Nuclear Fusion

might it make hydrogen before electricity?

William J. Nuttall
Senior Lecturer, Technology Policy
University of Cambridge
wjn21@cam.ac.uk

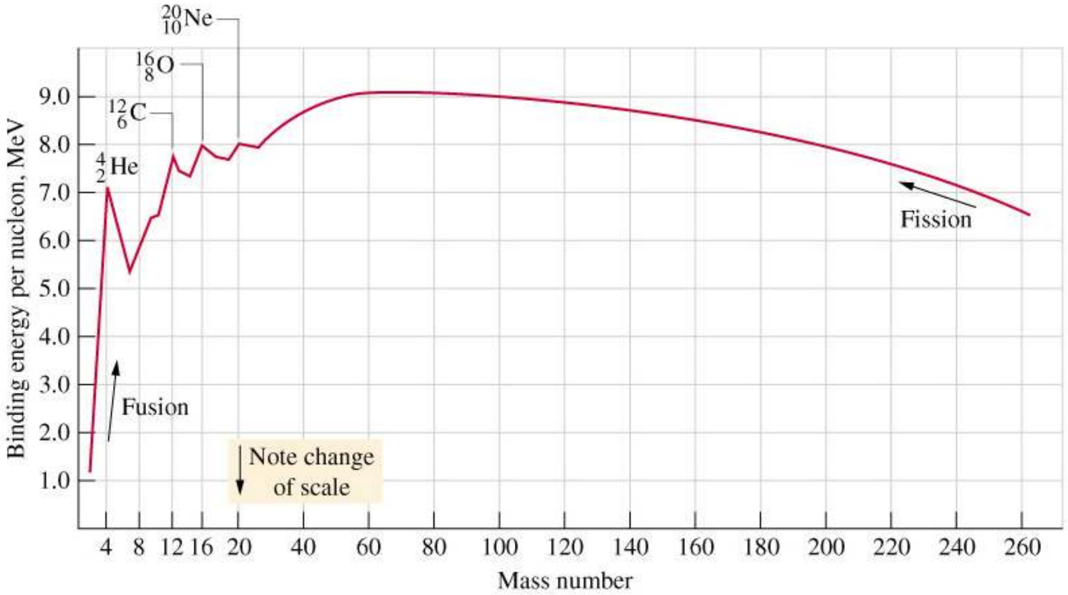
The Fusion Island team includes:

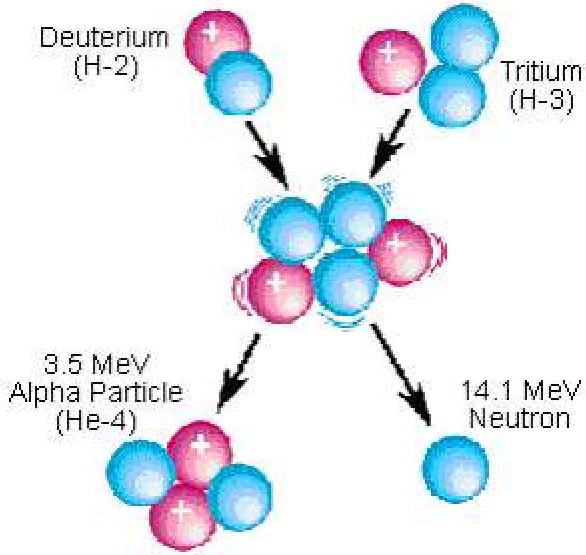
Leslie Bromberg (PSFC MIT), Michel-Alexandre Cardin (ESD-MIT), Richard Clarke (UKAEA Fusion), Jeff Freidberg (NSE & PSFC MIT), Bartek Glowacki (DMM-UC), Joe Minervini (PSFC MIT), Richard de Neufville (MIT ESD), Michael O'Brien (JBS)

For the multimedia version of what I am about to say check out Bartek Glowacki's film available as a streaming video from:

http://www.msm.cam.ac.uk/ascg/lectures/applications/fusion.php

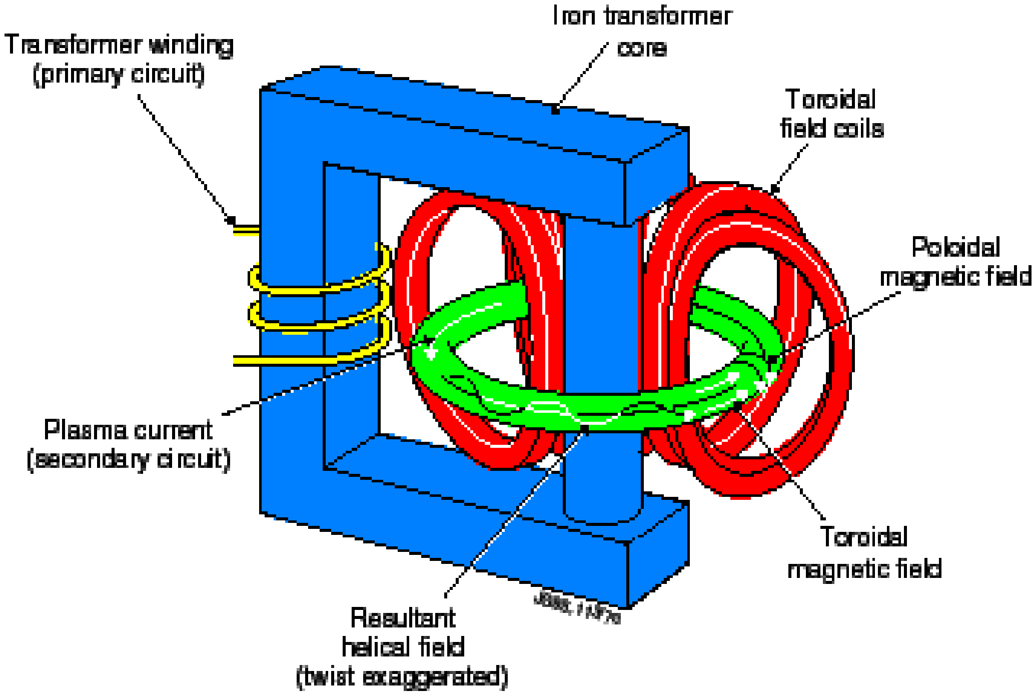
Nuclear fusion energy – the basics

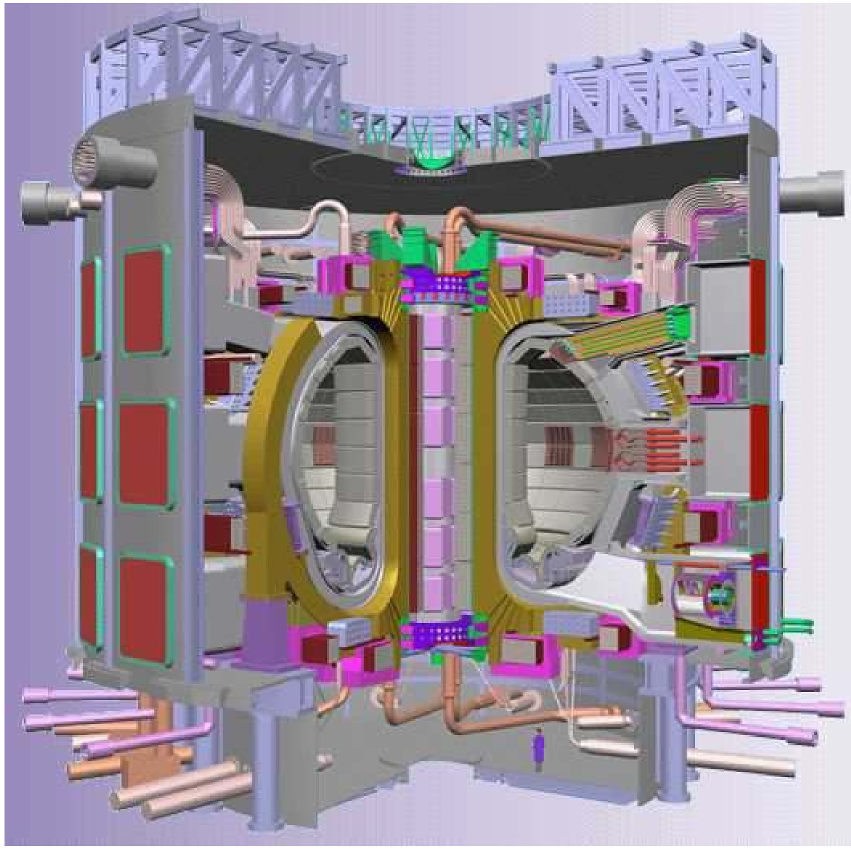




The 14MeV fast neutron takes 4/5ths of the fusion energy out of the plasma, the alpha particle moves within the plasma keeping 1/5th of the energy there.

The Tokamak – a magnetic bottle for hot plasma

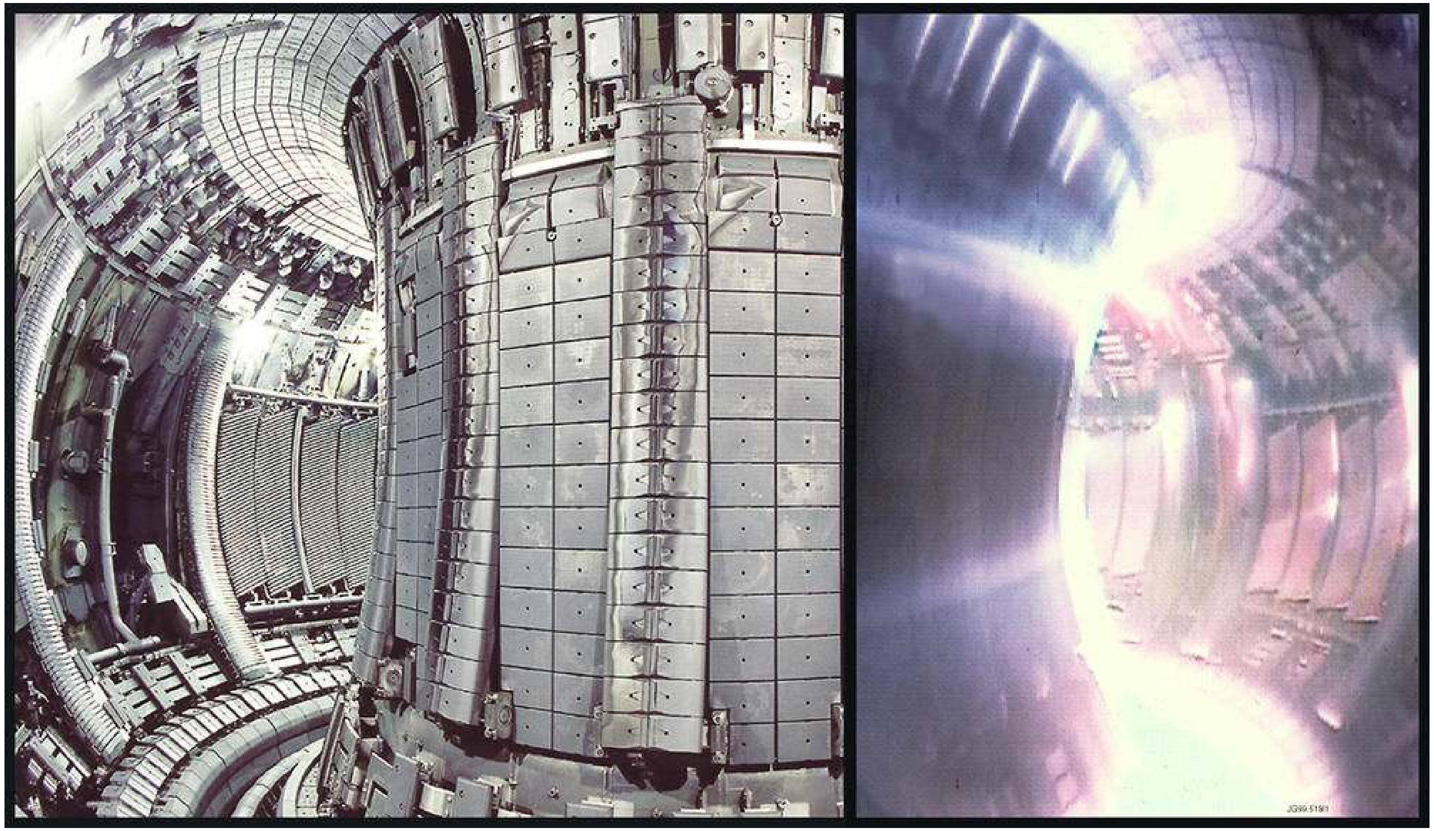




Conventionally fusion is to use Nb_3Sn magnets cooled by LHe

The ITER experiment – €10Bn machine (construction & ops) in operation in Cadarache, France from 2016

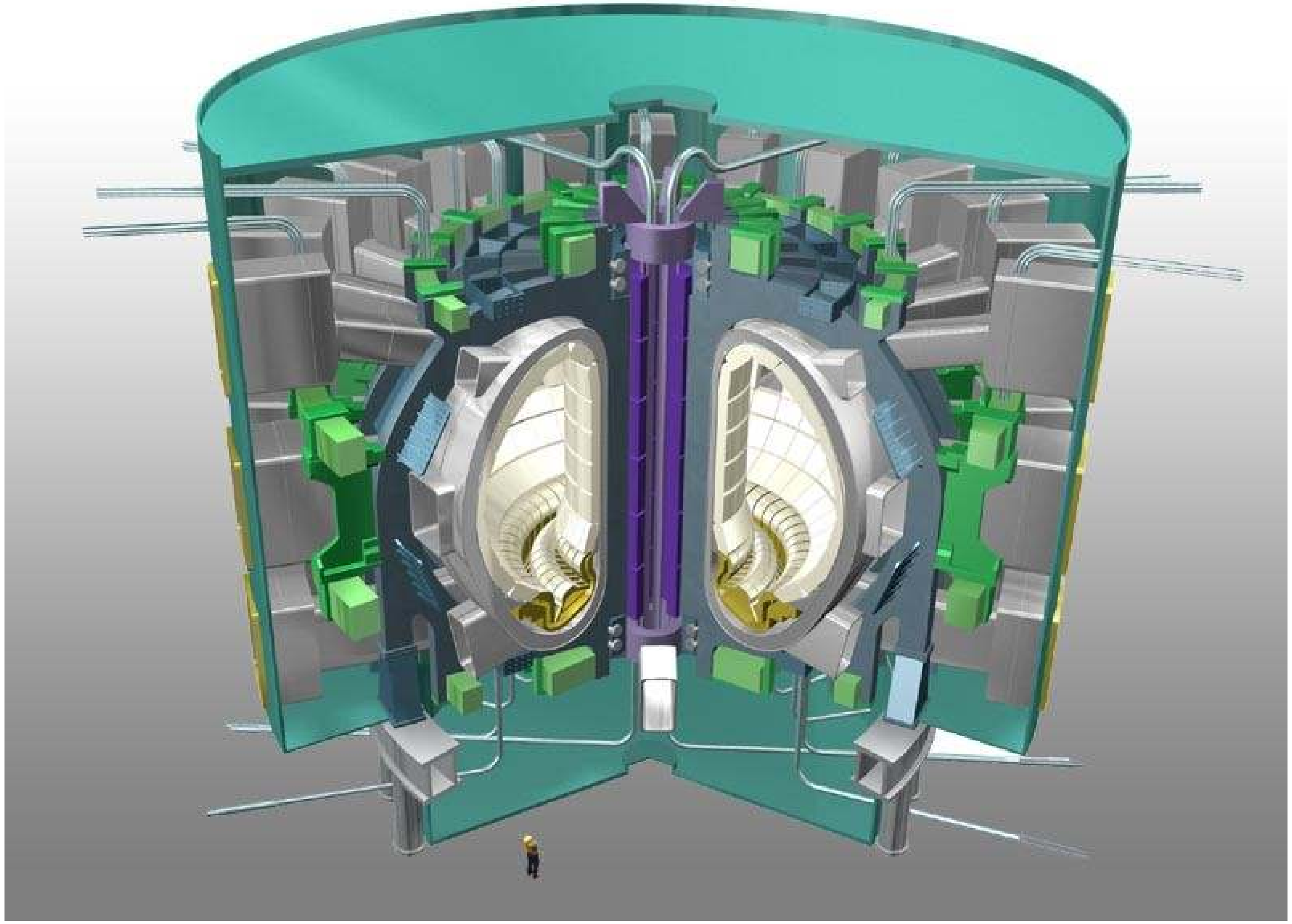
Big Tokamaks I – JET 1983- present



Images: EFDA, Culham

JET is the largest tokamak in the world, it is in Britain and it has been a success

Big Tokamaks II – ITER 2017-2035

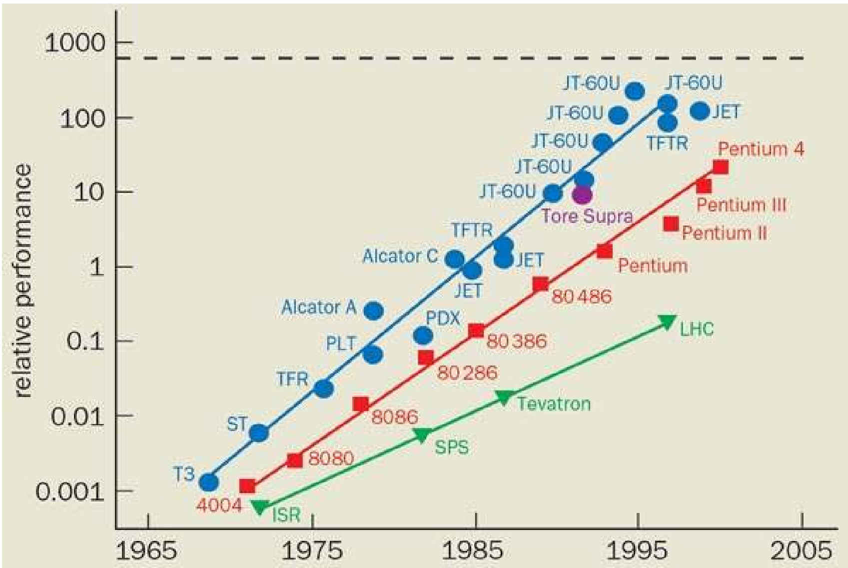


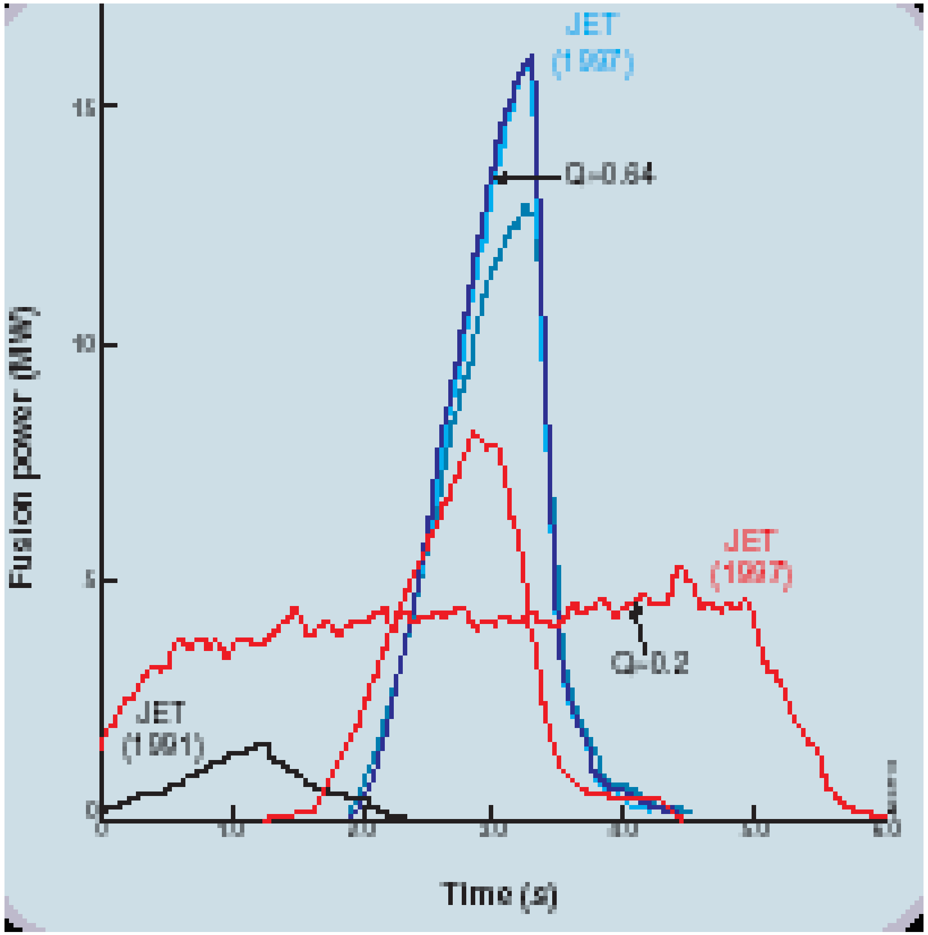
Images: EFDA, Culham

ITER will be a research machine – it will not generate electricity.

Fusion Physics Works

JET has given Britain and Europe a world lead

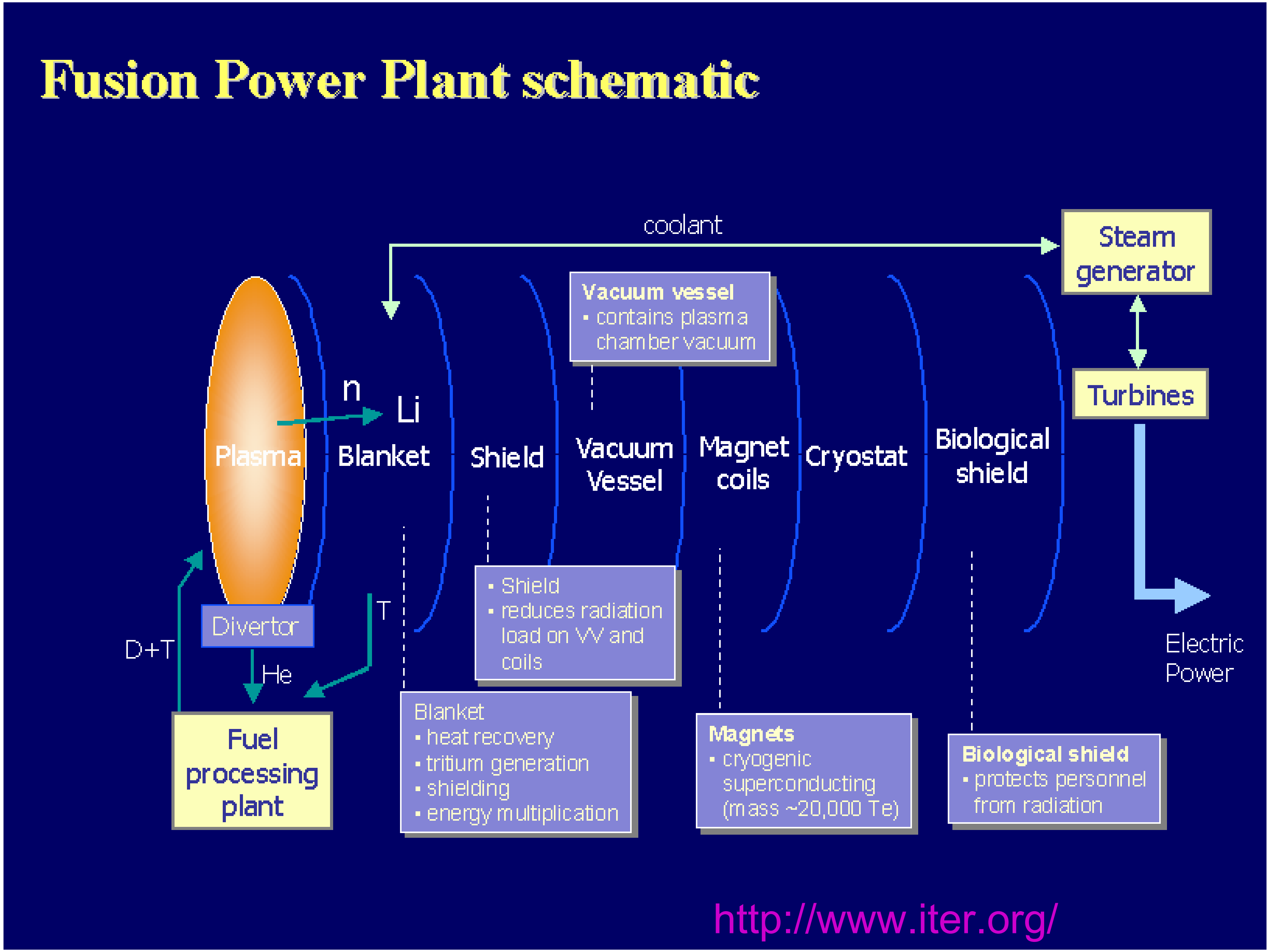




Images: EFDA, Culham

but, Engineering Will be a challenge

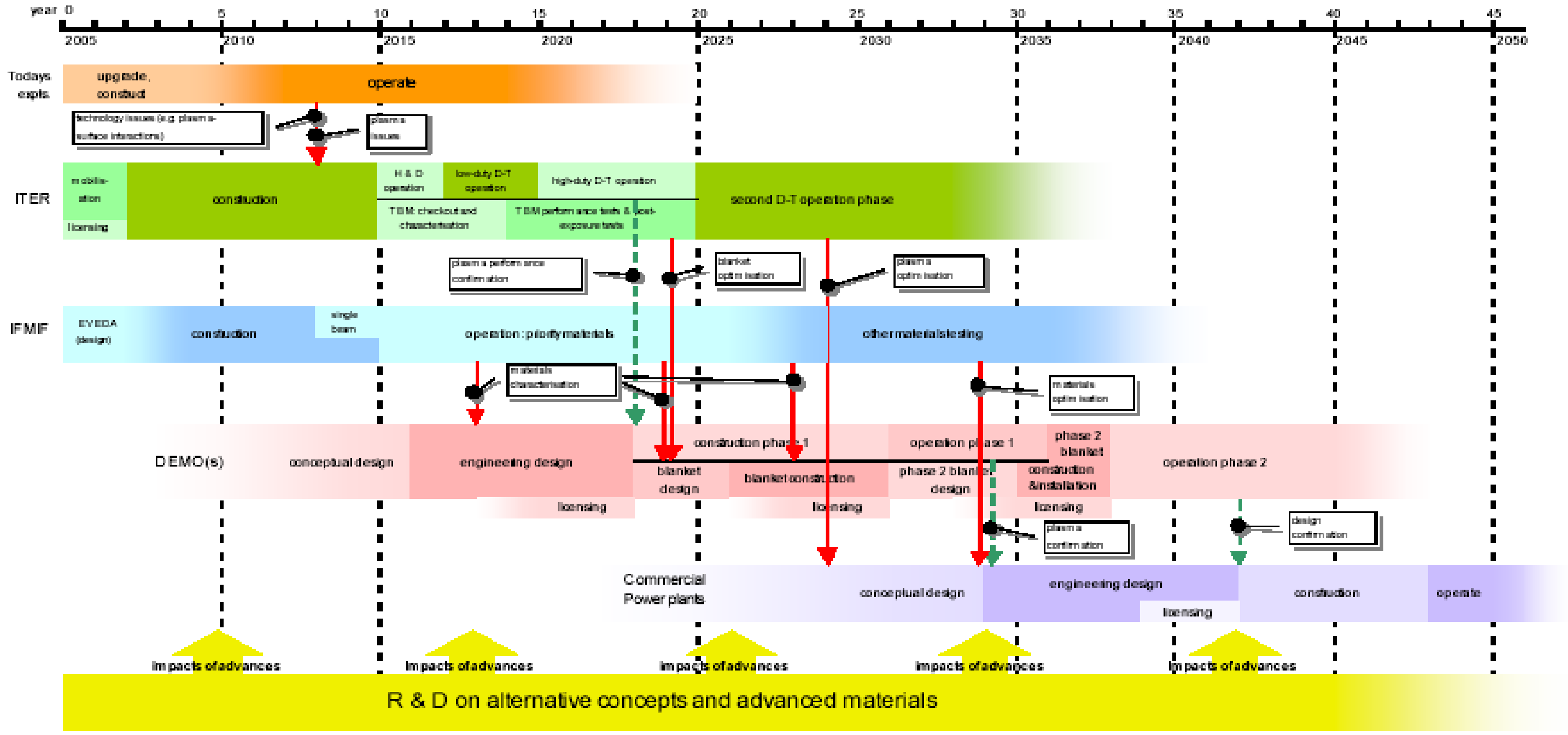
Conventionally fusion heat is expected to make electricity



Source: UKAEA

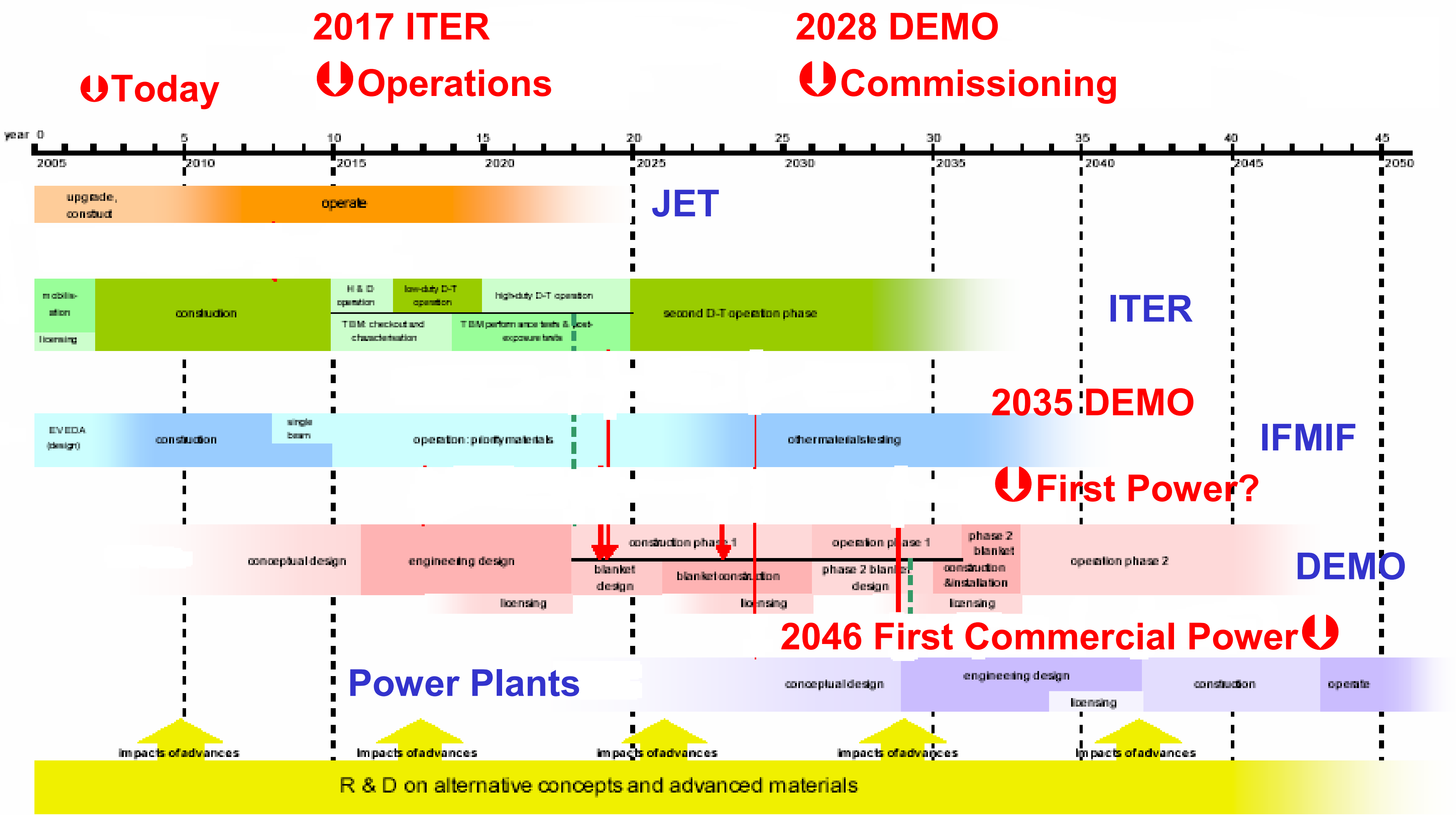
Fusion for Electricity – the current dominant paradigm

Fast Track - Pillars Only



Source: Chris Llewellyn Smith UKAEA Fusion

“Fast track” to fusion electricity – some key dates



First commercial power in roughly 38 years?

38 years?

Well, in our country," said Alice, still panting a little, "you'd generally get to somewhere else — if you run very fast for a long time, as we've been doing."

"A slow sort of country!" said the Queen. "Now, here, you see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!"

Lewis Carroll, *Alice Through the Looking Glass*

…, but what about Hydrogen?

Some context

Climate Change -RCEP 22nd report : *Energy – The Changing Climate,* June 2000 (http://www.rcep.org.uk/newenergy.htm)

World will probably need to achieve 60% CO_2 emissions reductions by 2050 to stabilise the climate – how can this be achieved?

Decarbonising electricity will be relatively straightforward. Some countries have done it already (e.g. France and Norway)

A *hydrogen economy* addresses the far more difficult global challenge – decarbonising transport.

In 2000 global petroleum production capacity was 75 Million bpd representing 39% of global energy supply (See AE Sieminski in *Energy & Security* by Kalicki and Goldwyn)

To decarbonise transport - the challenge is scale!

The Hydrogen Economy

- Like electricity, hydrogen is an energy carrier not a primary fuel
- It is well suited for relatively low temperature fuel cell applications producing water, heat and electricity to high efficiency
- Today Hydrogen is made by steam reforming methane – the high temperature reaction of steam and methane – Some oil companies favour this route if coupled with carbon capture and storage

  $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$
- Not a clean process, but already industrialised and relatively straightforward. The challenge will be carbon capture and storage (CCS).

Timescale of the hydrogen economy?

Hydrogen has long been a commercial product with a price

GM plans to commercialise fuel cell vehicles by 2020

But turn-over of the entire vehicle fleet could be very slow.

Toyota hybrid research roughly 20 years from R&D start to 1.2% of US market share.

Significant hydrogen demand for transport in the 2030s?

Note the BMW approach – cryogenic liquid H2 dual fuel internal combustion vehicles. Demonstrator cars built already on the normal production line.

Fusion for Hydrogen?

The Engineer 28 May 2004


COMMENT

Fusion should put its energy into oil

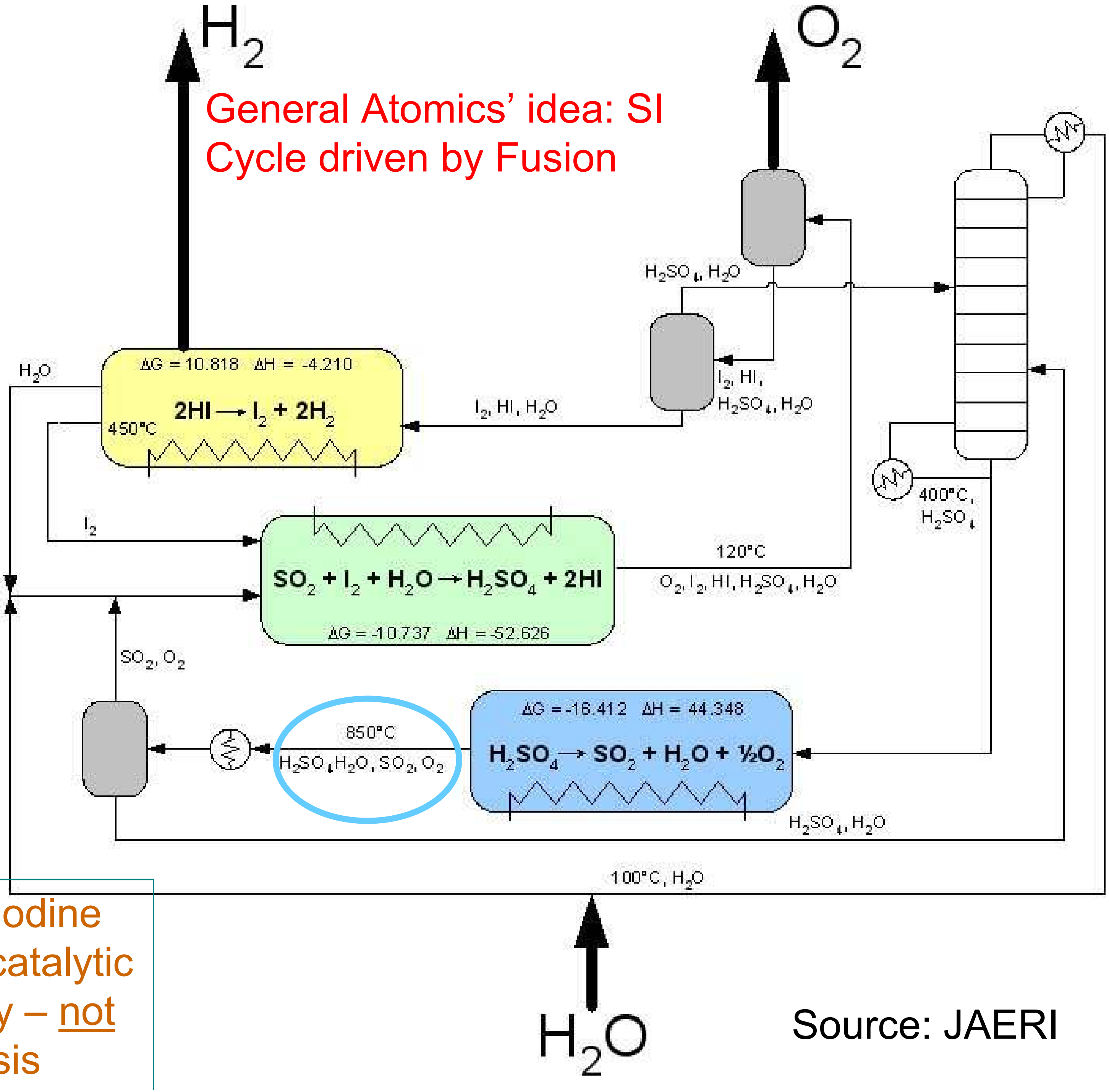
The energy industry is facing a crossroads. The future is fusion, suggests **Dr William Nuttall**, but funding must come from private money — and where better to go than to the major oil companies

The oil industry is risk taking and comfortable with highly complex engineering systems

My original interest in Fusion for Hydrogen was inspired by technical ideas emerging from General Atomics in San Diego (Ken Schultz and colleagues) – why not use nuclear fusion as a source of industrial process heat for hydrogen production?

Furthermore in May 2004 I observed that the risks of fusion might be better matched to the culture and strategies of the international oil companies than to electricity utilities

General Atomics' idea: SI Cycle driven by Fusion



Sulphur Iodine Cycle – catalytic chemistry – <u>not</u> electrolysis

Source: JAERI

Hydrogen without inefficient electricity generation and electrolysis?

- One possibility - high temperature catalytic thermo-chemical cracking of water
- Heat (800°C or more) + $2H_2O \rightarrow 2H_2 + O_2$
- Only real candidate technologies are solar thermal or nuclear power (Fission and Fusion). Fusion is safer (perceptions are important), cleaner and potentially hotter (?) than fission
- No CCS Required

Fusion Plant as a Source of Heat

Much forward strategy for fusion research and development looks to a future in which fusion energy is used to generate base-load electricity.

However this leads to some key challenges:

- Continuous operations with few scheduled shutdowns
- High reliability – few unscheduled shutdowns
- Competition with existing clean electricity technologies

Fusion as a heat source allows fusion to avoid these difficult challenges

Fusion for electricity will probably work, but it will not be easy…

Fusion Electricity One Scenario:

February 1st 2040 "Fusion 1" enters into first base load contract to supply 2.0 GWe for one week.

February 3rd 2040 5.00pm "Fusion 1" trips off-line – merely a faulty tritium alarm. Automatic plasma shutdown

February 3rd 2040 6.30pm fault rectified – request made to Grid SO for 400MWe to restart – 400 MWe not available owing to tight short-term capacity margin

Why Is Fusion Process Heat a Good Way to Make Hydrogen?

- Intrinsically fusion is a low CO_2 route to Hydrogen (Hydrogen with no CCS required)
- It would have better safety issues than fission (no critical mass, no chain reaction and no long-lived wastes)
- Excellent energy security - no fuel delivery required – only workers, helium(?) and electricity to start (?)
- Good for national balance of payments – no need to buy fossil fuels – it would be a very high value-add process (money and brainpower turns water into hydrogen)
- Timing fits scenarios of fuel supply security, hydrogen demand and necessary CO_2 reduction in transport (Fusion hydrogen is a technology for the 2030s not the 2050s?)

Why is Fusion better than other thermochemical routes to hydrogen?

- Unlike solar thermal it does not require high solar irradiation
- Fusion is perhaps safer and cleaner than Gen IV Fission – there is very little stored energy and no actinides or fission products – far easier for safety regulators to licence fusion next to a thermochemical plant
- Fusion Plant easier to shut-down than a fission plant (no need to manage decay heat) – with thanks to Ron Ballinger PSFC MIT for this observation

Fusion and Energy Security

- The plant needs fuel – *not a problem*
- Workers – *an opportunity, not a problem*
- Helium – what will helium availability be like in the 2040s?
- How much will helium cost in the 2040s?
- How much helium would fusion require?
- These are questions we have been examining for a separate research project for UKAEA and Linde-BOC
- Helium will be the key consumable for conventional fusion power plants – it is a by product of the natural gas industry

This leads us to …

“Fusion Island”

Fusion Island – the vision

Ten years before Fusion Energy is first used for commercial electricity production, Fusion Island could be producing clean bulk liquid hydrogen to fuel the vehicles of the 2030s? Fusion Island might have no connections at all with National Electricity Grids

(Concept: Nuttall, Glowacki and Clarke –*The Engineer* 31 October 2005)

The hydrogen economy:

hydrogen as a fuel

and *hydrogen as a coolant*

Fusion Island
– the concept so far

On *Fusion Island* hydrogen will be:

• The product sold commercially – in cryogenic form. Plan for an LH2 supply chain (by tanker) to forecourts where off-gas H2 is sold for high pressure vehicle fuelling. Merchant ships H2 fuelled - akin to LNG.

• <u>LH2 MgB2 magnets</u> might reduce costs compared to conventional SC technology – 20K not 4.2K – no He supply security risk. Option to run with LHe if need be. Key insights have come here from Dr Bartek Glowacki

• A means to avoid the machine ever taking power from the grid – 100MWe on-site H2 GT generation (?) with accumulation capacity (for restart, safety case and near-continuous cryo-plant operation).

Fusion Island
– the concept so far,
… continued

On *Fusion Island* hydrogen will be:

•A link to an industry willing to invest – deployment funding from the oil majors?

•An opportunity for sophisticated superconducting energy accumulation (flywheel technology and SC magnetic energy storage [SMES])

• No need for continuous operations or high levels of machine reliability – product is stored and shipped providing a buffer against intermittency of operation.

• Use of LH2 removes a possible security of supply risk to fusion – the long term availability of helium.

•Note also possible valuable by-products e.g. Liquid Oxygen for Oxyfuel combustion (facilitating CCS), or ammonia.

Why Might Fusion-Hydrogen Fit Business Needs Well?

- It avoids the need to establish high levels of reliability – this allows Fusion for Hydrogen to be deployed more quickly than fusion for electricity?
- Fusion for Hydrogen possesses better option characteristics for businesses, possibly allowing some key business risks to be hedged – e.g multiple products are possible.
- Planning for pulsed operations may allow for simpler and cheaper tokamak designs

Fusion Island Developments 2007

11 & 12 April 2007 at Culham Science Centre and Worcester College Oxford we hosted a UK Energy Research Centre funded workshop entitled ***Sustainable Hydrogen production – a role for fusion?***

The workshop was organised by Richard Clarke (UKAEA), Geoff Dutton (RAL), Miles Seaman (I.Chem E.), Jane Palmer (UK-ERC) and me. A record of the meeting is available from the UK-ERC Meeting Place website at:

http://www.ukerc.ac.uk/TheMeetingPlace/Activities/Activities2007/0704SustHydrogenProduction.aspx

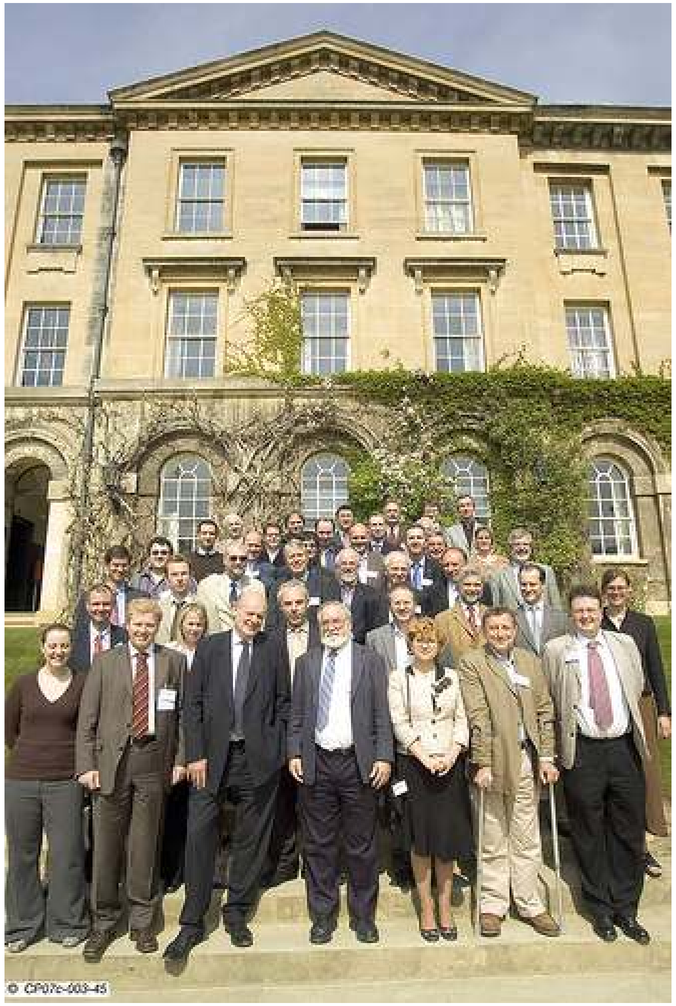


Photo courtesy UKAEA Culham Science Centre

Fusion Island Research Challenges

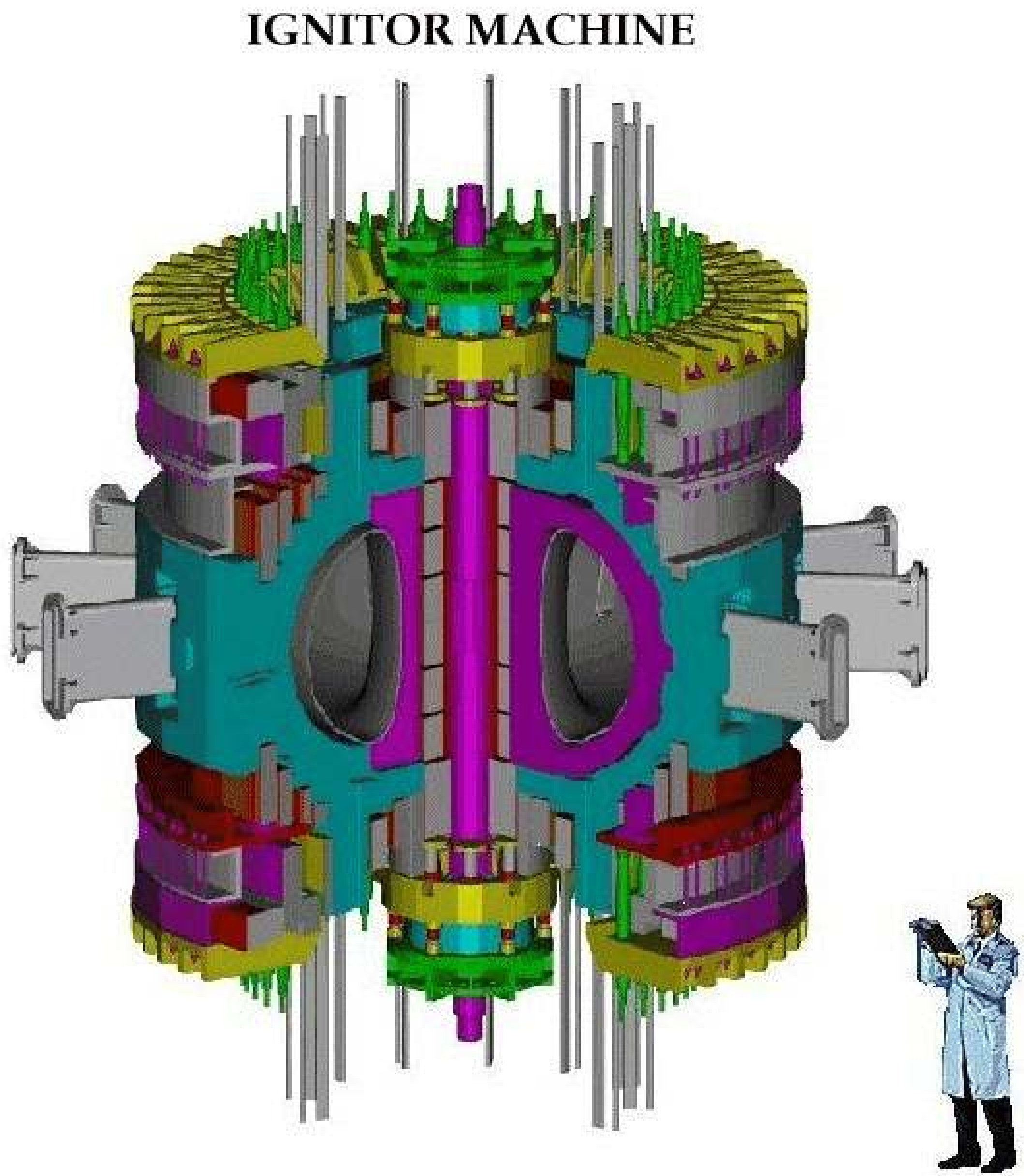
The main R&D questions for Fusion Island are:

- What level of availability of fusion energy is required?
- What should the blanket temperature be 500ºC or 800ºC?
- What should the heat exchange medium be – liquid metal or gas?
- How large should the machine be?
- Is liquid hydrogen cryogenic superconductivity sufficient for fusion?

Fusion Island Sources of Inspiration

We seek inspiration from the simplest fusion tokamak concepts such as the “Ignitor” and “Fire-6” concepts developed at MIT.

The cheapest and easiest route to fusion ignition?

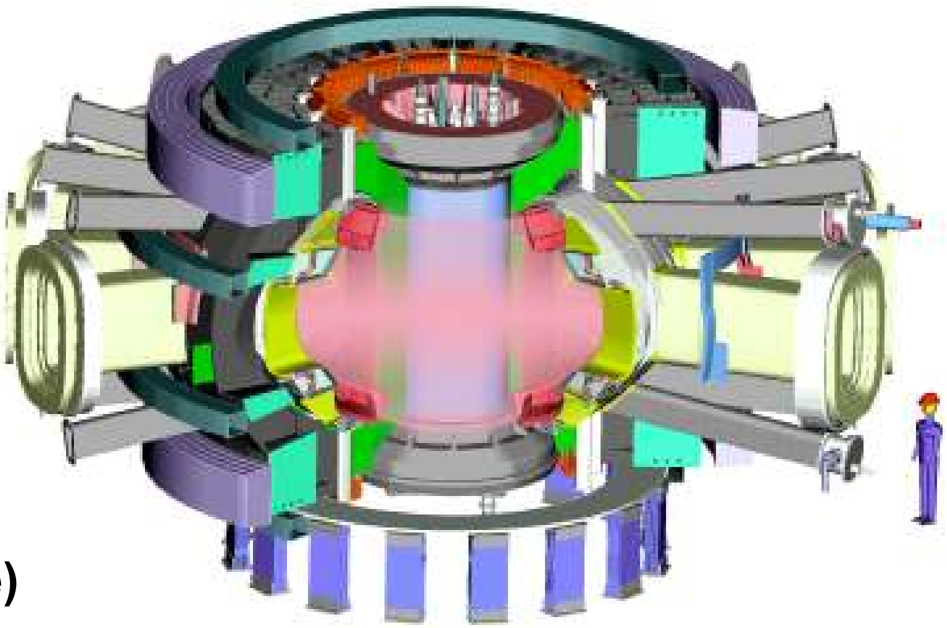


Ignitor concept leader Bruno Coppi MIT

Another MIT-related low cost route to fusion:

Fusion Ignition Research Experiment (FIRE)

- R = 2.14 m, a = 0.595 m
- B = 10 T, (~ 6.5 T, AT)
- I_p = 7.7 MA, (~ 5 MA, AT)
- P_{ICRF} = 20 MW
- $P_{LHCD} \leq$ 30 MW (Upgrade)
- P_{fusion} ~ 150 MW
- Q ≈ 10, (5 - 10, AT)
- Burn time ≈ 20s (2 τ_{CR} - Hmode)
  ≈ 40s (< 5 τ_{CR} - AT)
- Tokamak Cost = $350M (FY02)
- Total Project Cost = $1.2B (FY02)



1,400 tonne
LN cooled coils

Mission: to attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas

Source: Dale Meade PPPL an ARIES project in collaboration with MIT PSFC

Fusion Island would be a Source of Hydrogen, but it is also something else…

Fusion Island is a radical vision for an accelerated path to commercial fusion energy.

- It aims to consider low-cost innovative approaches to cryogenics and superconductivity
- It aims to consider simple, cheap tokamak concepts optimised for process heat applications
- and It aims to be the first major fusion project initiated and funded using private industry resources.

Energy is a commercial commodity traded in international and increasingly competitive markets. At some point fusion will need to transition from government push to private pull – we hope to play a role in that transition. We believe it might come sooner than most people expect

Are there any Low Hanging Fruit For Industry?

Our pitch to industry is currently focussing on hydrogen-cryomagnetics for diverse high-field and pulsed applications.

We are interested in a range of SC and normal conductors cooled by LH2

These applications will occur on timescales shorter than Fusion island.

Such approaches include issues of comparative cost and safety.

Summary & Conclusions I

Fusion for hydrogen production has the possibility of being:

The Best Early Use of Fusion?

I.e. easier, faster, cheaper and better matched to energy industry needs than fusion for electricity?

and

The Best Way to make Hydrogen?

I.e. cleaner, safer, at a larger scale, more suitable for northern Europe, with better security of fuel supply and better matched to existing industry supply chains than other routes to hydrogen?

Summary & Conclusions II

Will fusion for hydrogen be deployed commercially before fusion for electricity?

Well, of course we don't know …

The issues are both technical and institutional, but we suggest that at least the possibility should be considered.

Thank you

Acknowledgements

with many thanks to:

- UK-Energy Research Centre Meeting Point
- *CESSA: Coordinating Energy Security in Supply Activities* (EC, DG Research FP6 Contract No. 044383)
- Cambridge-MIT Institute Partnership Programme
- *The Engineer* magazine
- East of England Energy Group Innovation Awards
- University of Cambridge RSD Partnerships Team
- UKAEA Fusion
- Linde-BOC & UKAEA – for Helium Resources project
- Zhiming Cai for research work on Helium Resources project
- Professor Malcolm Haines, Imperial College for advice