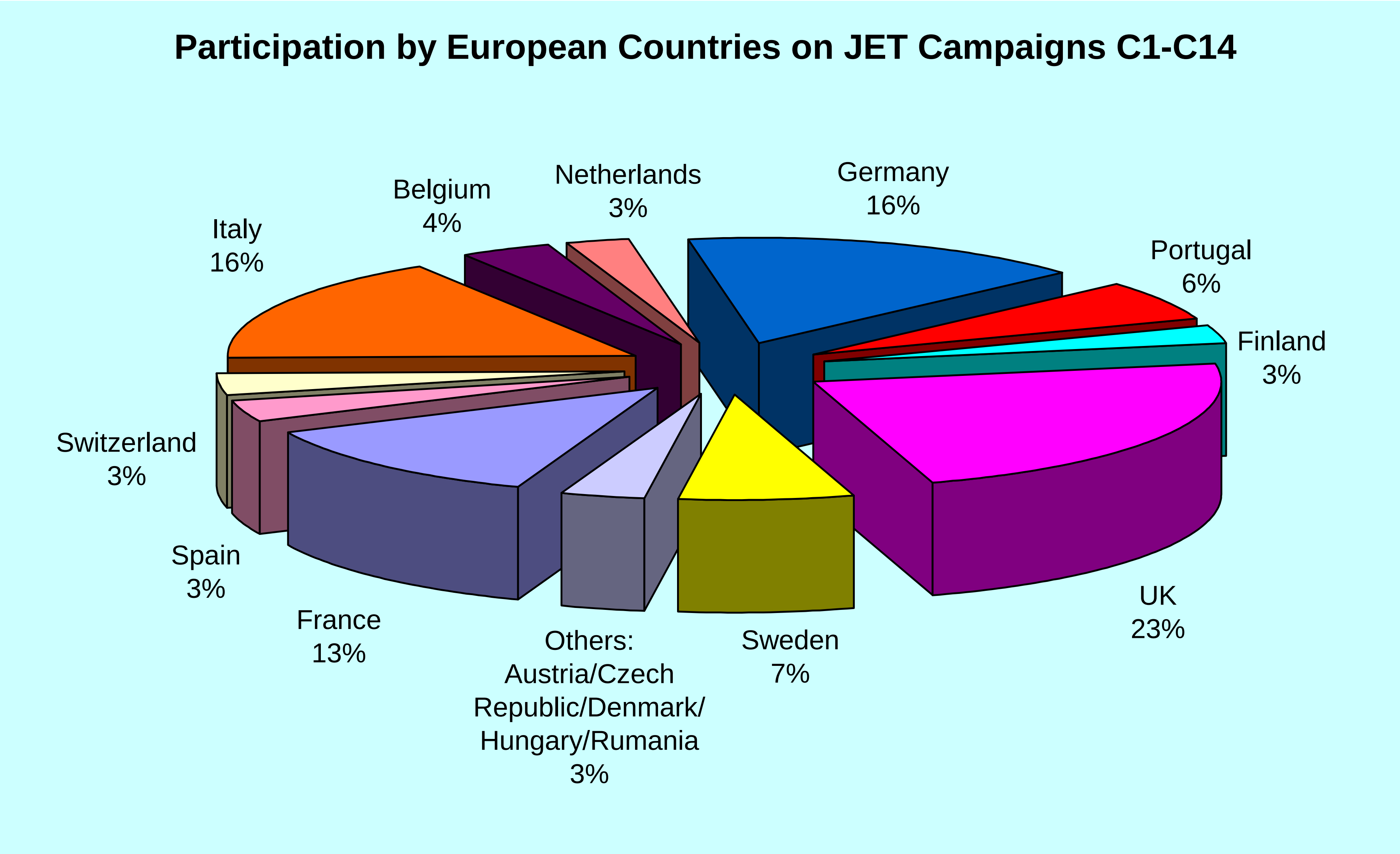
•**Auxiliary heating is necessary** (MWs)

- neutral beam injection (50- 350 keV$\Rightarrow$ 1 MeV at ITER) } **also used to drive current**
- microwave heating (10s of MHz to 10s of GHz)

JET


Divertor spectroscopy
Reciprocating probe (b)
14MeV Neutron spectrometer
Edge LIDAR Thomson scattering
LIDAR Thomson scattering
Divertor LIDAR Thomson scattering
2.5MeV Time-of-flight neutron spectrometer
Fast ion and alpha-particle diagnostic
Fast ion and alpha-particle diagnostic
High energy neutral particle analyser
VUV and XUV spectroscopy of divertor plasma
14MeV Neutron spectrometer
Reciprocating probe (a)
50kV lithium atom beam
VUV spatial scan
Neutron activation
4/5
5/6
Multichannel far infrared interferometer
2.5MeV Time-of-flight neutron spectrometer
3/4
Laser injected trace elements
Active phase soft X-ray cameras
14MeV Neutron spectrometer
Bragg rotor x-ray spectroscopy; VUV broadband spectroscopy
6/7
Active phase neutral particle analyser
Neutron activation
7/8
8/1
VUV spatial scan
Hard X-ray monitors
CCD viewing and recording
X-ray pulse height spectrometer
Grazing incidence XUV broadband spectroscopy
Divertor spectroscopy
Bolometer cameras
Compact, VUV camera
2.5MeV Neutron spectrometer
H-alpha and visible light monitors Brem
Hard X-ray monitors
Compact, in-vessel soft x-ray camera
Correlation reflectometer
Compact, re-entrant soft x-ray camera
Charge exchange recombination spectroscopy
Time resolved neutron yield monitor
Time-resolved neutron yield monitor
O-mode microwave interferometer
Bolometer cameras
Active phase soft X-ray cameras
E-mode reflectometer
Hard X-ray monitors
Electron cyclotron emission heterodyne
2/3
High resolution X-ray crystal spectroscopy
7/8
Neutron yield profile monitor and FEB
Divertor gas analysis using Penning gauge
1/2
JG00.32/1c
Endoscope
8/1
Neutron activation
CCD Viewing and Recording

UKAEA Operates JET on Behalf of Scientists in Euratom Member States



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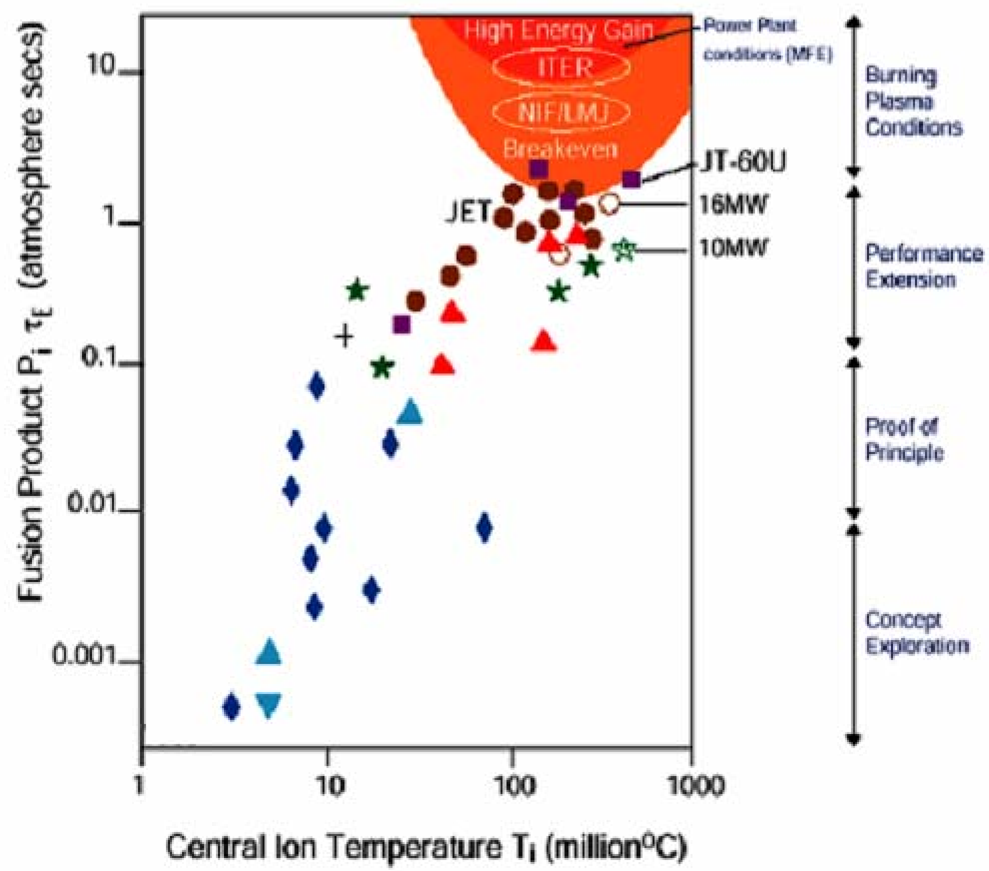
Major progress in recent years

- 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, GigaWatt-scale



NEXT STEPS FOR FUSION

- **Construct ITER (International Tokamak Experimental Reactor)**

  $\Rightarrow$ energy out = 10× energy in

  $\Rightarrow$ "burning" plasma

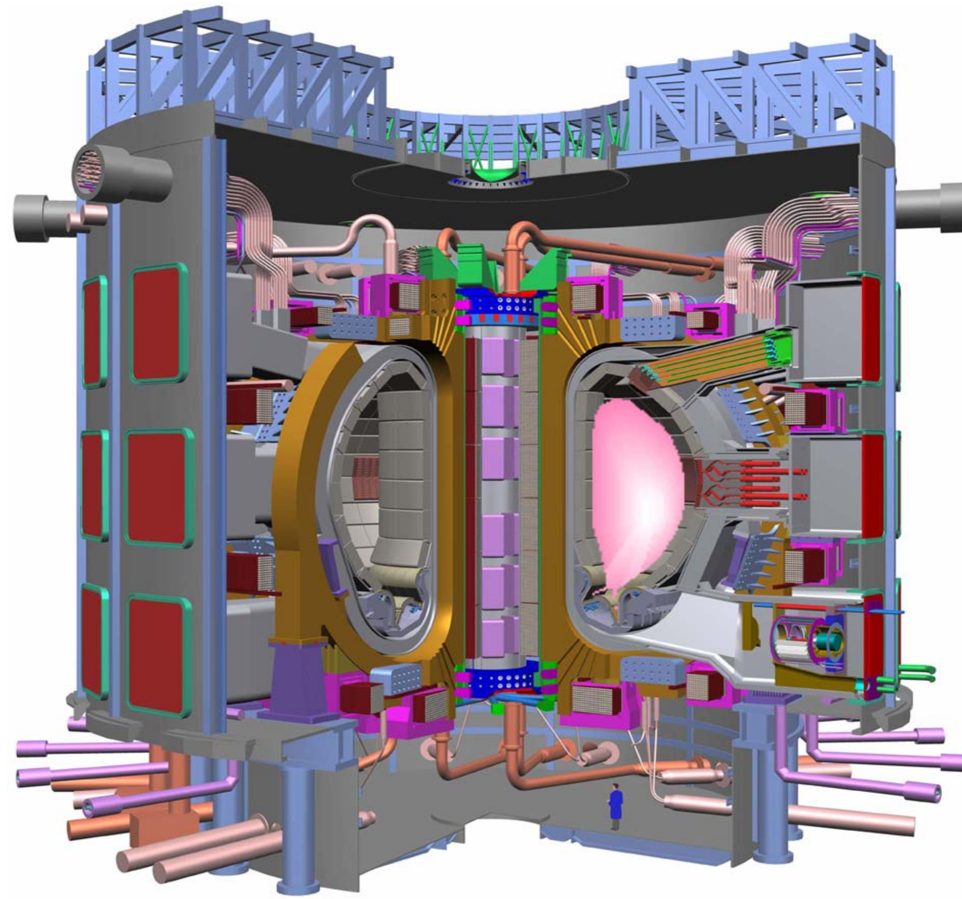
  Project involves Europe, Japan, USA, Russia, China, S Korea

  Close to approval (for construction in France or Japan)

- **Intensified R&D on materials for plasma facing and structural components**

ITER

- Aim is to demonstrate integrated physics and engineering on the scale of a power station
- Key ITER technologies fabricated and tested by industry
- 4.5 Billion Euro construction cost
- Europe, Japan, Russia, US, China, South Korea
- Candidate sites in France and Japan
- Decision hoped for in near future



MATERIALS

- **Structural materials – subjected to bombardment of 2 MW/m^2 from 14 MeV neutrons ⇒ 20 displacements per atom per year**

  Note: 14 MeV ⇒ much bigger cascades than in fission + new effects as helium is generated in material

- **Plasma facing material subjected to an additional 500 kW/m^2** in form of particles + electromagnetic radiation (up to 20 MW/m^2 on 'divertor'!)

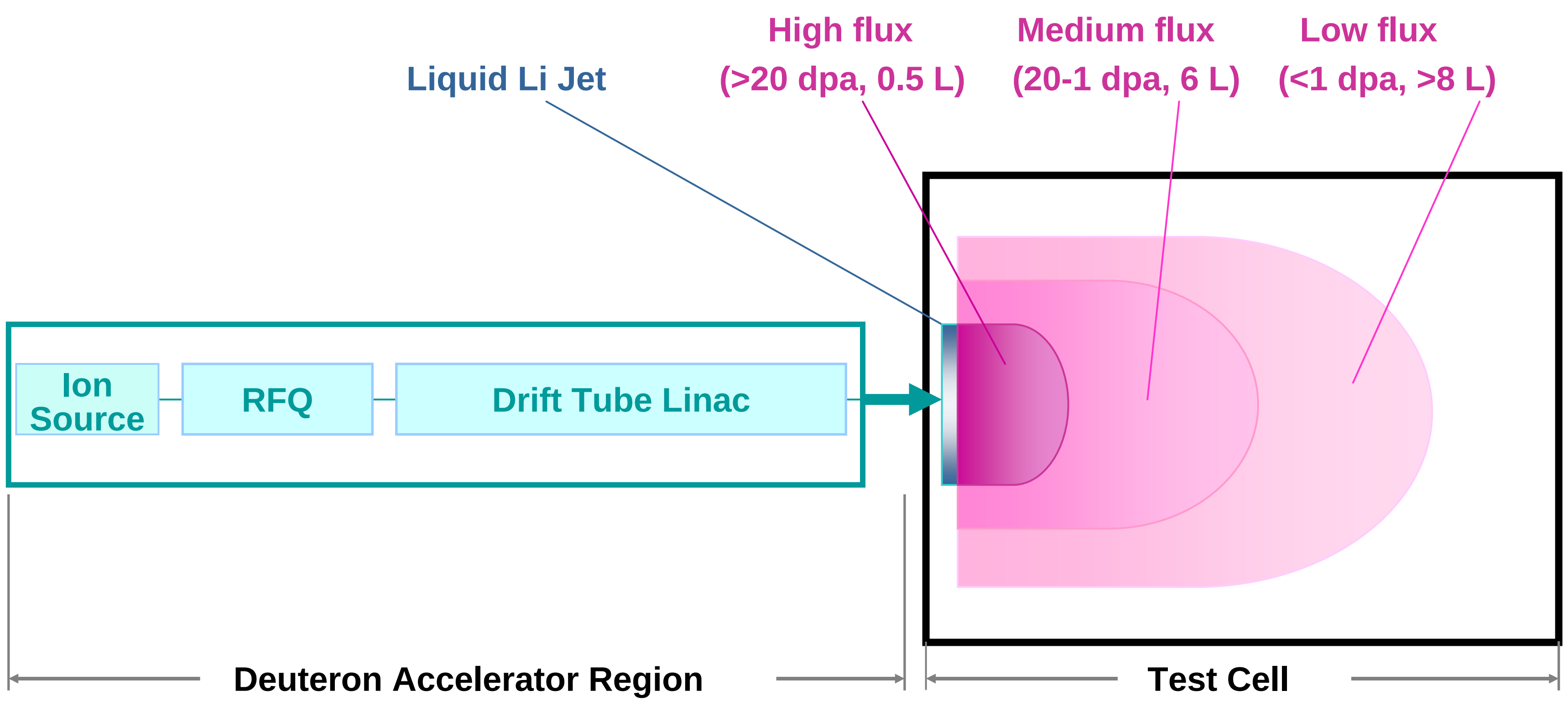
- **Various materials have been considered, and there are good candidates, BUT:**

- **Lots of interesting physics to be done – modelling + experiments essential**

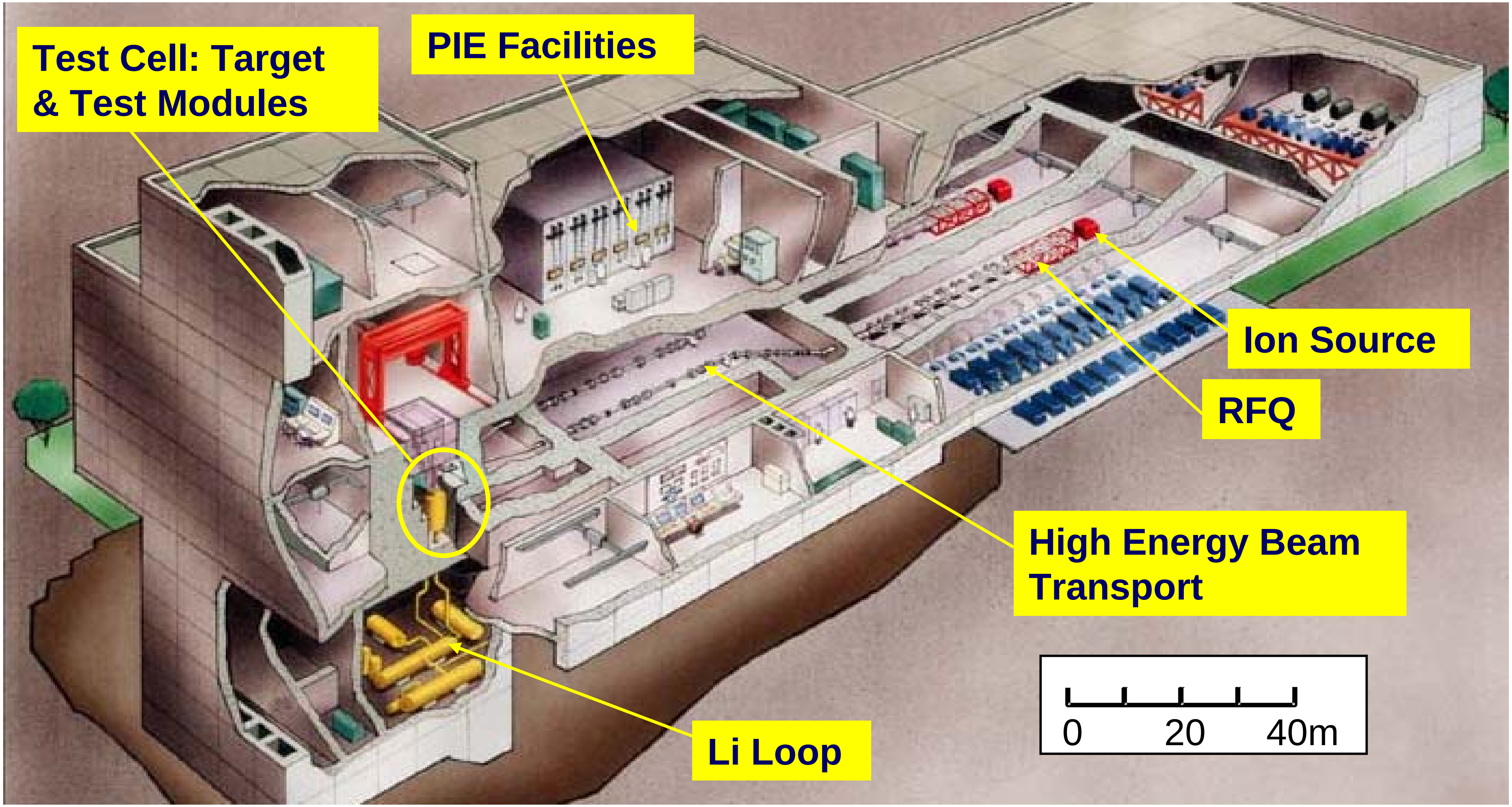
Only a dedicated ($800M) accelerator-based test facility (IFMIF) can reproduce reactor conditions: results from IFMIF will be needed before a prototype commercial reactor can be licensed and built

Mission, Users' and Operational Requirements
Anatomy of *IFMIF*

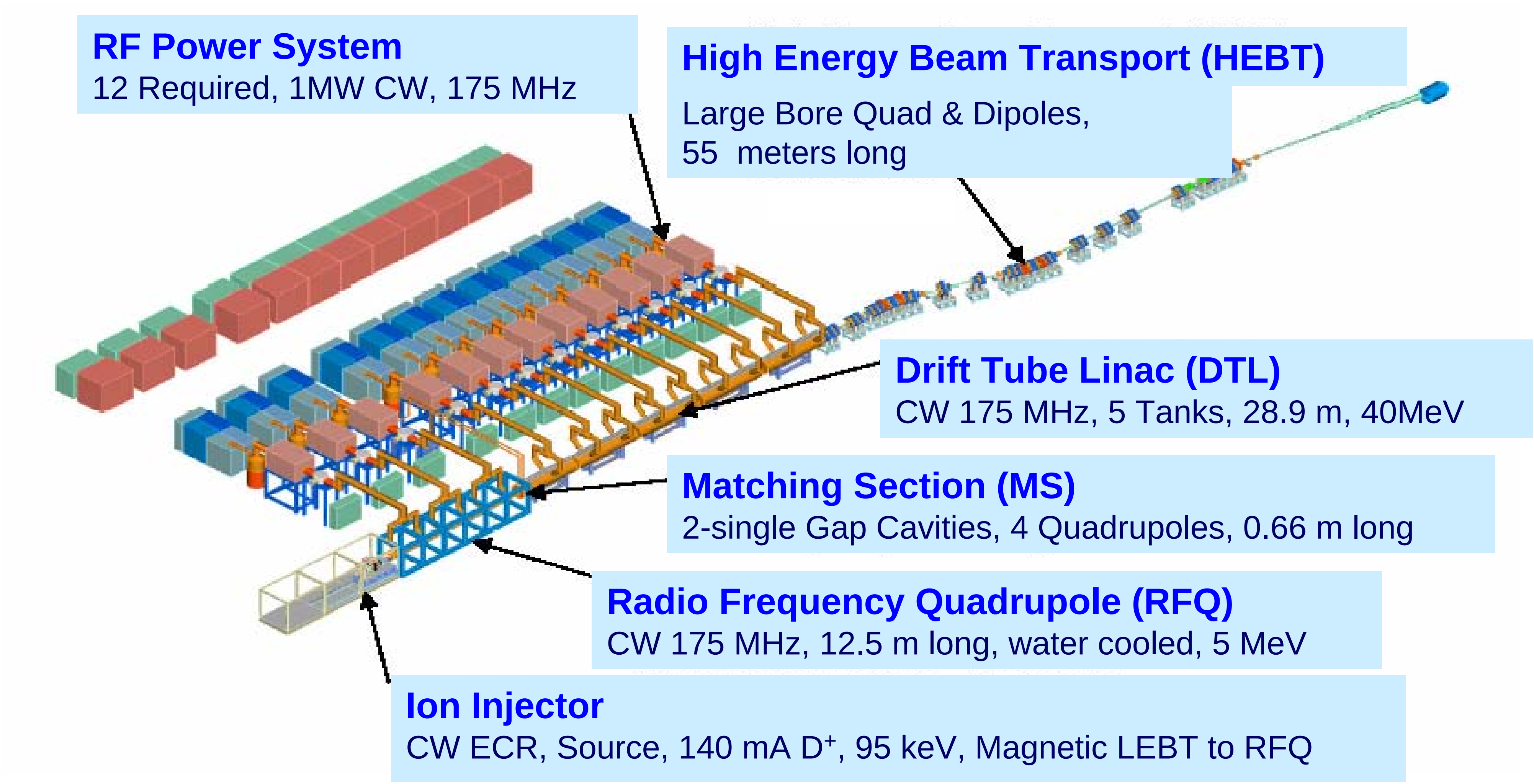
Typical Reactions:	**$^{7}Li(d,2n)^{7}Be$**	**$^{6}Li(d,n)^{7}Be$**	**$^{6}Li(n,T)^{4}He$**
Deuterons:	**40 MeV**	**2x 125 mA**	**Beam footprint 5x20 cm^2**



IFMIF System Design

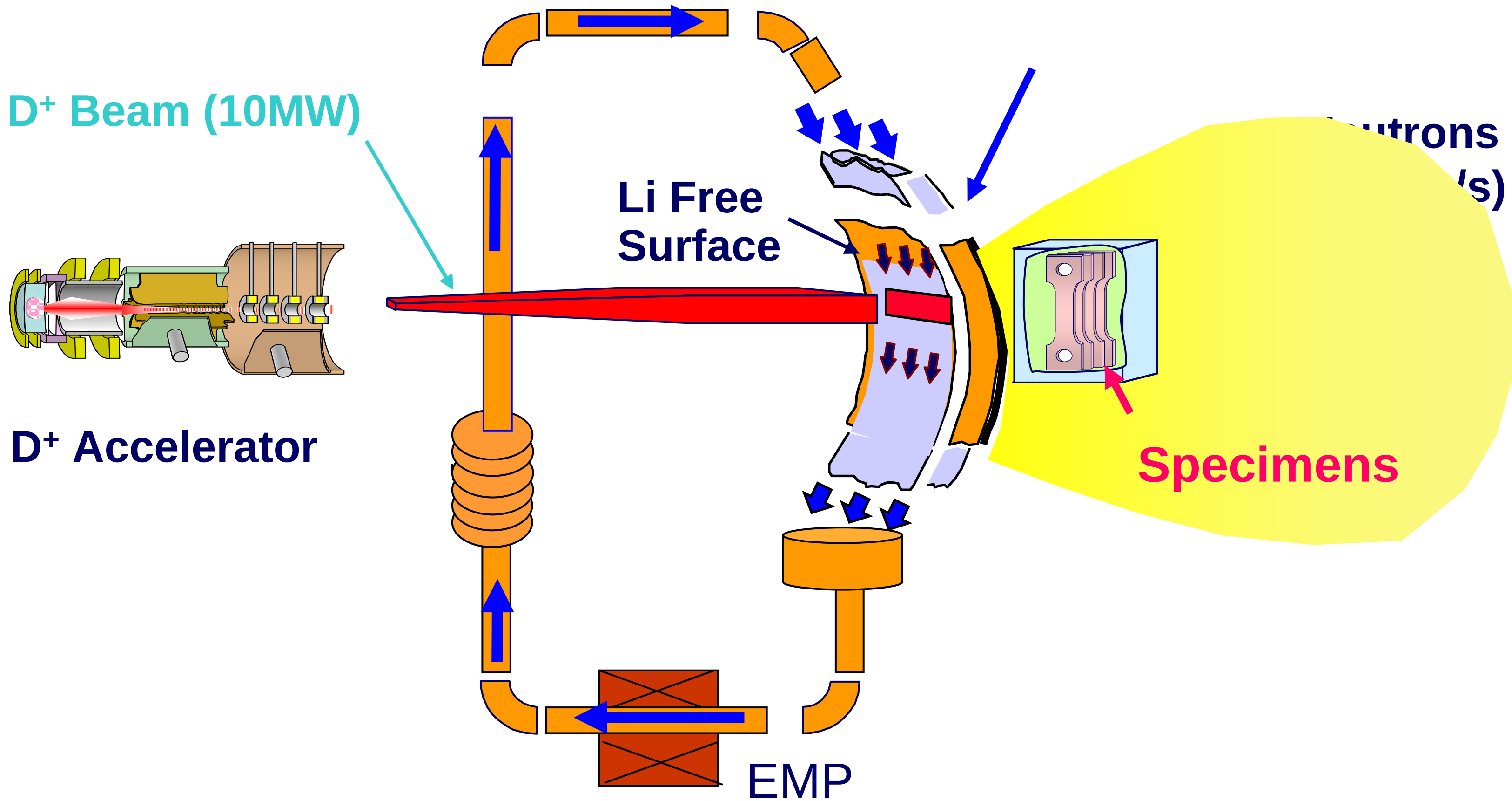


IFMIF System Design   Accelerator Facility



IFMIF System Design

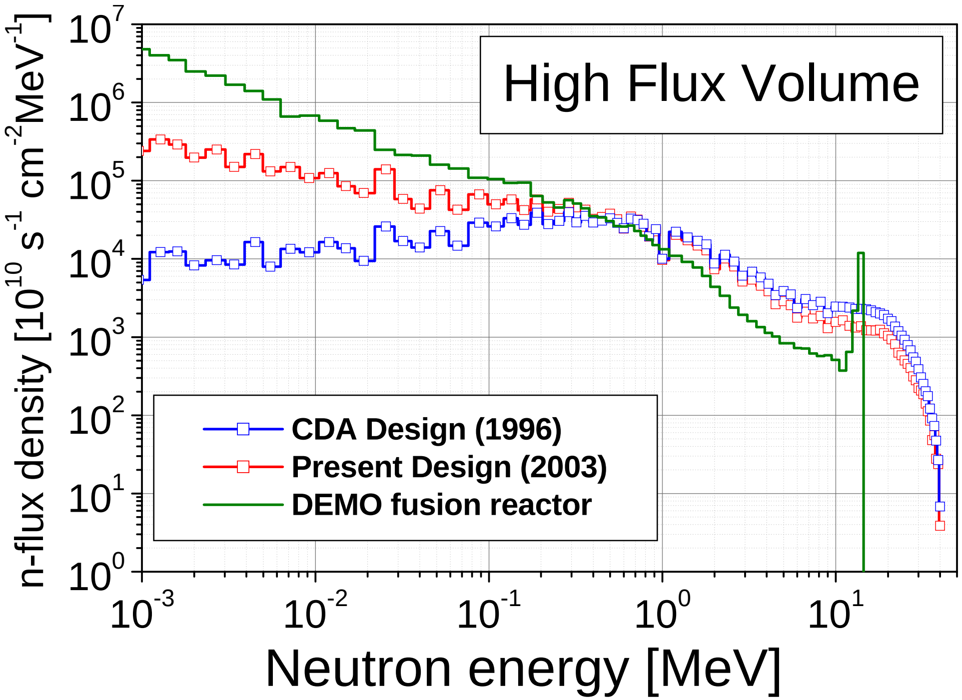
Target – Schematic view

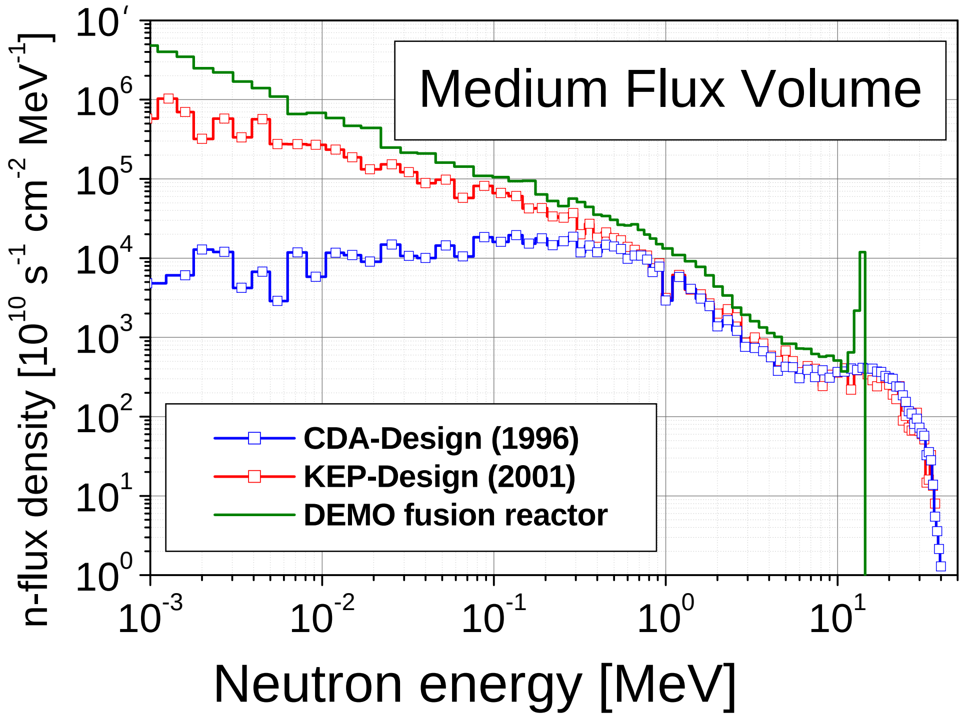


Mission:

Obtain stable and high speed Li flow during 10 MW D^+ beam loading

IFMIF Irradiation Conditions
Neutron Spectra





Neutron moderator & reflector:

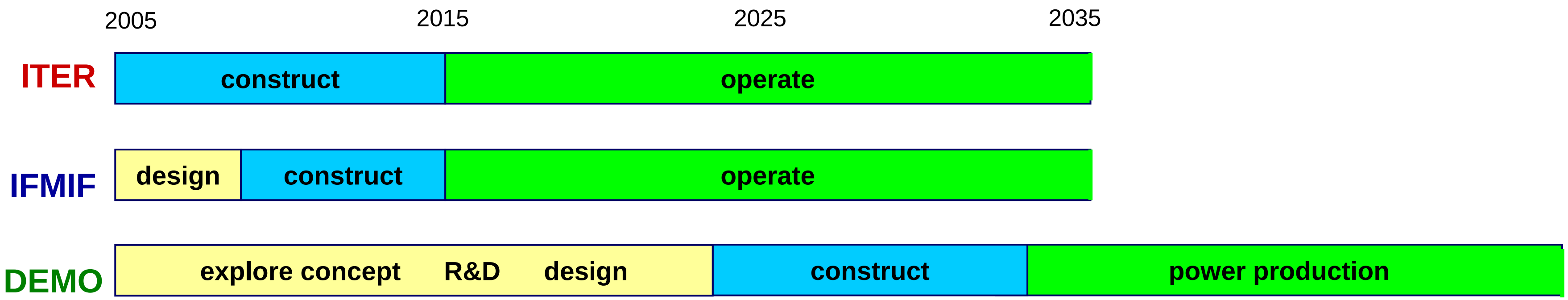
- Substantial improvements in neutron spectrum shape
- Increase of irradiation volume by ~20%

FUSION FAST TRACK: WHAT IS NEEDED

- **Approve ITER now**
  - during ITER construction $\rightarrow$ operate JET $\rightarrow$ speed up/improve ITER operation
  - continue configuration optimisation (MAST, . . .)
- **In parallel intensify materials work, approve and build IFMIF**
- **Then move from ITER directly to Prototype Power Plant**

$\Rightarrow$ **Fusion a reality in our lifetimes**

THE BROADER/FAST-TRACK APPROACH TO FUSION



This aggressive timetable can in principle be met given

- **Funding* to begin IFMIF in parallel with ITER, <u>and *also*</u> to maintain a strong accompanying programme**, including continued operation of JET, technology development, start on design of DEMO**

- **No major surprises!**

** cf world electricity market ~ $1 trillion p.a. : meanwhile fossil fuels (⇒ carbon-dioxide, pollution) are running out, while fission faces problems*

*** ITER construction budget mainly to industry, not to fusion R&D*

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CONCLUSIONS

The great Russian plasma physicist Lev Artsimovich stated (~1972)

"Fusion will be ready when society needs it"

With so few other cards in the energy pack*,

let us hope that he was right

***** apart from burning fossil fuels (which $\Rightarrow$ climate change and will run out sooner or later), nuclear fission (which faces problems) and solar (which is mostly in the wrong places and currently far from economic), only fusion is capable in principle of producing a large fraction of the world's energy needs