Strengthening and Accelerating the Development of Fusion Power

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INTRODUCTION

- It is quite easy to convince (most) people of the importance of developing **fusion** as **(potentially) an environmentally responsible source of almost limitless energy**
- **My favourite argument:**

  The Lithium in one laptop battery + 45 litres of water (used to fuel a fusion power station) → 200,000 KW-hrs

  = (total US electricity production for 15 years)/(population)

  – *with no CO_2*

  ⇨ **unless/until we find an obstacle, this is sufficient reason to develop fusion**
- This always raises the questions
  – **How much longer will it take?**
  – **If it's so great, why's it taking so long?**
  – **How can we strengthen and accelerate the path to fusion power?**
  – **Is a major speed-up possible with an Apollo project approach?**

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How Much Longer?

- **Reference "Fast Track" programme** (no major set backs):

10 years	+ 10 years	+ 10 years ≈ **30-35 years**
build ITER + IFMIF	*exploit ITER + IFMIF*	*build DEMO*

  + 15 (?) years → widespread deployment ("commercial fusion power") ***which is of course the final goal***

- This timetable is **underwritten by global collaboration in building ITER** and **a Japan-EU collaboration** with is carrying out **design and prototyping work for IFMIF** *(and **assumes** an early decision to build IFMIF)*

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Why so long?

- **Cannot demonstrate on a small scale**: (power out)/(power to operate) grows faster than (size of fusion device)^2 – need GW scale to be viable

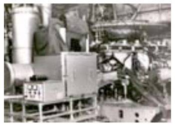
- **Not funded with any urgency** – otherwise from agreement on basic geometry in 1969, could have reached today's position 15 years ago (note that energy R&D boosted by oil crisis but then collapsed)

- **It is very challenging**
  - need to heat ~ 2000 m^3 of gas to over 100 M ^{0}C, without it touching the walls
  - find robust materials with which to make the walls (able to withstand intense neutron bombardment and heat loads)
  - ensure reliability of very complex system

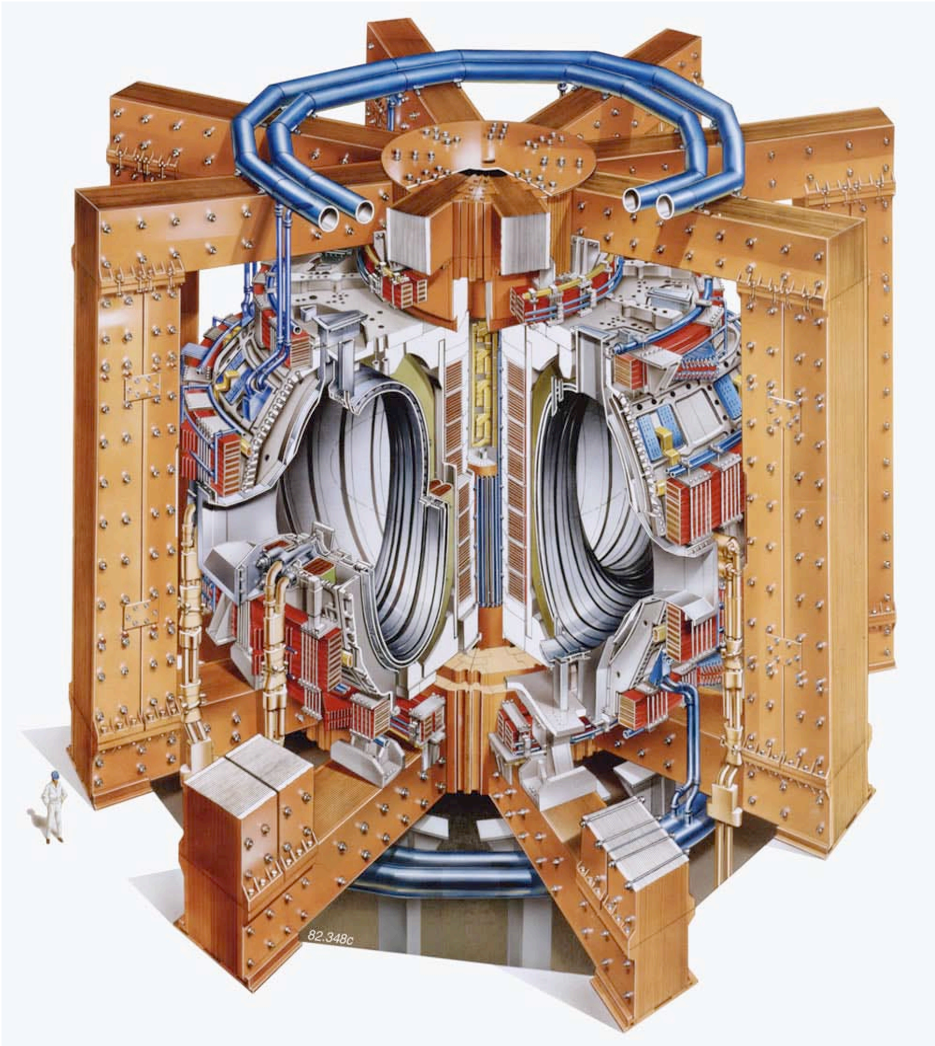
Nevertheless huge progress: from T3 to JET and from JET to ITER (next 2 slides)

Progress in Fusion

has been enormous, but even **JET** (currently the world's leading fusion research facility) is not large enough to be a (net) source of power



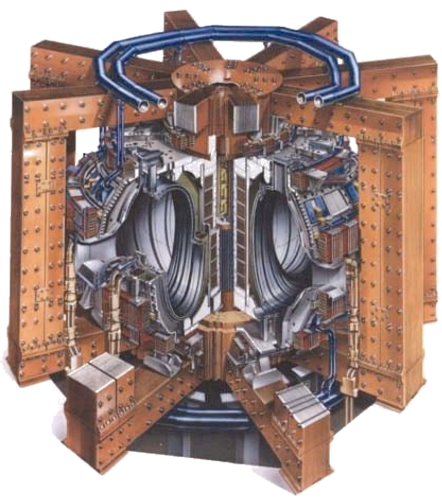
T3: Volume ~1 m^3
Temperature ~ 3 M ^{0}C
Established tokamak as best configuration (1969)

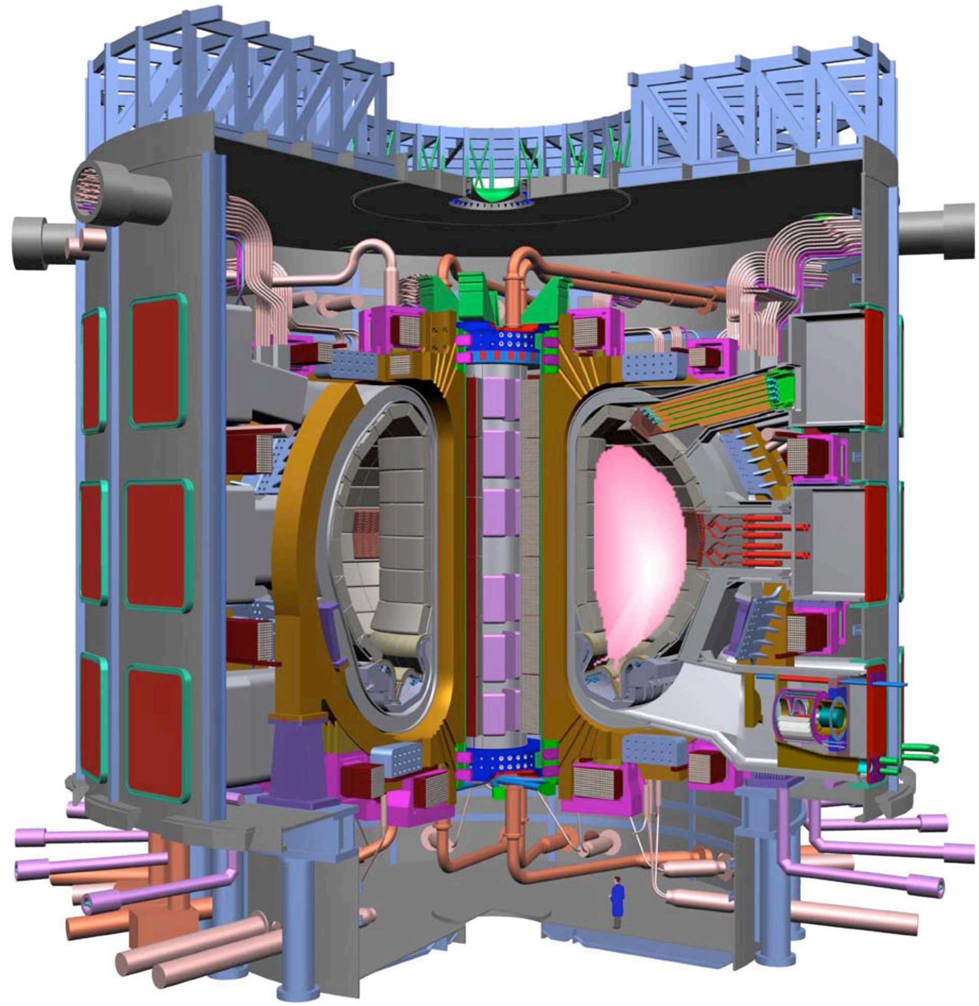


JET: Volume ~100 m^3
Temperature ~ 150 M ^{0}C
World record (16 MW) for fusion power (1997)

ITER

JET (to scale)





Strengthening the Programme

1) **'Gap Analysis'** - identify issues that definitely cannot be resolved pre-DEMO with existing and approved/expected devices (including ITER, JT60-SA and IFMIF) & **plug gaps**

   Will see that the open issues ~ enabling technologies and materials and component performance and lifetimes

   Then consider reinforcing programme in areas where success is least certain

2) **Looking beyond DEMO, consider cost of fusion generated electricity as a function of parameters**

   Will see that the most critical* parameter is the availability of the plant (as found for fission)

   *apart from the cost of borrowing capital

⇨ **Technology and reliability are the key issues for long-term viability**

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Gap Analysis

	Issue	Approved devices	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
Plasma performance	Disruption avoidance	2	3		R	R	R
	Steady -state operation	2	3		r	r	r
	Divertor performance	1	3		R	R	R
	Burning plasma (Q>10)		3		R	R	R
	Start up	1	3		R	R	R
	Power plant plasma performance	1	3		r	R	R
Enabling technologies	Superconducting machine	2	3		R	R	R
	Heating, current drive and fuelling	1	2		3	R	R
	Power plant diagnostics & control	1	2		r	R	R
	Tritium inventory control & processing	1	3		R	R	R
	Remote ha ndling	1	2		R	R	R
Materials, Component performance & lifetime	Materials characterisation			3	R	R	R
	Plasma -facing surface	1	2		3	4	R
	FW/blanket/divertor materials		1	1	3	4	R
	FW/blanket/divertor components		1	1	2	3	R
	T self sufficiency		1		3	R	R
Final Goal	Licensing for power plant	1	2	1	3	4	R
	Electricity generation at high availability				1	3	R

Output:		
	1	Will help to resolve the issue
	2	May resolve the issue
	3	Should resolve t he issue
	4	Must resolve the issue

Input:		
	r	Solution is desirable
	R	Solution is a requirement

UKAEA September 2007 (revised/improved version of original table in UKAEA FUS 521, 2005).

The Cost of Fusion Generated Electricity

varies (according to David Ward's semi-empirical formula) **as:**

$$\text{coe} \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta_{th}^{\;0.5}\, P_e^{\;0.4}\, \beta_N^{\;0.4}\, N^{0.3}}$$

A - plant availability

η_{th} - thermodynamic efficiency

P_e - net electrical output of the plant (which can be chosen)

β_N - normalised plasma pressure

N - normalised plasma density

So if design value for β_N changed from 3 →2 ⇨ 18% more expensive,

but A = 75% → 50% ⇨ 28% more expensive

[It seems there are no "show-stopping" minimum values associated with any of these parameters, although all are potential degraders of economic performance]

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Conclusions from Gap Analysis + CoE

- **ITER is key for resolving plasma physics issues,** but ensuring success will need the support of other devices (JT60-SA, KSTAR, EAST, DIIID…) and a flexible ITER programme
- **IFMIF** ~ narrow but **crucial role**
- **Major gaps in enabling technologies + component performance/ lifetime issues**. **Need to identify necessary test facilities,** e.g. magnets, heating & current drive, remote handling, heat flux, corrosion testing …
- **Long term viability ~ availability** (reliability, buildability, operability and maintainability)
- A **Component Test Facility** (volume neutron source) which could test whole components in fusion power station conditions (highly desirable before DEMO, *if possible*) **will be needed in parallel to and/or beyond DEMO** (ensure rapid advent of reliable, large-scale fusion power + continue optimisation for second generation fusion power stations)

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Component Test Facility

= a relatively small/flexible (compared to ITER) **driven device** that would **test, develop and qualify whole components* in close to full power station conditions** (neutrons [1MW/m^2 on ~ 10m^2, 1-2 weeks continuous operation, Total fluence ~ 4MW-yr/m^2], heat and particle fluxes, e-m fields, corrosion from coolant, . ..)

* breeding blankets (key component – but none has ever been built or tested), plasma facing components, welds & joints, . . .

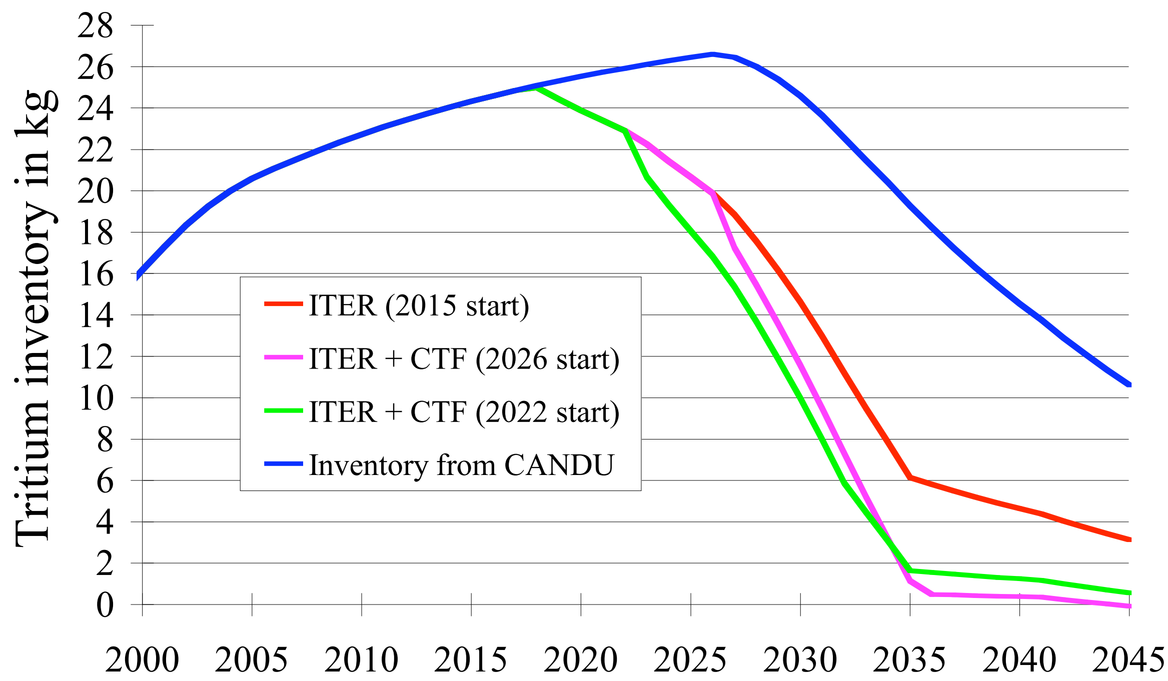
☹ parameters + availability very hard to achieve, but

☺ trying to achieve would provide a focus for developing many of the systems needed in a fusion power station

■ **Note need to severely limit tritium consumption *or* assume success in generating tritium** *(one of the things a CTF is supposed to develop and test)*

World tritium supply from Candus – not allowing for use by ITER – 26 kgs in 2026

Tritium From Canadian Candu Reactors

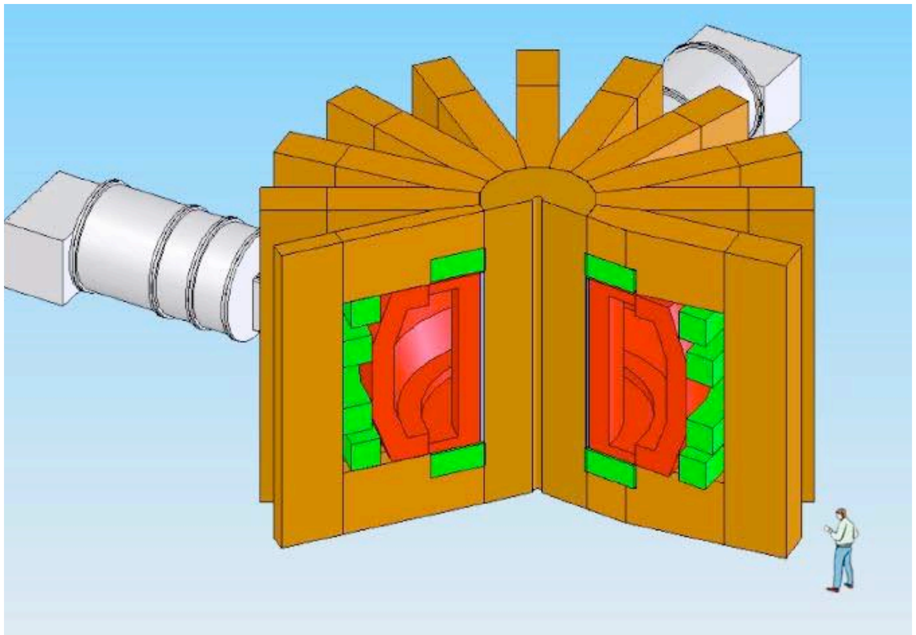


Note -1 GW of fusion power requires burning 56 kgs pa

- the CTF line is for a very small device (35 MW fusion power, operating 30% of the time) burning only 600 g pa
- there are other sources of tritium
- a fission reactor can (at a cost) produce 2-3 kg of tritium pa: thought should be given soon to producing enough tritium for fusion development

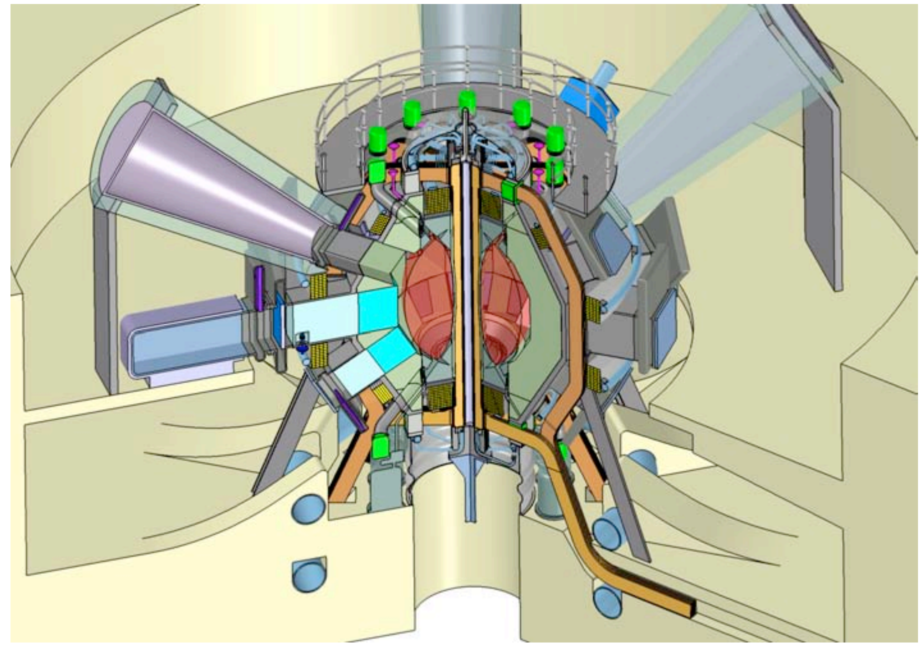
Possible CTFs

The GA FDA



Burns 5 kgs of tritium/year
Operation consumes 500MW of power

The Culham ST CTF



More compact: only uses 0.6 kgs of tritium/year, but operation still consumes 400MW of power. ***Very challenging.***

Speeding up Fusion Development

- **Have discussed strengthening, and speeding up, the programme by greater investment in technology**, including construction of a CTF

- **What about reducing the time to DEMO?**

  Can tinker with the 10 + 10 + 10 = 30-35 years time to DEMO, *but cannot shorten it radically*

  except by starting DEMO construction *without waiting for (full) results from ITER and IFMIF* – a possibility raised* *as an option to be studied* by a **DEMO/CTF Design Group with substantial industrial participation** (which should be set up as soon as money and manpower permit without a negative impact on ITER)

* by group convened to provide input to the EU's **S**trategic **E**nergy **T**echnology **P**lan: C Llewellyn Smith, E Bogusch, M Gaube, F Gnesotto, G Marbach , J Pamela, M Q Tran, H Zohm - *all participating as individuals, not as representatives of their parent organisations*

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Obvious Questions

- Why a DEMO design group with industrial involvement?
- What might and Early DEMO ('EDEMO') be like?
- Would building EDEMO be desirable?

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Why a DEMO Design Group with Industrial Involvement?

- **Early/major involvement of industry would bring a stronger culture of 'design for buildabilty, operability, reliability and maintainability' into fusion** (cf remarks on the importance of availability). Research scientist will aim for the best, but according to Voltaire: "Le mieux est l'ennemi du bien'/ "Il meglio è l'inimico del bene" *("The best is the enemy of the good")*

- **Currently we are developing** (or planning to develop)

  - Plasma physics at existing devices…ITER, JT-60-SA,…

  - Materials in parallel at IFMIF

  - Technology/reliability in a 'just in time/just enough' manner for ITER…

  Really serious **DEMO design/R&D would put us on a parallel track in attacking all three sets of problems**

  ⇨ **ensure DEMO works in ~ 30 years** (not 35 years or more; *perhaps* faster with EDEMO), **and speed up the subsequent large scale deployment of fusion power**

What might and Early DEMO ('EDEMO) be like?

- **The 'canonical' DEMO**, which **would follow ITER and IFMIF**, is supposed to demonstrate electricity production with performance (plasma, availability, materials, cost/kW-hr) close to that required for a "commercial" fusion power station

- **EDEMO have less ambitious goals** (plasma performance ~ ITER and known materials [ferritic steel] in a device that might initially be pulsed [~ 5-10 hours]) ***but would demonstrate electricity production earlier***

  Such a device could *(in the most aggressive imaginable case, with an Apollo project approach and an immediate start)* demonstrate electricity production in ~ 20 years

- **The proposed DEMO design group should study whether** *(building on expected results from ITER, IFMIF, JT60-SA,...)* EDEMO could be followed by high performance 'commercial' fusion power stations without an intermediate step

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Would Building EDEMO be Desirable/speed up the advent of ("commercial") fusion?

Two aspects:

Political - *positive feedback* (greater support, industrial funding) *of early demonstration of electricity production could produce a significant net benefit* (but if EDEMO failed . . . ☠)

2. **Technical -** obvious advantages of 'learning by doing' and necessity of a holistic approach ***but***

   - the answer would be 'no' if an additional step ("PROTO") was needed after EDEMO **unless**

   the "conventional" DEMO development/construction programme continued in parallel, somewhere in the world **as part of a global cooperative programme** (would need sufficient funding, and *enough expert manpower*, *which is the biggest non-financial resource limitation to a crash fusion development programme)*

Major Acceleration of Fusion Development will require Greater International Cooperation

to provide sufficient: Expert manpower, Funding

Currently

- **ITER** – collaboration is providing greater combined expertise and more funding, but also there are also some obstacles
- **EU-Japan 'Broader Approach':**

  Total €678 M = ¥92 Bn (2005 prices) provided 50:50 by EU: Japan

  - IFMIF EVEDA: €150M – engineering design & prototyping
  - Activities @ IFERC*: €208M – provision of supercomputer
  - JT60-SA: €320M – enhancement of capabilities

  * International Fusion Energy Research Centre
- Numerous **bilateral cooperation agreements**, and **IEA Implementing Agreements**

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Expanded International Cooperation

- **Probably best to aim for cooperation** e.g. EDEMO in one region feeding experience into conventional DEMO in another *(collaboration in fully joint project would inevitably slow things down: site selection, negotiating terms of agreement, complex governance,…)*

- Dealing with **Intellectual Property** will be a formidable challenge

Nevertheless, I think the fusion community should aim to convince the world that a **much more aggressive approach to fusion development based on global cooperation would be justified** *(with a quick decision on IFMIF, early establishment of a DEMO design group, the ambition to build several DEMOs [maybe including an EDEMO],…)*

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- **A more aggressive approach is needed*** because of fusion's potential *as one of very few options* for large-scale , environmentally responsible power production as the climate change threat grows and fossil fuels dwindle

  *and to energy R&D funding generally. Funding (private + public) is half what it was in 1980, in real terms. Public funding is $10bn pa – less than 0.25% of the $4.5 trillion pa energy market. This is not even peanuts; the world peanut market is $24 bn pa ($1bn for nuts)

- **Three reasons why I think that a more aggressive approach might succeed:**
  1. The public increasingly understands the need for more energy options (cf Apollo project questions from audiences)

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2. **The evolving attitudes of Governments, e.g.**

- The Decision to build ITER
- The EU's adoption of the Fast Track, and the EC's encouragement of aggressive input to the SETP
- Korea will "start commercial generation of electricity from nuclear fusion by 2040" according to President Roh Moo-hyun
- "After 2031, Russia hopes to design and start building commercial fusion power plants" according to Velikhov

3. **Increasing support from opinion makers**, e.g. quotes (from the UK) on the next slide

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“Even if ITER runs well over budget, its spending level is unlikely to exceed $1bn per year, a small price to pay for a reasonable chance to give the world another energy option for a time when it will no longer be possible to burn fossil fuels on the profligate scale of the earlier 21st century” Leading article in the Financial Times, 25/11/04

“We need a portfolio of energy sources, with nuclear playing a major part, at least until fusion becomes a practical option . . . . Provided that engineering problems do not prevent the building of practical and efficient fusion power stations, I think that these will be the future source of electricity” James Lovelock, “The Revenge of Gaia” (2006)

“Priorities for scientific progress in the energy sector should include PV, biofuel conversion technologies, fusion, and materials science” Stern Review: The Economics of Climate Change (2006), which argued that energy R&D budgets should be doubled

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Conclusions

- **Fusion** development is **very challenging,** but the **potential is enormous**
- Thanks to ***international collaboration in ITER and IFMIF****, and assuming*

  - the absence of major adverse surprises

  - more investment in technology

  DEMO could be in operation in ~ 30 years
- The stakes are so high that **a much more aggressive approach would be justified**, *with even greater international collaboration to provide the necessary expertise and funding*, **designed to increase greatly the chance of success at a relatively early date**

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