The Abdus Salam
International Centre for Theoretical Physics

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Winter College on Optics and Energy

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Introduction to Laser Fusion: the HiPER project

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Introduction to Laser Fusion
The HiPER Project

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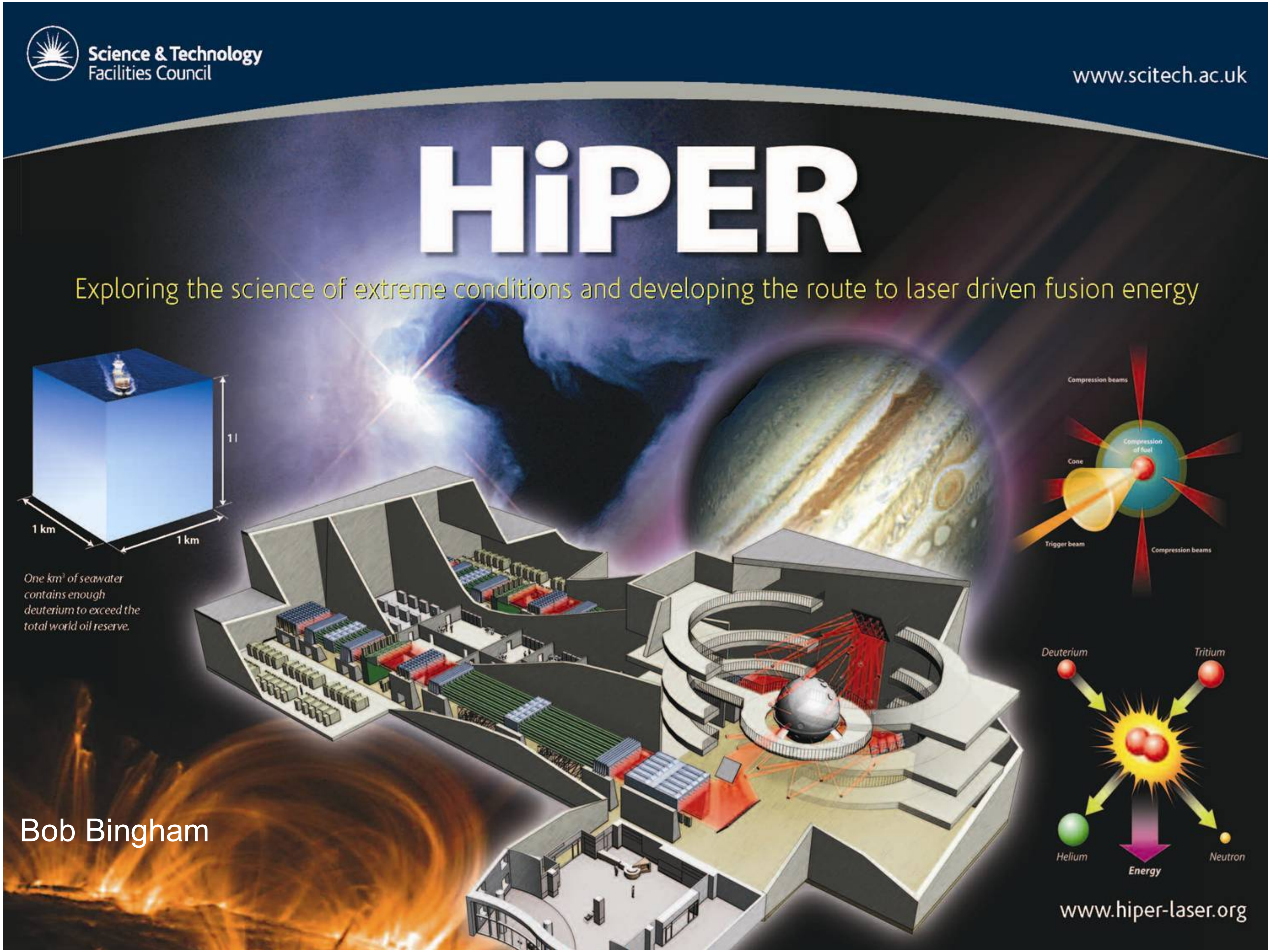
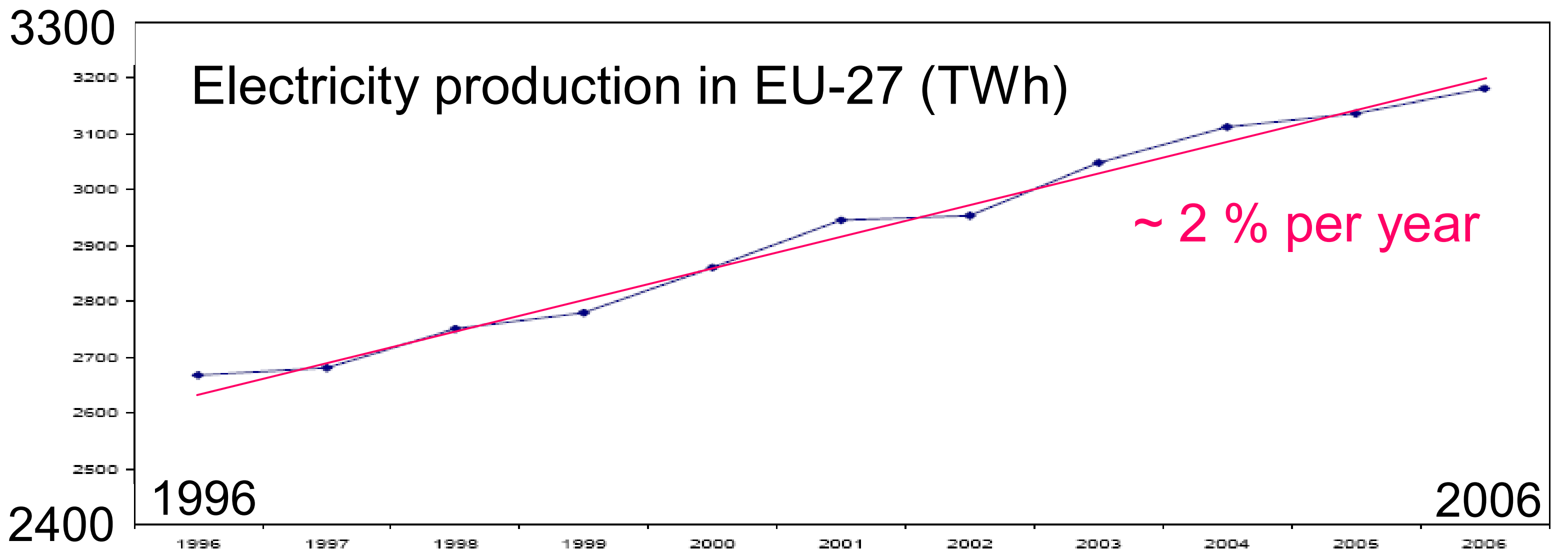

Science & Technology Facilities Council
www.scitech.ac.uk
HiPER
Exploring the science of extreme conditions and developing the route to laser driven fusion energy
1 l
1 km
1 km
One km³ of seawater contains enough deuterium to exceed the total world oil reserve.
Compression beams
Compression of fuel
Cone
Trigger beam
Compression beams
Deuterium
Tritium
Helium
Energy
Neutron
Bob Bingham
www.hiper-laser.org

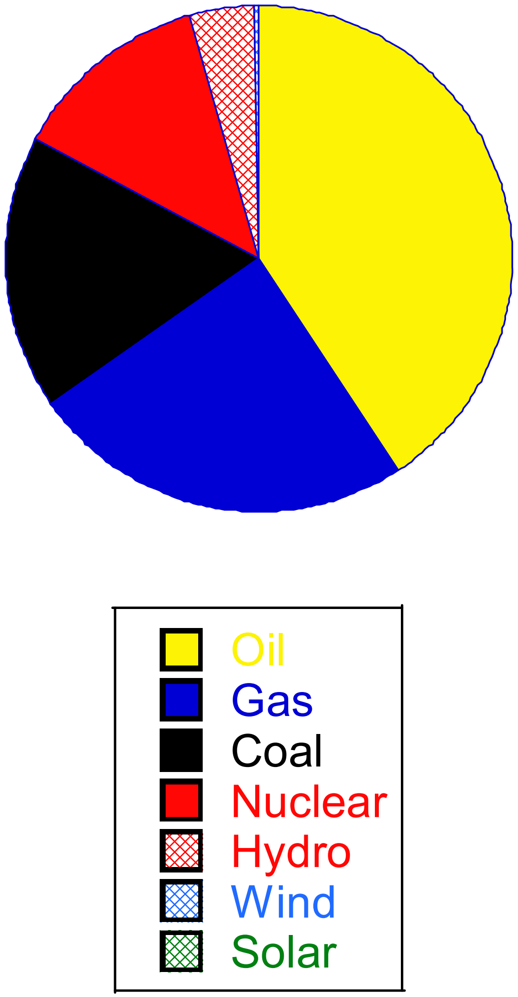
Ludwig Boltzmann:

"The struggle for existence is the struggle for available energy"



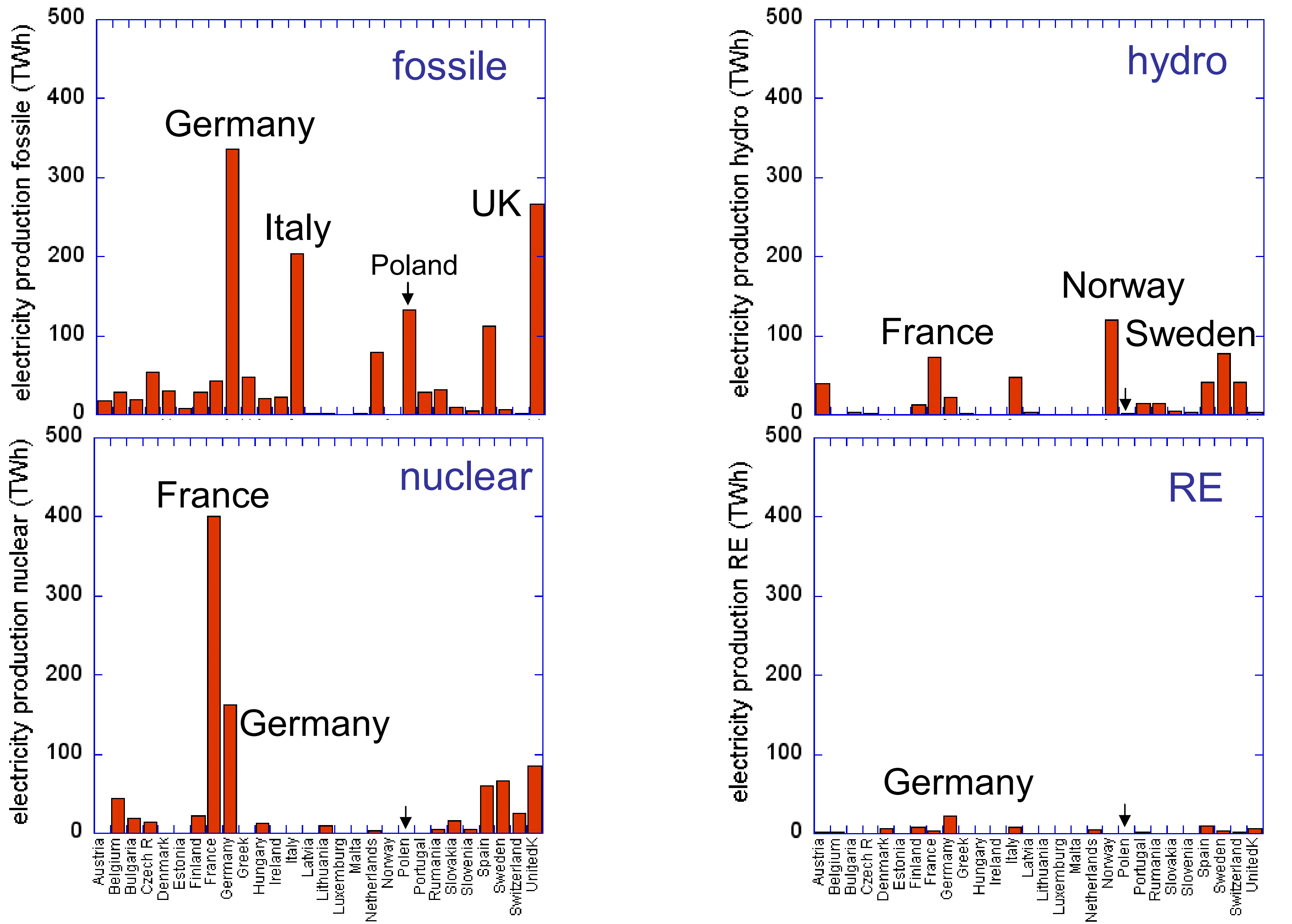
The overall EU energy situation (2006)

Primary energy consumption: 20×10^{12} kWh



	Oil	Gas	Coal
proved reserves / consumption	39.6 yr	63.7 yr	196 yr
share of reserves in EU-25	0.55 %	1.3 %	3.9 %
EU-25 production / EU-25 consumption	15.5 %	40.7 %	56.3 %

Electricity production from sources



Share of RE in electricity production in EU

The transition from a largely carbon based supply
To one based on RE is a tremdous task

Total electr. consumption(2005):	3138 TWh
Hydro:	341 TWh (11 %)
Wind:	71 TWh (2.3 %)
PV:	1.5 TWh (0.05 %)

The expansion of RE happens at different speeds within Europe.

No other EU country follows Germany in the enforced development of PV energy and wind energy .

The actual potential of Europe is not used
(Wind at the coast, PV in the south)

Energy Future

Europe is strongly dependent on energy import.

This dependence will grow and will be specifically serious for the gas market.

A warning seems appropriate for those who recommend to meet the Kyoto goals by replacing coal by gas

The CO_2-fate of the earth is not in the hands of Europe

Fusion – Energy for the future.

The energy diversity of Europe

Electricity production in Europe's countries ranges from

~ 100% carbon-based to ~ 100% carbon-free

The present situation shows how gigantic the task is

to replace the fossil fuels by Renewables

specifically with the boundary condition to exclude nuclear energy

The role of physics in energy technologies

Measured in a scale from 0 to 3:

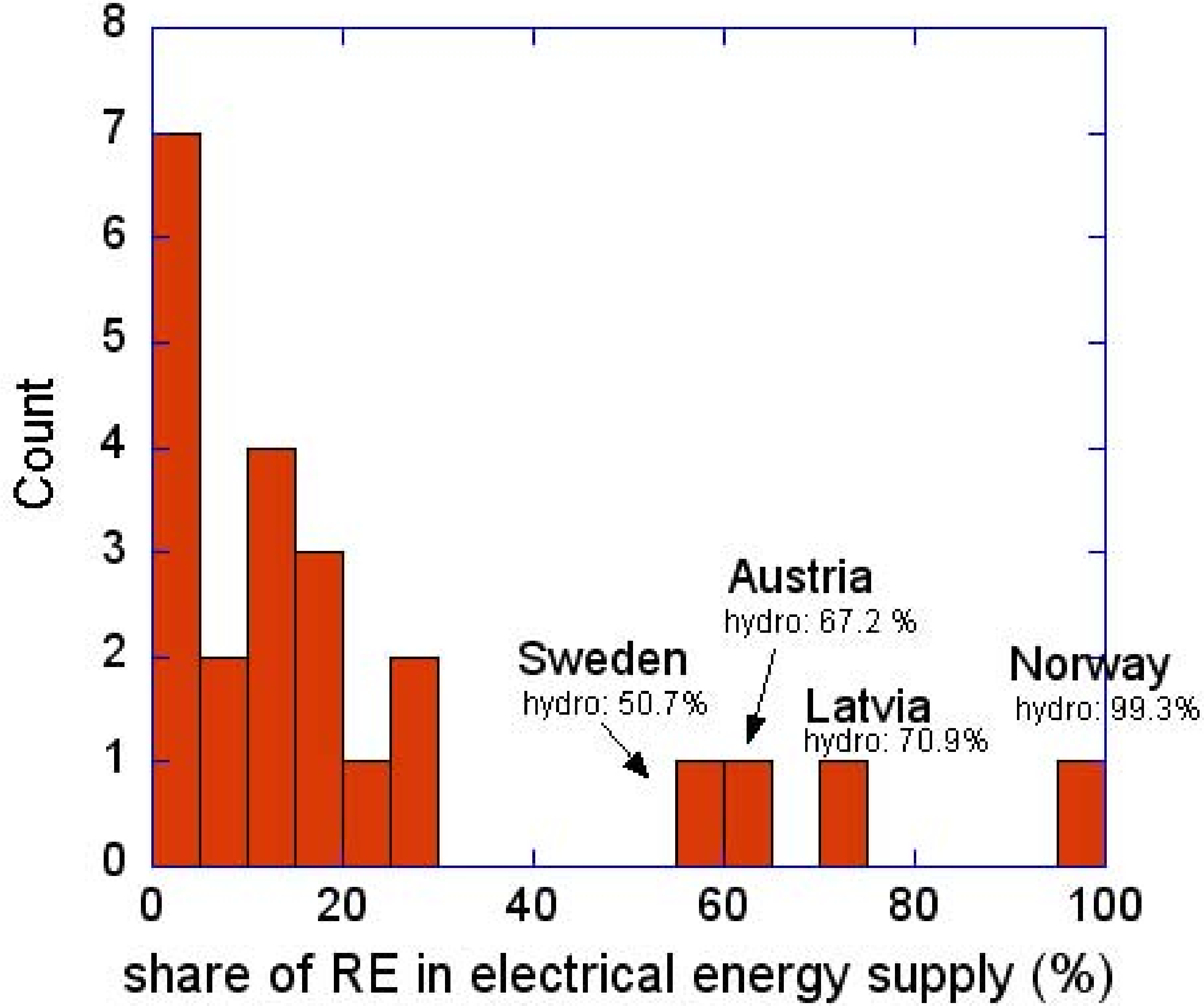
CO2-free electricity sources	
on-off-shore wind	1
PV	3
solar thermal	0
hydro-electricity	0
wave- and tidal power	2
geo-thermal	1
nuclear fission	3
nuclear fusion	3

electricity saving	2
electricity distribution	
conventional technology	2
HT-superconductor	3
electricity storage	
conventional measures	2
hydrogen	2
HT-superconductor	3
conversion into electricity	2

HiPER

Renewable electricity in EU
Distribution of RE in EU countries

Number of countries with the following share of RE in electricity production



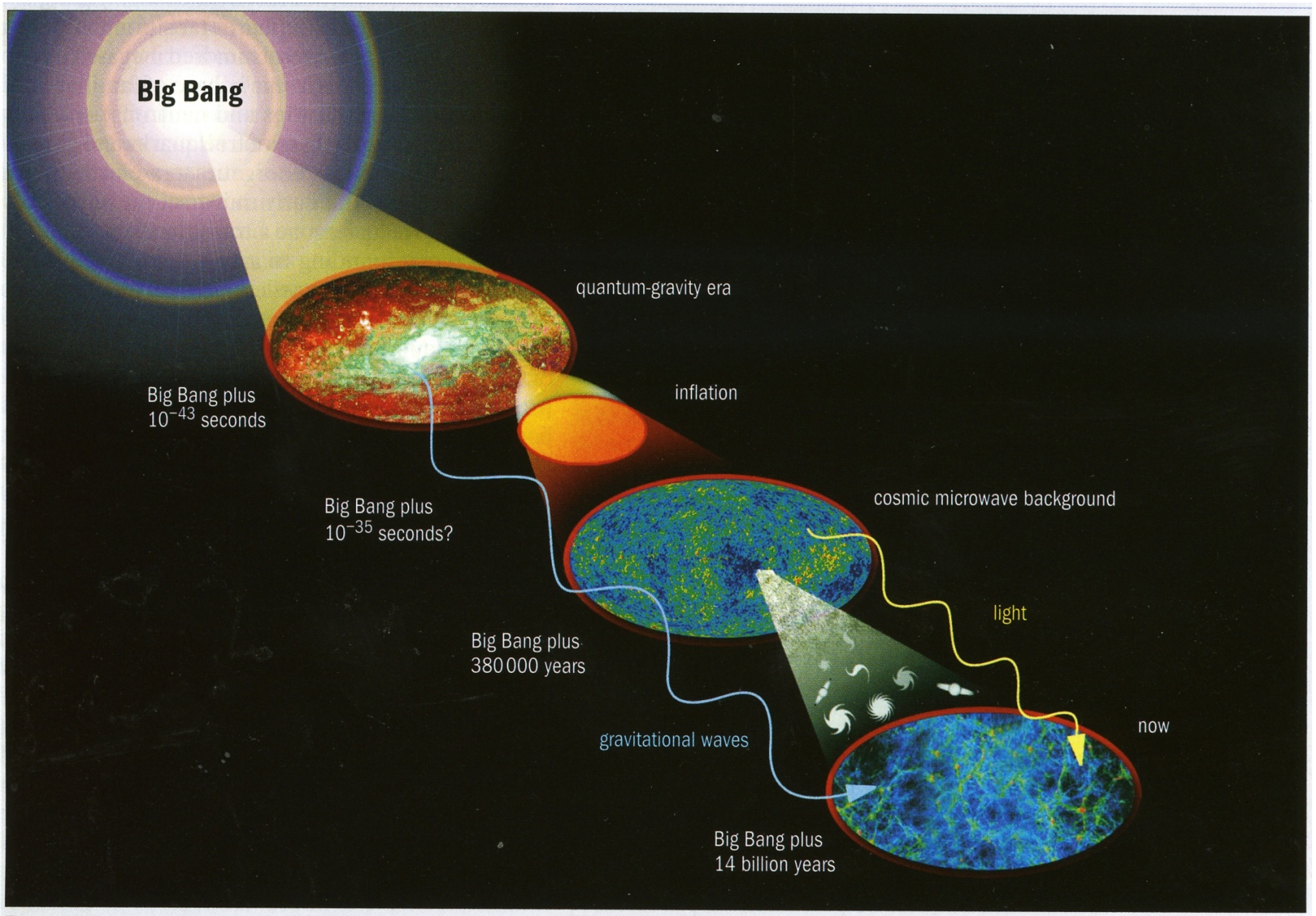
Why Fusion?

- Fusion energy

$$D + T = He + n + 17.6\ MeV$$

- Supply of fuel is almost limitless
  - Deuterium ~60 billion years
  - Lithium (tritium) ~30 million years

Cosmic Evolution



The universe has undergone several dramatic changes in its 13.7 billion-year history, although our knowledge of the early universe contains some gaps. The cosmic microwave background reveals the intensity and polarization of primordial light as it was 380 000 years after the Big Bang when the universe became transparent to light. We therefore cannot use electromagnetic radiation to directly study the universe before this time, although fluctuations in the temperature and polarization of the microwave background on very large scales do preserve much earlier events that took place during cosmic inflation. Gravitational waves, on the other hand, propagate directly to our detectors from the very beginning of time itself, carrying information about cosmic events on all scales throughout cosmic history.

Origin of the Chemical Elements: Fusion

Phys Rev 1st April 1948 Alpher, Bethe, Gamow

→ Hot Big Bang, $\alpha\beta\gamma$. (Shown to be in Error)

How hot was the Big Bang? No. of photons/baryons

Ratio of baryons to photons ~ $6\text{x}10^{-10}$

$$\eta = \frac{\text{Baryon No.}}{\text{Photon No.}}$$

Small η - hot Big Bang → No nucleosynthesis

Large η - cold Big Bang → most nucleons end up in most stable state (largest binding energy) i.e. iron.

HiPER Amazing Chain

- An amazing chain of events was unleashed by the Big Bang, culminating some 14 billion years later in us and everything we see around us!

- The first matter to appear would be the quarks and leptons.

- These would quickly (microseconds!) be assembled into protons and neutrons.

  and the cooling fireball of the Big Bang "cooked" the first elements (nuclei) – deuterium, helium, helium-3 and lithium …

  … and nothing else –

- the rest of the periodic table of elements requires STARS to manufacture them – maybe a billion years later!

- The first elements are the initial building blocks of fusion in stars.


Could we build a miniature sun on earth?
Could we use it to power our civilization?
NIF-0205-10343L2

Short tutorial on fusion

HiPER

Sun: 4 p ⇨ He^4 + 27 MeV

Energy gain: $\Delta E = \Delta mc^2$

technical: d+t ⇨ He^4+n+ 17.6 MeV

t from breeding reaction:

n + ^7Li ⇨ ^4He + t + n‘ - 2.5 MeV

He (3.5 MeV) provides the internal heating => ash removal

n carries its energy (14.1 MeV) to the outside.

Ignition and burn conditions:

Source: $P_{heat} = n_d n_t \langle \sigma v \rangle_{fus} E_\alpha$

Radiation loss: $P_{brems} = c_1 n_e^2 Z_{eff} (k_B T)^{1/2}$

Conduction loss: $P_{loss} = 3n\, k_B T/\tau_E$

Tripple product

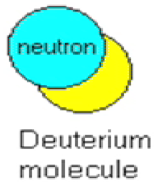
$n T \tau_E > 6\ 10^{21}\ m^{-3}$ keV s

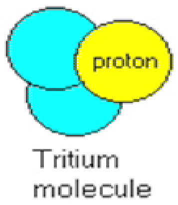
T=15 keV;

τ_E **is energy confinement time**

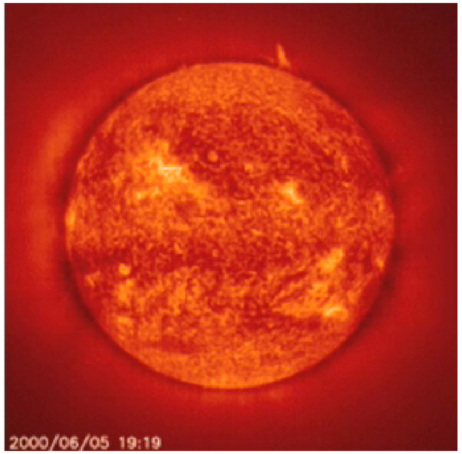
HiPER Fusion: energy for the future

movie





The Sun: a natural fusion reactor



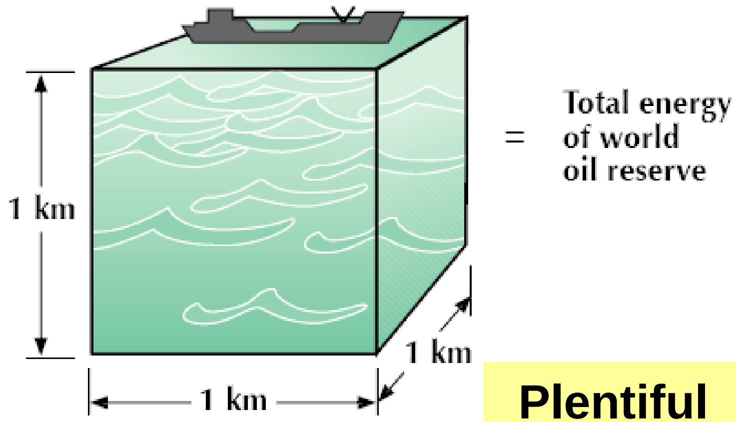
movie

$$\mathrm{D + T \rightarrow He + n}$$

3.5 + 14.1 MeV

This energy is ~ a million times greater than in chemical reactions

$$E = mc^2$$



Plentiful fuel

The potential of fusion

Deuterium

Lithium

electricity for a family per year

HiPER

The case for fusion energy

- **Plentiful** fuel (scale = mankind's long term needs)
- **Energy Security** (extraction from seawater + breeding)
- **Clean** (no carbon emissions, and no long-lived radioactivity)
- **Safe** (no stored energy)
- **Complementary** solutions (magnetic, laser, …)
- **Hydrogen** production (for local energy)

A 100 ton (4200 Cu ft) ***COAL*** hopper runs a 1 GWe Power Plant for ***10 min***

Same hopper filled with ***IFE targets***: runs a 1 GWe Power Plant for ***7 years***

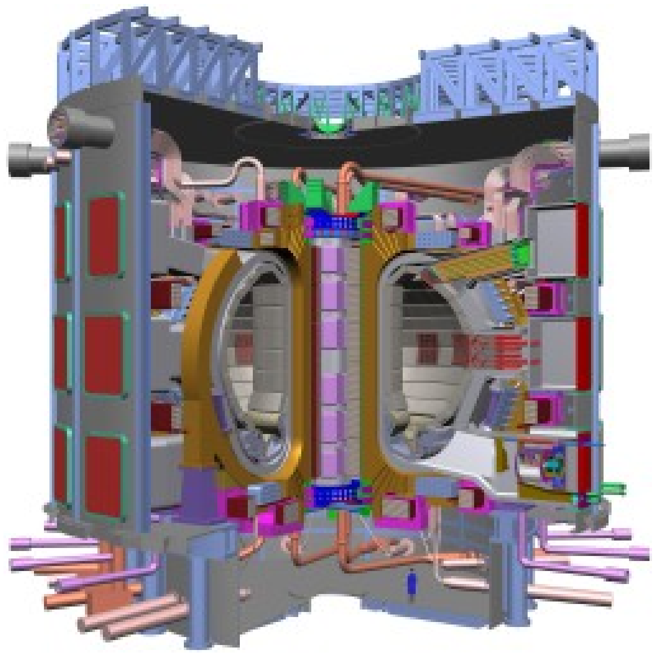
- Plasma Science is the science that underpins fusion.
- Economic Security & property
- Plasma Technology:-
  - Micro-electronics manufacture
  - Material hardening – e.g. Turbine blades, hip replacements
  - Lighting, plasma screens
  - Telecommunications
  - Hydrogen fuel production

- $2 trillion industry worldwide.

Fusion: We are entering a new era

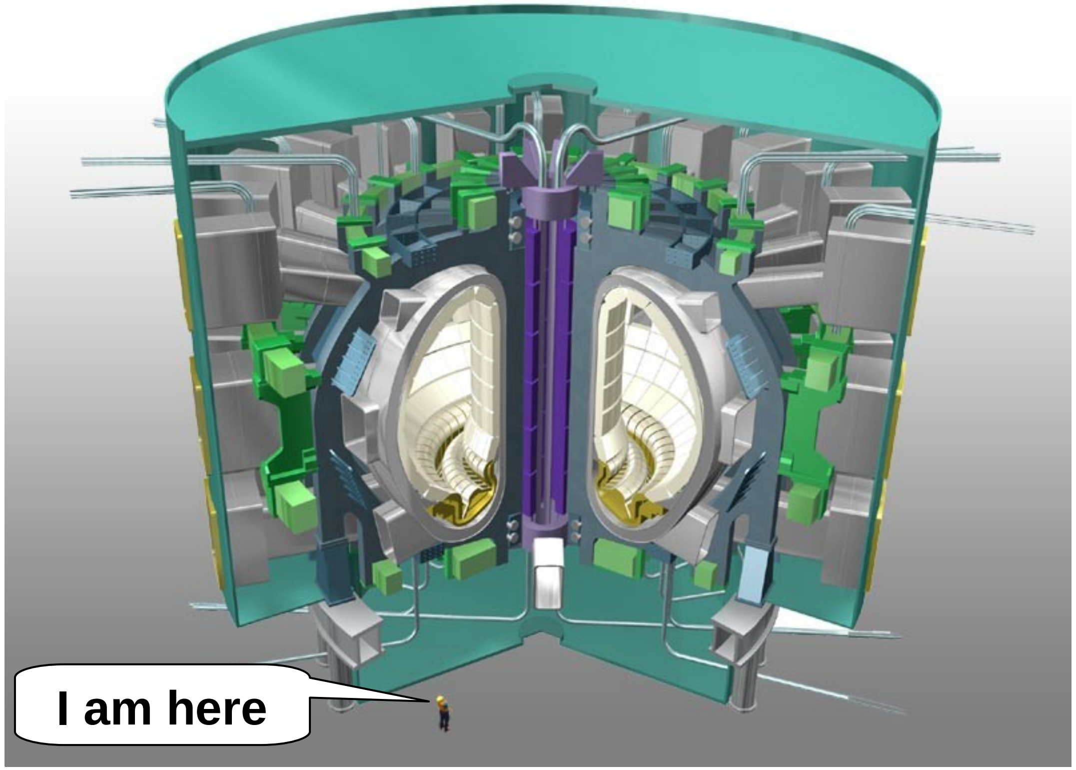
- Demonstration of net energy production from laser fusion within **the year.**
- Commitment to fusion via ITER, NIF, LMJ (multi-$B investment)
- **These are fundamental step-changes in our field**
- **Huge implications for our science and energy programmes**

- **The route for driving this field forwards is very clear**

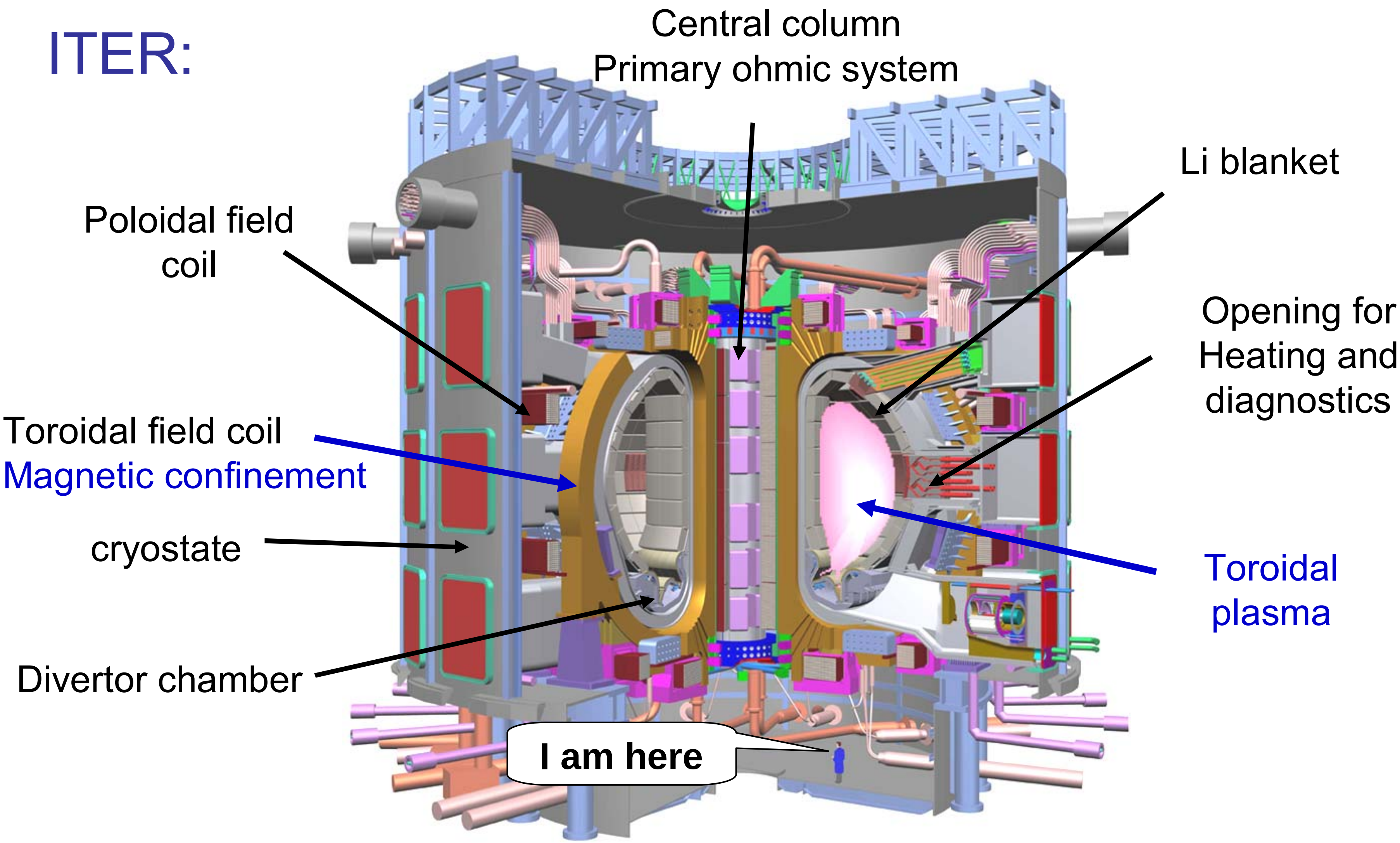


ITER

Fusion power	500 MW
Power amplification	10
External heating	70 MW
Pulse lenght	> 8 Min.
Plasma current	**15 MA**
Plasma volume	**840 m^3**
Plasma energy	350 MJ
Magnetic field (SC)	**6 T (12 T)**
Energy of the field (2 – 3 Eurofighter at Mach 2)	10 GJ

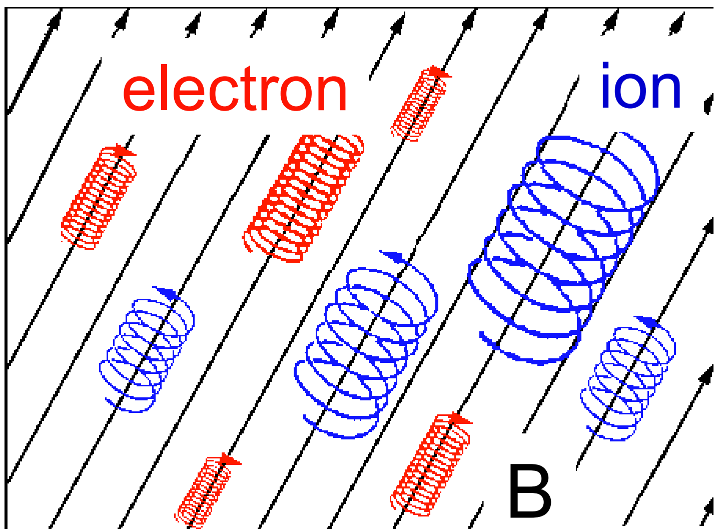


ITER:

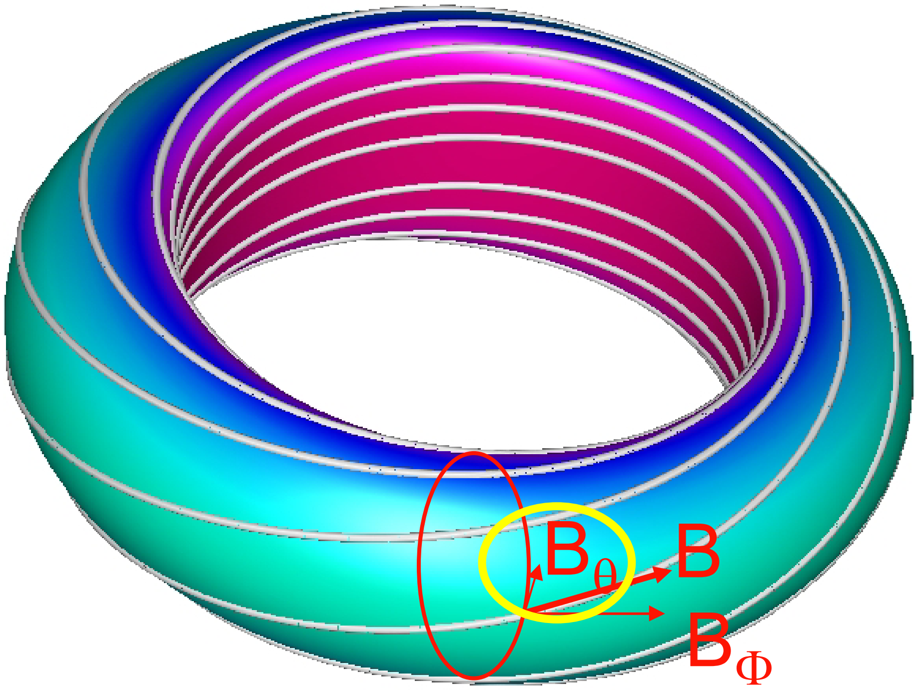


Goal: 0.5 GW Fusion power; pulsed (10 min)

Charged particles in magnetic field

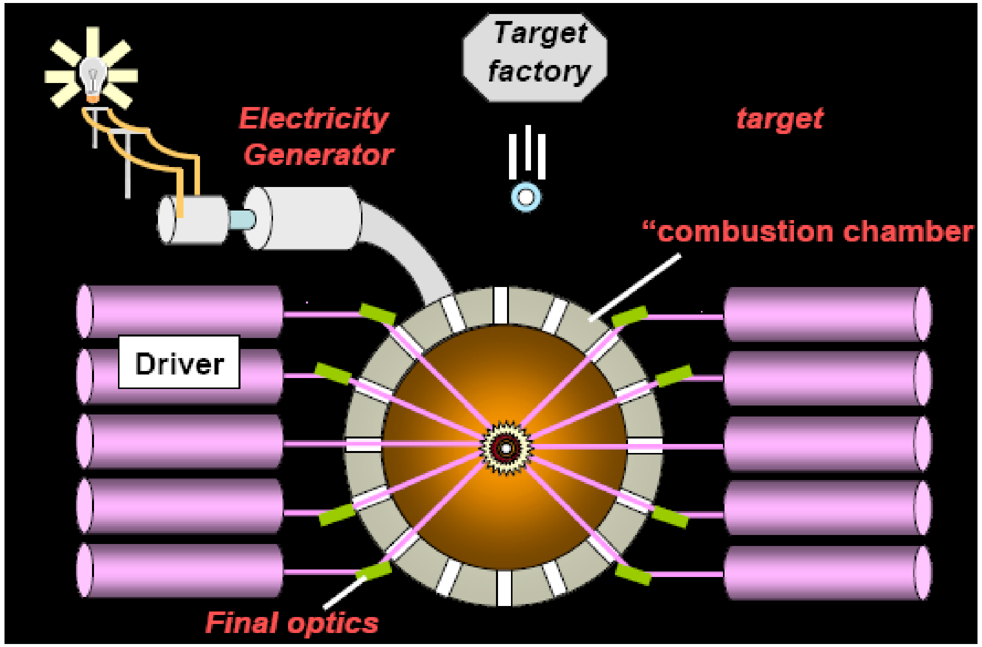


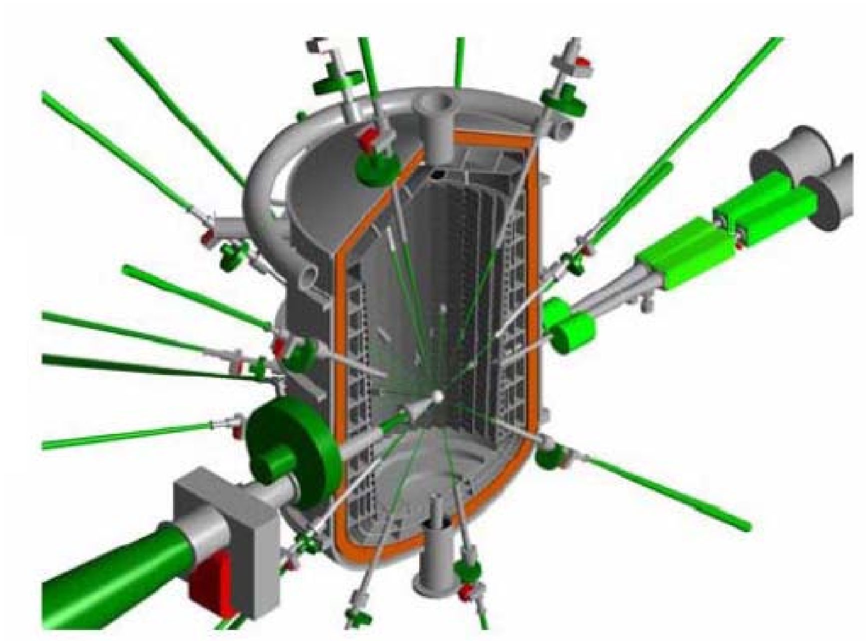
Geometry is a torus



Tokamak or Stellarator

Inertial (Laser) Fusion

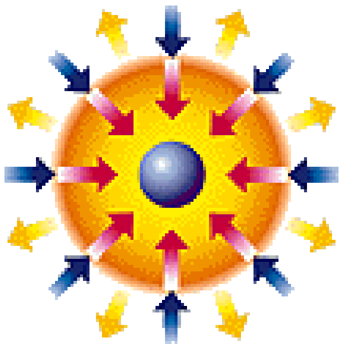




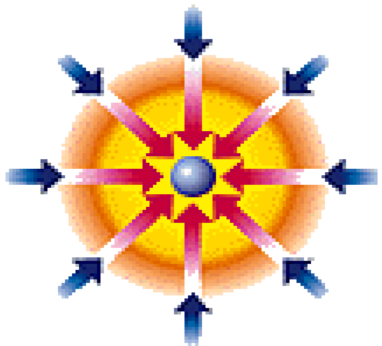
- Complementary approach - scale of the problem demands multiple options
- Inertial fusion has been proven to work (1980s)
- What now remains is to achieve this in the laboratory (2010) and define the route to commercial and scientific exploitation

Conventional approach to IFE

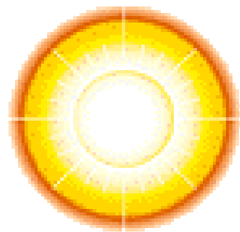
Lasers or X-rays symmetrically irradiate pellet



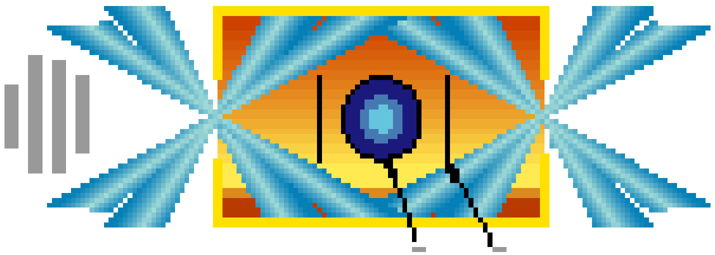
Hot plasma expands into vacuum causing shell to implode with high velocity



Material is compressed to ~1000 gcm^{-3}



Hot spark formed at the centre of the fuel by convergence of accurately timed shock waves



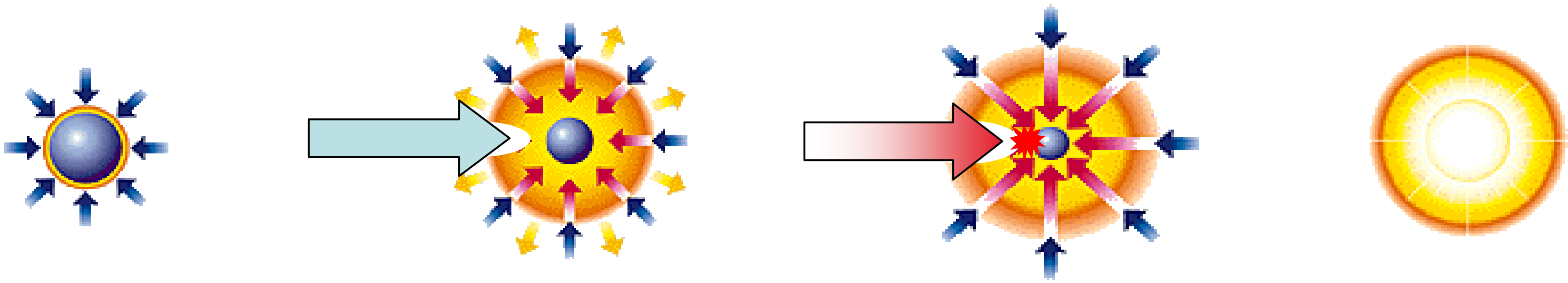
Indirect Drive

Laser fusion has been driven by the defence community. For 2 reasons:

- **open demonstration of capability**
- **to attract scientists with relevant expertise (plasma physics, turbulent hydro, materials under extreme conditions)**

IFE "Fast Ignition" approach

An alternative approach to conventional ignition is to ignite the fuel directly using e-beam, p-beam or KE from multi-PW laser interaction



Lasers or X-rays symmetrically irradiate pellet

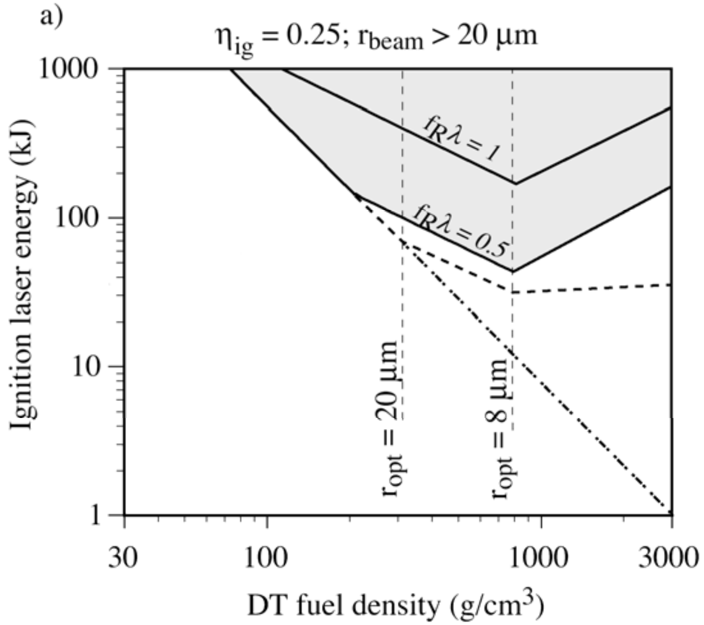
Matter compressed to ~300 gcm^{-3} Guide needed for the PW pulse (via a laser or static gold cone)

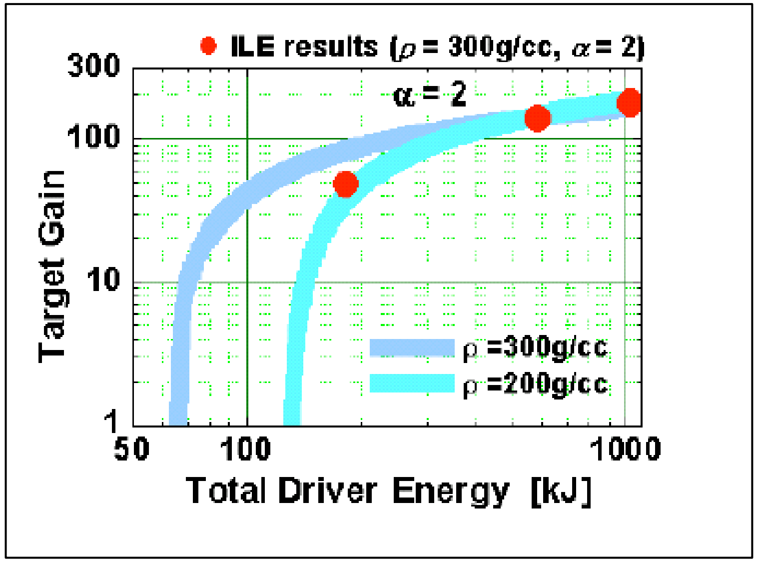
PW laser pulse is launched into channel generating MeV electrons that are stopped in the dense fuel

Off centre spark is formed, creating a burn wave that propagates through the fuel

- **Relaxed requirements on the laser, and thus cost (~10x)**
- **Breaks the principal link to defence science (radiative implosions)**
- **This allows a civilian approach to be pursued**
- **FI facility will have unique capabilities for a broad science programme**

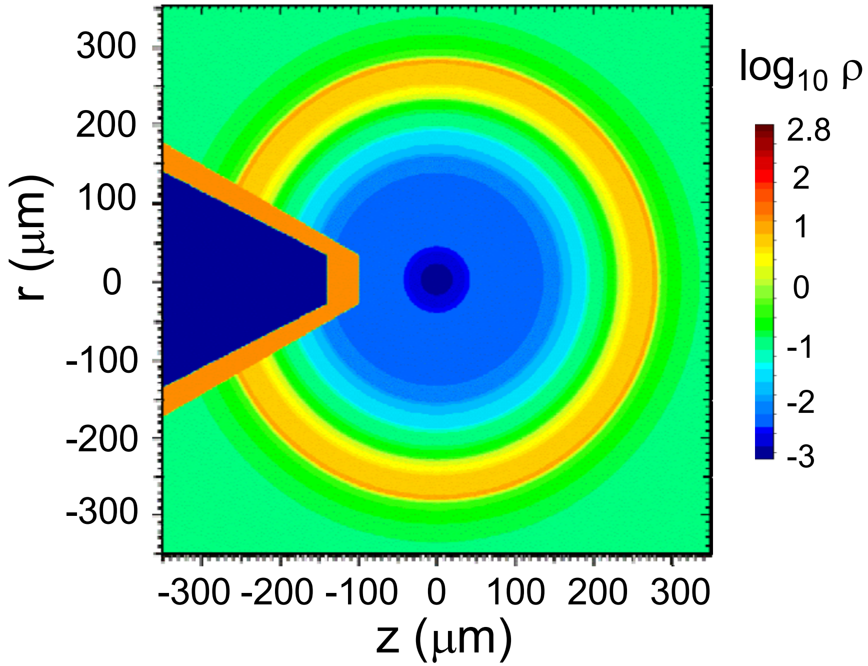
Specification based on initial modelling





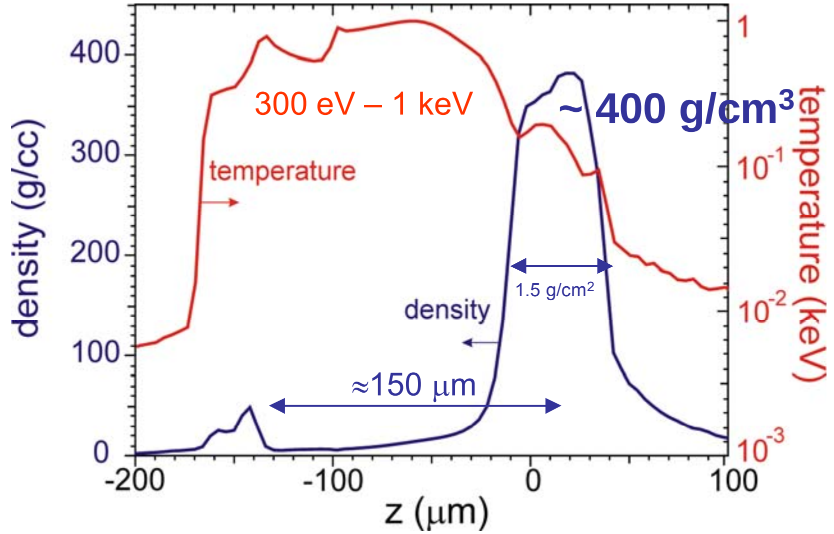
Analytical scaling laws

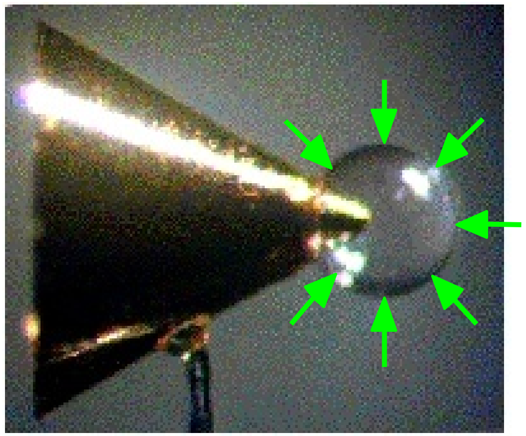
Specification based on initial modelling



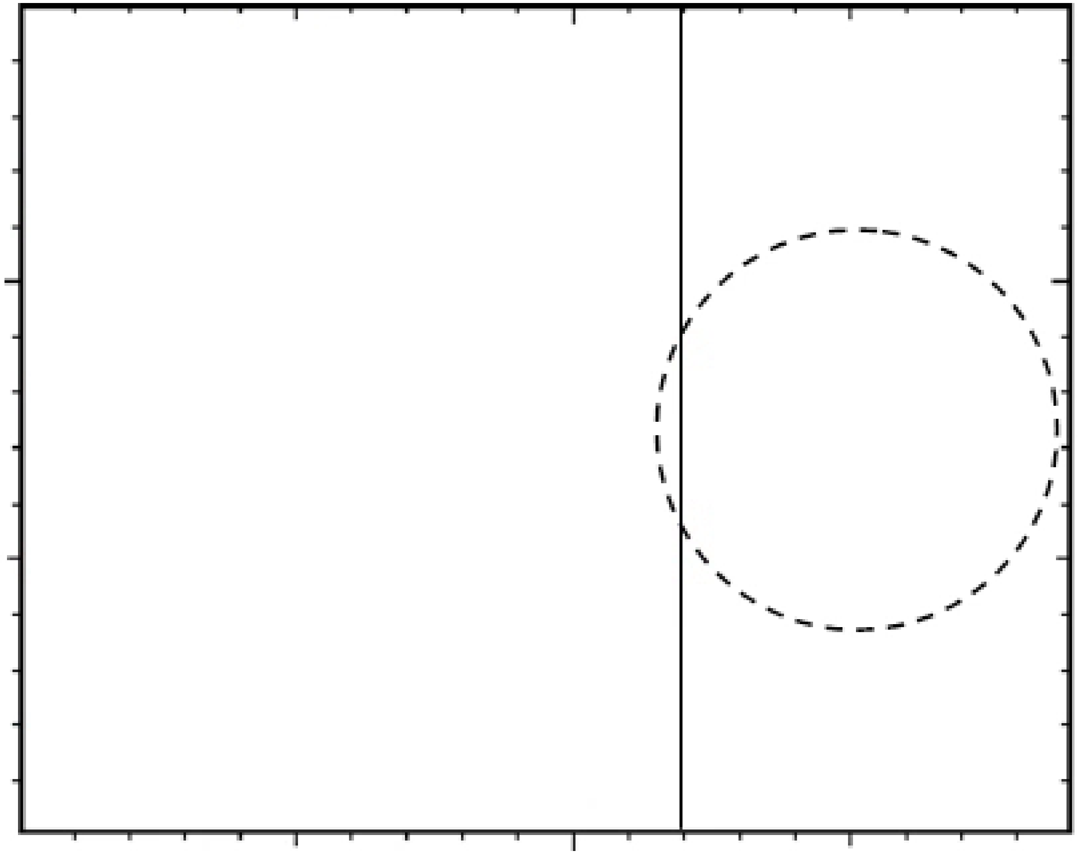
Analytical scaling laws

2D radiation hydrodynamic Implosion simulations





Specification based on initial modelling

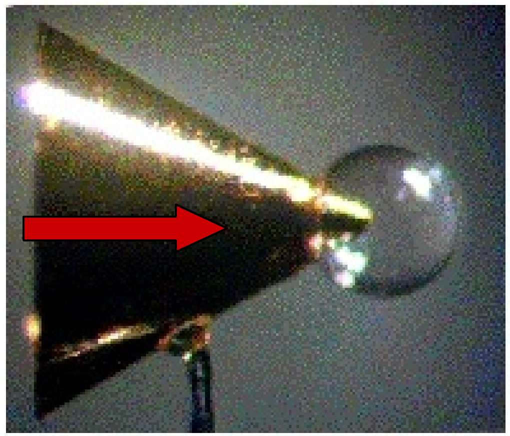


movie

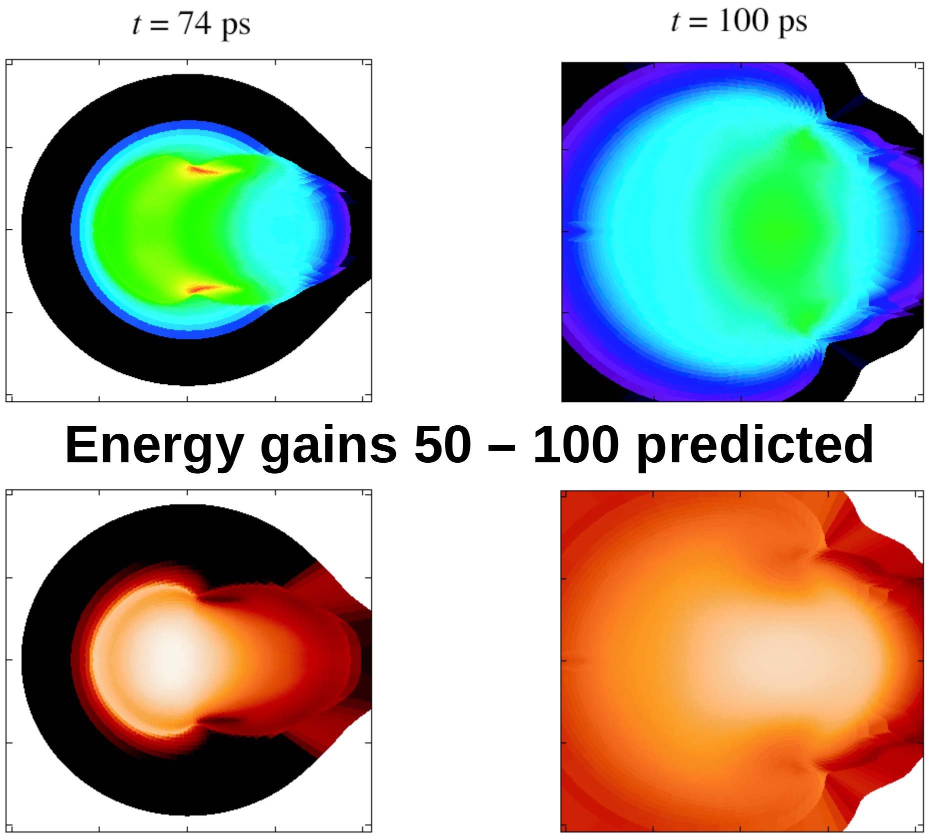
Analytical scaling laws

2D radiation hydrodynamic
Implosion simulations

3D hybrid kinetic models of electron transport



Specification based on initial modelling



Energy gains 50 – 100 predicted

Analytical scaling laws

2D radiation hydrodynamic
Implosion simulations

3D hybrid kinetic models
of electron transport

Thermonuclear burn

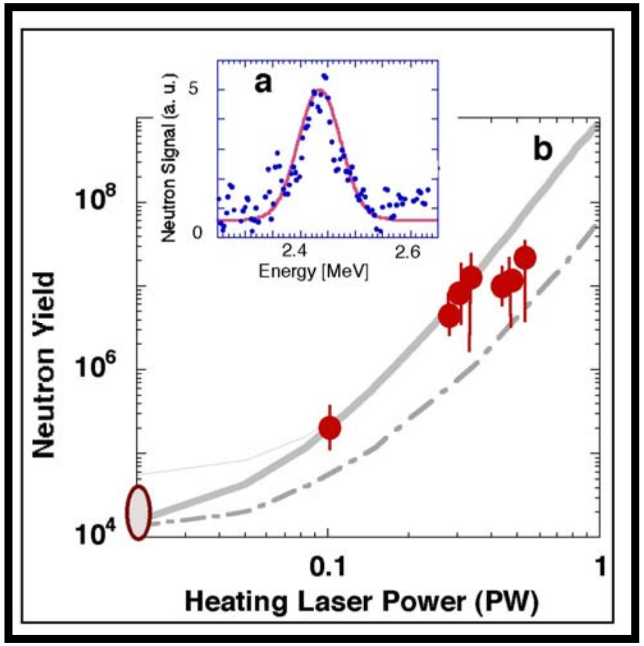
<u>Questions</u>: Are these simulations believable?
Flexibility for other advanced ignition options?

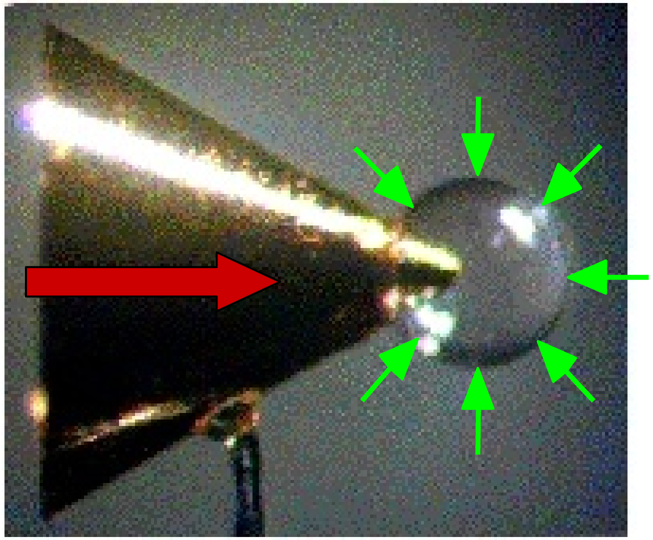
Answer via specific point designs on integrated facilities

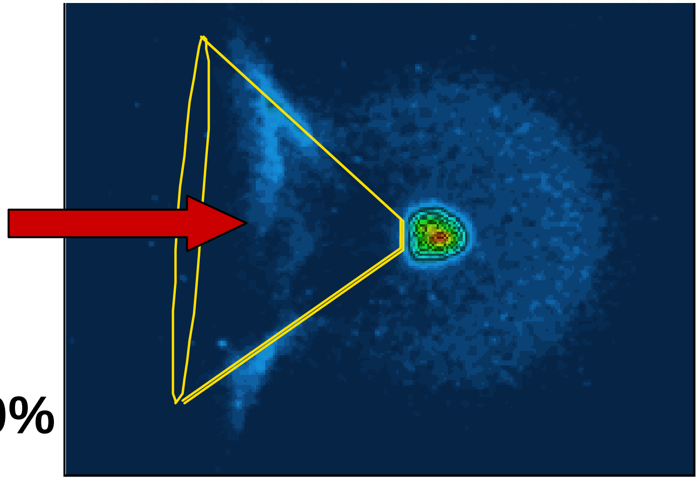
Experiments to date are promising

Cone-guided compression

• demonstrated recently by a UK / Japan team using the Vulcan and Gekko XII lasers.



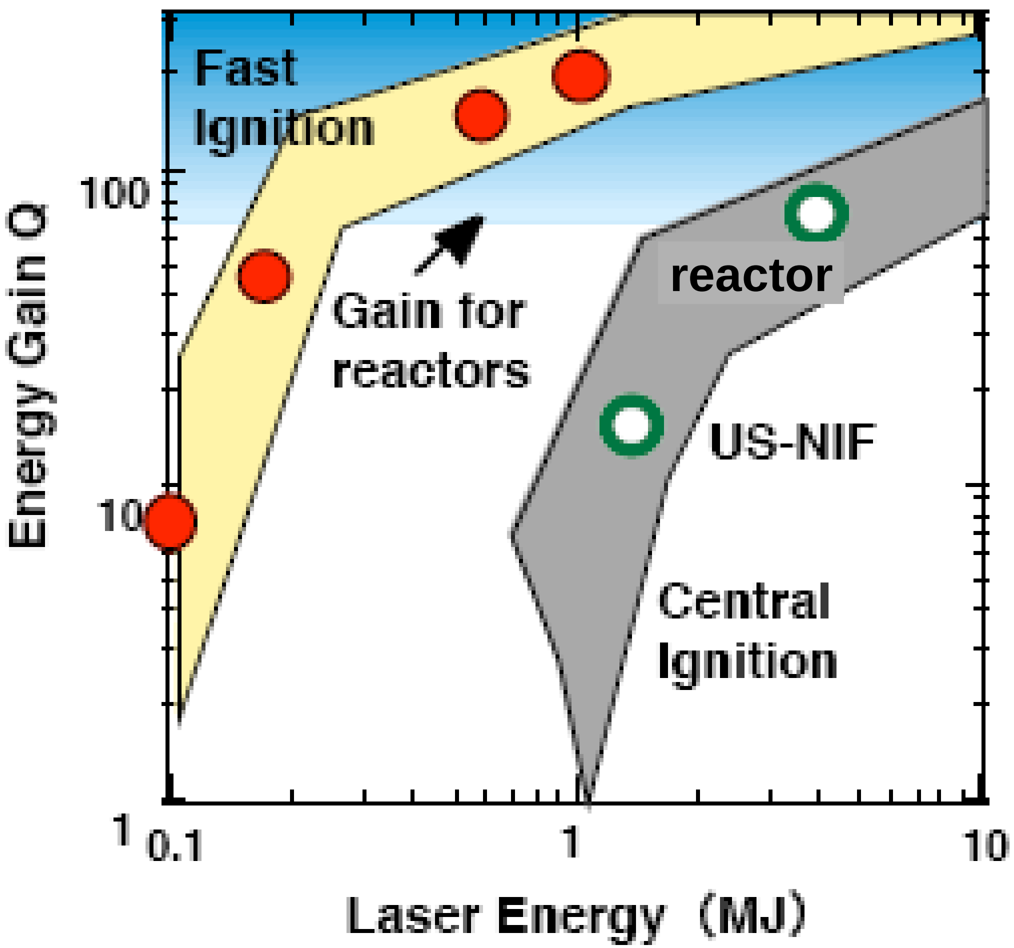




- **Neutron yields increased by factor 1000**
- **Laser to thermal energy conversion 20%-30%**

Advanced IFE designs should now be explored, with application to defining the route to a credible fusion power plant

Fast Ignition

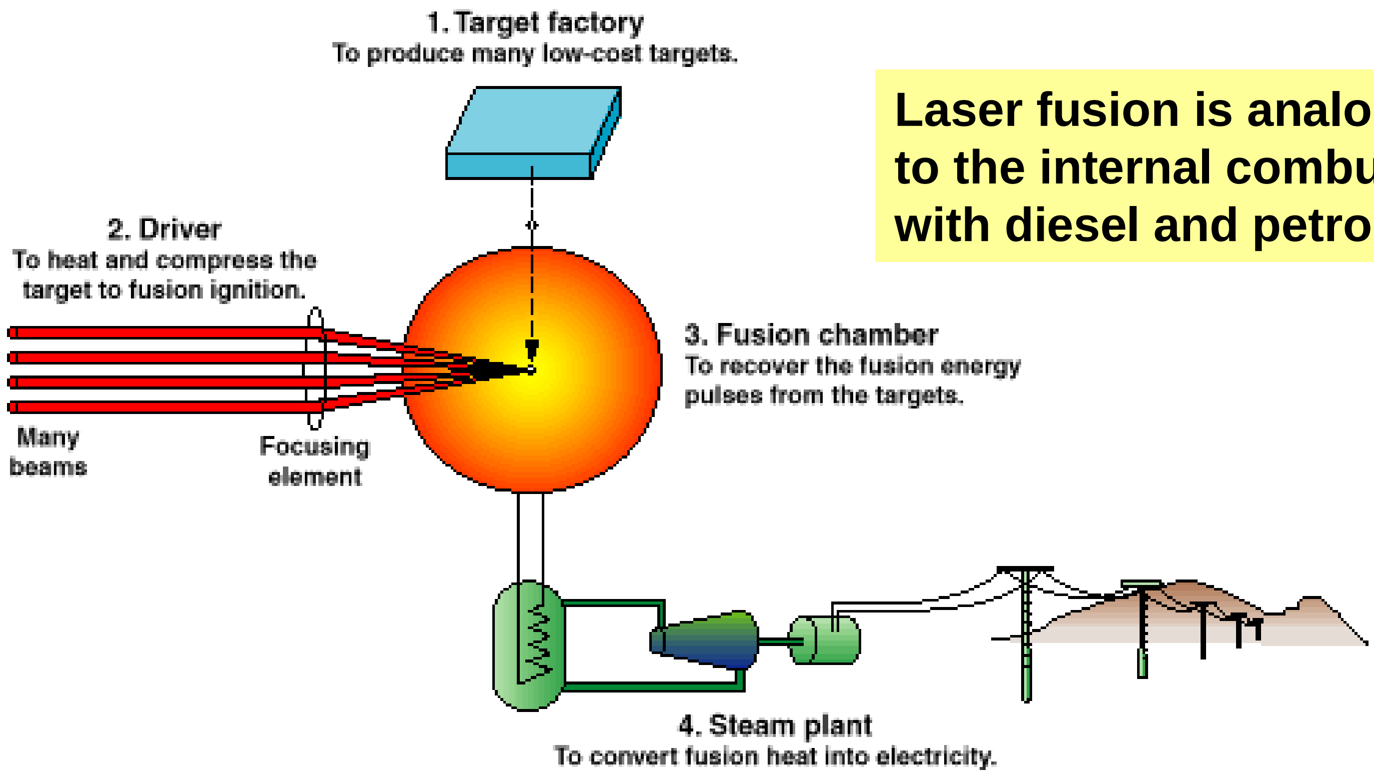


If successful, FI offers:

- High energy gain
- Smaller infrastructure
- Cheaper electricity (based on LLNL analysis)
- Unique science facility

Inertial Fusion Power Plant

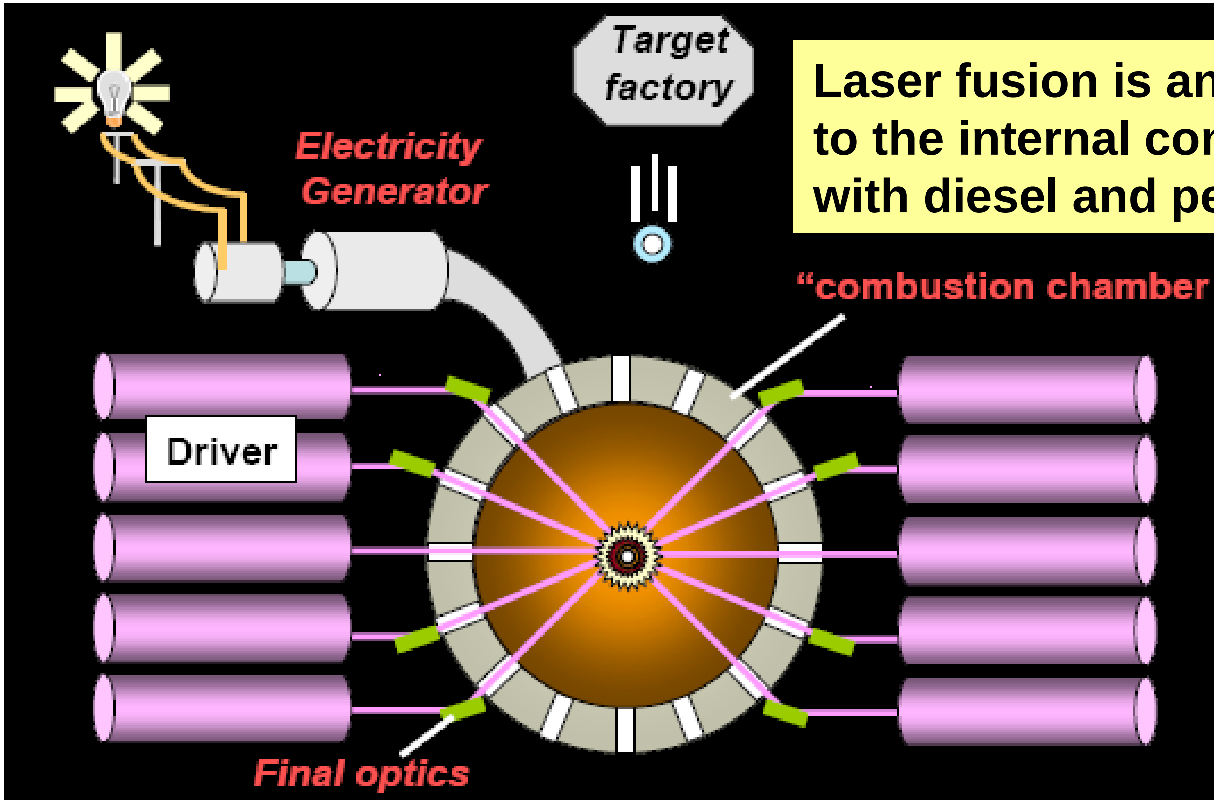
- **Complementary approach - scale of the problem demands multiple options**
- **Inertial fusion has been proven to work (1980s)**
- **What now remains is to achieve this in the laboratory (2010) and define the route to a commercially viable power plant**



Laser fusion is analogous to the internal combustion engine: with diesel and petrol variants!

Inertial (Laser) Fusion

The science of extreme conditions
can be combined with a truly global imperative



Laser fusion is analogous to the internal combustion engine: with diesel and petrol variants!

- **Complementary approach - scale of the problem demands multiple options**
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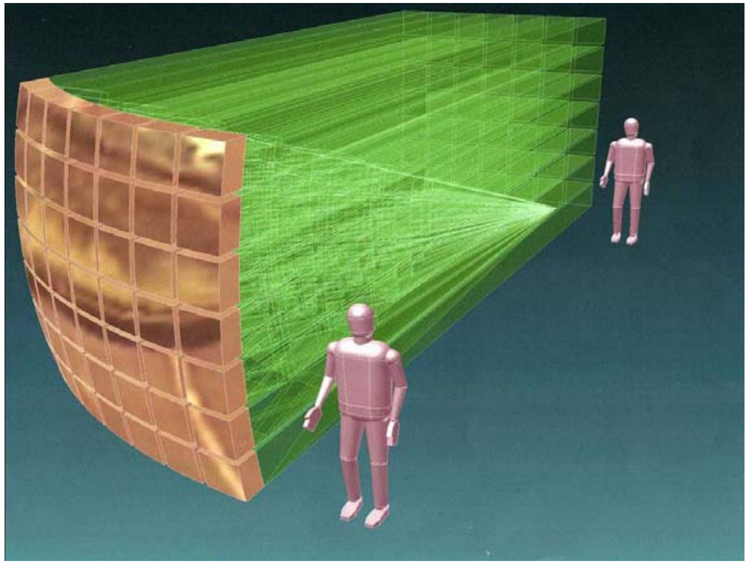
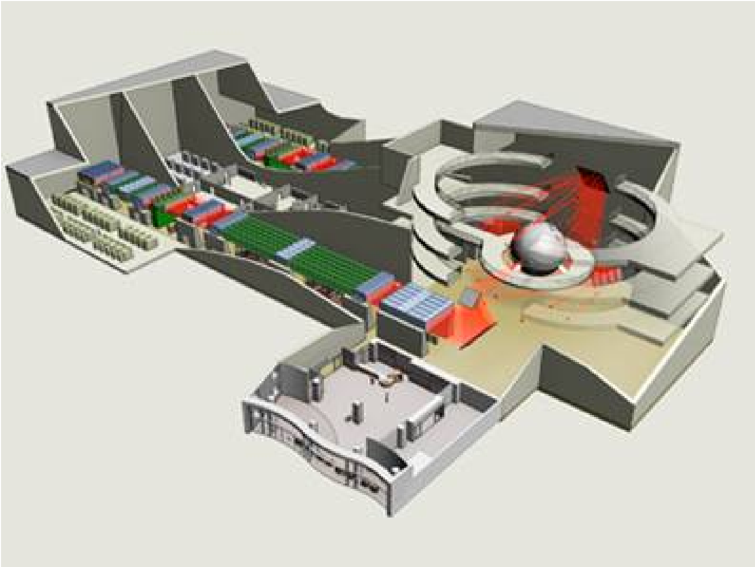
Baseline laser specification

1. Implosion laser
   200 kJ 10ns

2. "Sparkplug" laser
   70kJ, 10ps, 2ω

3. Parallel development of IFE building blocks
   Target manufacture
   DPSSL laser
   Reactor designs





HiPER Fusion energy is entering a new era

- **Demonstration of IFE ignition within ~ 1 years**
- **Visibility of fusion via ITER (and IFMIF)**

Need to ensure we provide options to move from scientific demonstrations to a commercial fusion energy program

- **International cooperation will be essential**
  - Linking of facility developments within Europe towards a common goal
  - Coordinated research programs (plasma physics, targets, laser …)
- **Parallel development of IFE building blocks**
  - Demonstration facility for high energy gain
  - High repetition rate, efficient driver
  - Mass production of complex targets
  - Laser fusion reactor design

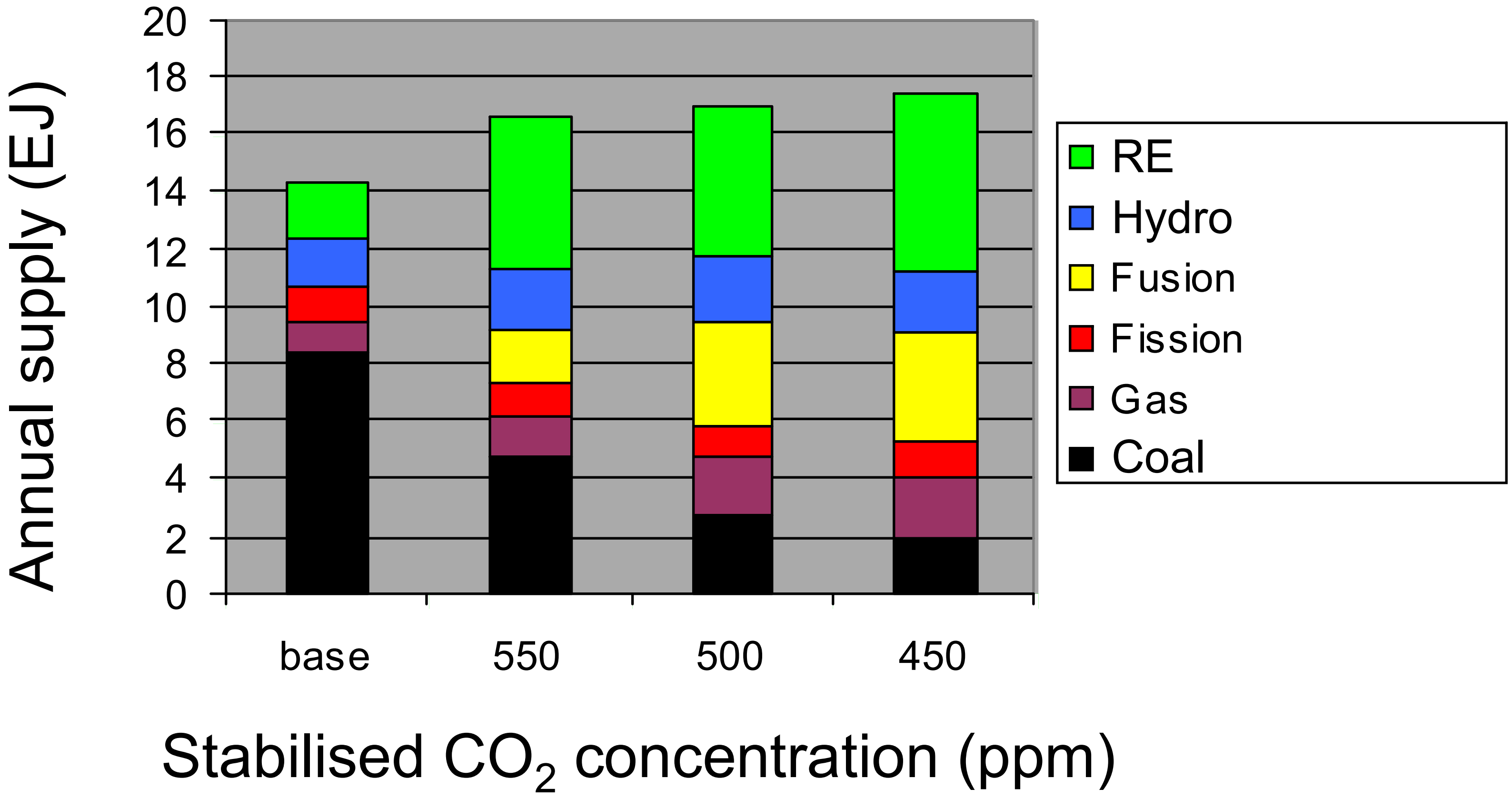
Fusion in the laboratory is imminent …

NIF (USA) and LMJ (France) due to demonstrate laser fusion "ignition" (i.e. energy gain) within the year

How will we respond to this transformational event?


Target
Chamber
NIF-0105-10124
31EIM/dj
P8136

Energy scenario with fusion



Fusion reactor: Summary

Cheap fuel basically for ever
No gas release which damages environment
Inherent safety

- no chain reaction
- low energy density, large surfaces
- slow energy release

Limited damage in case of accident

- no α-radiators
- no evacuation, no exchange of soil

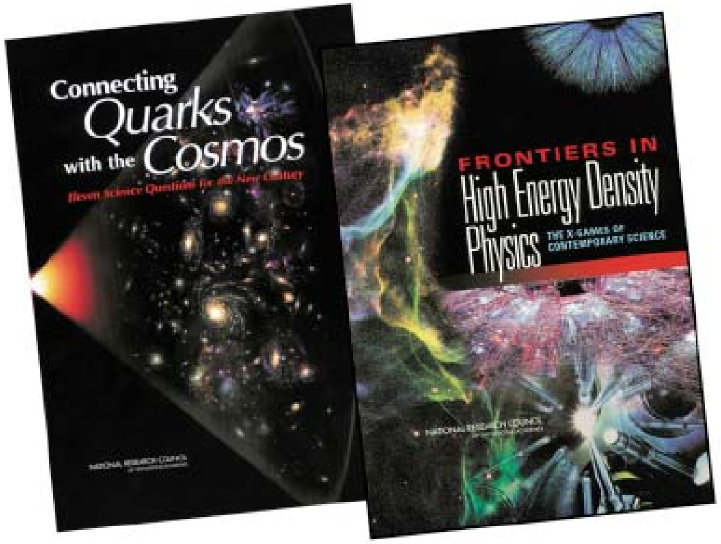
Controlable waste situation

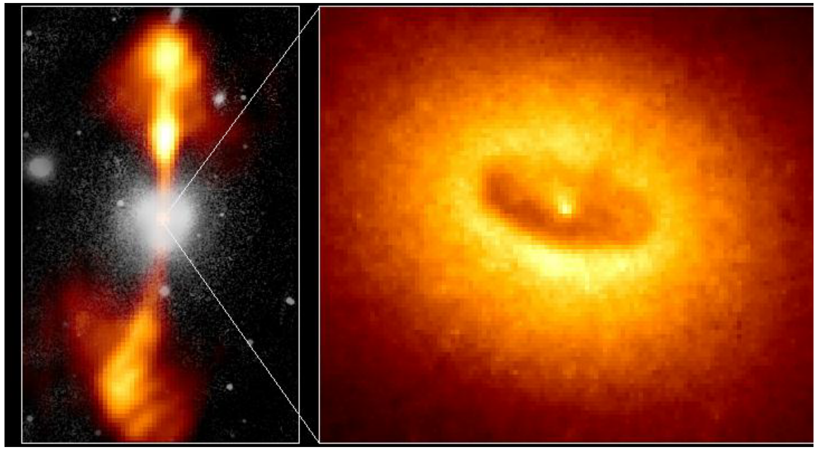
- low afterheat, no active cooling
- activated materials can be recycled after about 100 a

Cost of electricity: about 50% more than fission

Fusion facilities enable a broad science programme

- **Material Properties under Extreme Conditions**
  Unique sample conditions & diagnosis
  Non-equilibrium atomic physics tests
- **Laboratory Astrophysics**
  Viable non-Euler scaling & diagnosis
- **Nuclear Physics**
  Access to transient nuclear states
- **Neutron Scattering**
  Potential for IFE based neutron scattering source
- **Turbulence**
  Onset and evolution in non-ideal fluids
- **Radiation transfer and HED physics**
  Unique sample conditions & diagnosis
- **Development of new particle beam sources**
- **Fundamental strong field science**





Summary

- We are entering a new era for Fusion Energy
- A concept for a next-generation European facility has been proposed
- Includes significant development of laser, target and code capability
- Included on national & European roadmaps
- Next stage is detailed facility design – needs coordinated, international approach

Thank you.

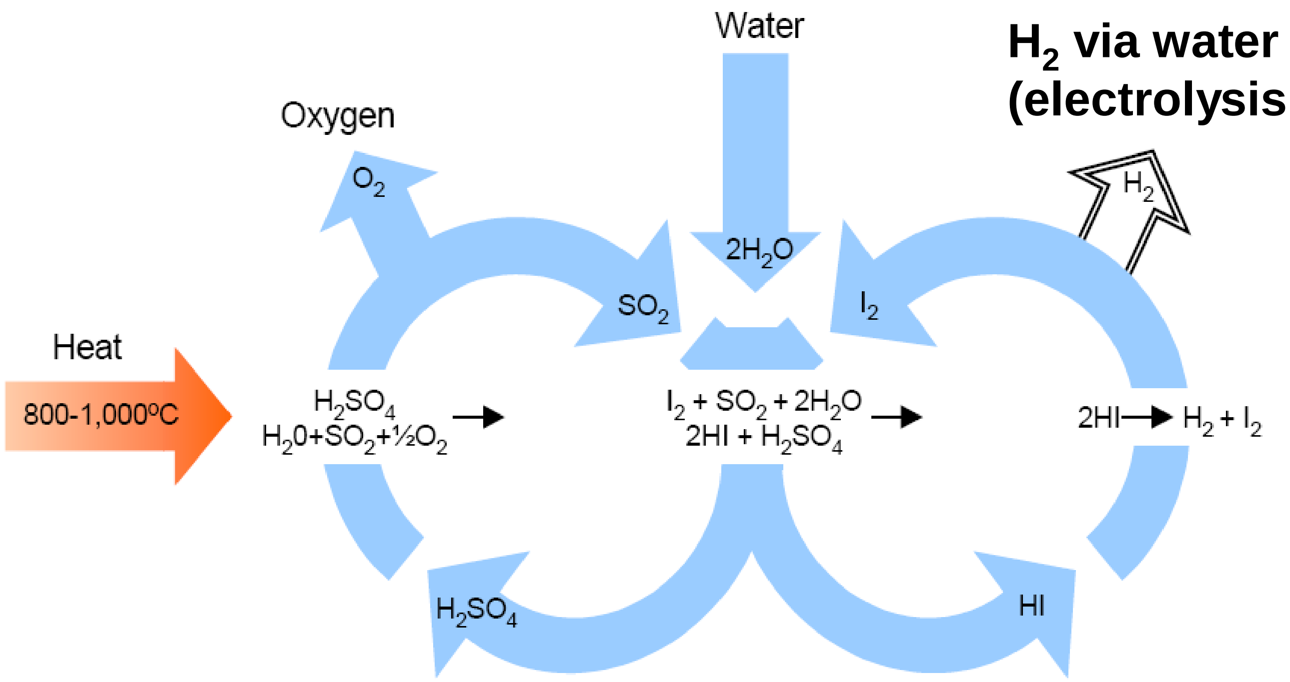
Background Slides

Why pursue fusion energy?

- **Plentiful fuel source**
- **No carbon emissions, and no long-lived radioactivity**
- **Intrinsically safe reactor (no stored energy)**

- **Would provide a source of Hydrogen (high temperature environment)**
- **Advanced H_2 cycles do not suffer from CO_2 by-product**

H_2 via water decomposition (electrolysis + chemical cycle)



How big is the laser we need?

Energy: *pitifully small*

– Largest lasers in the world have comparable energy to a cup of tea!

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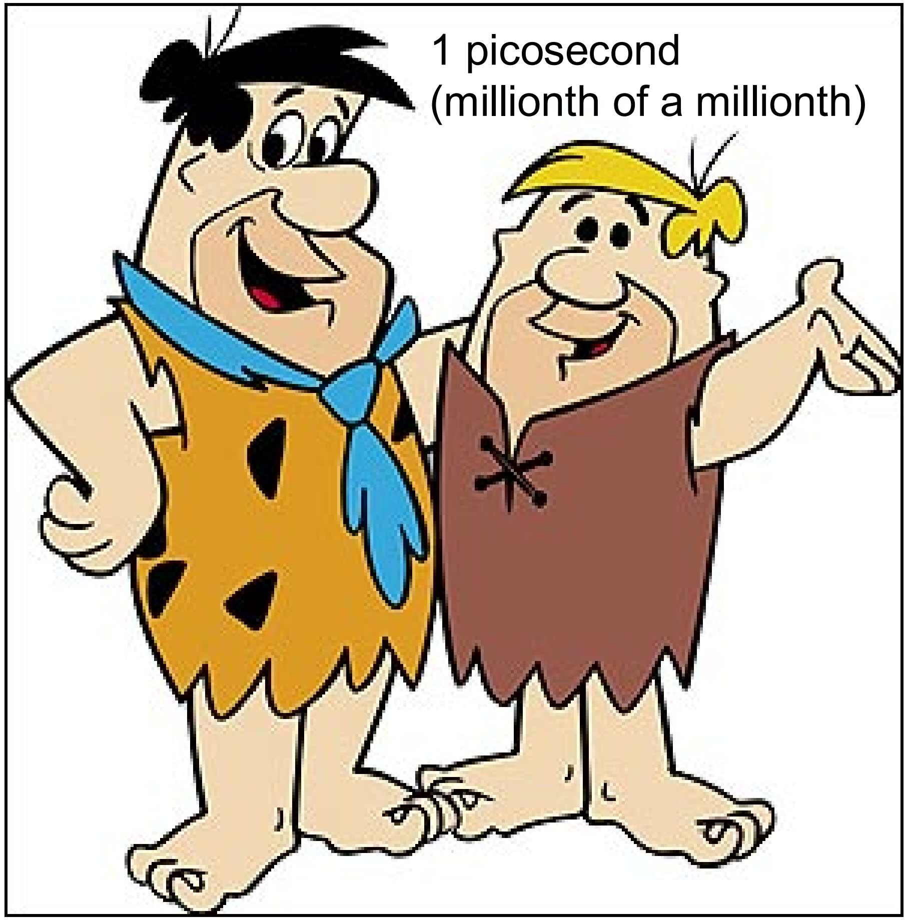
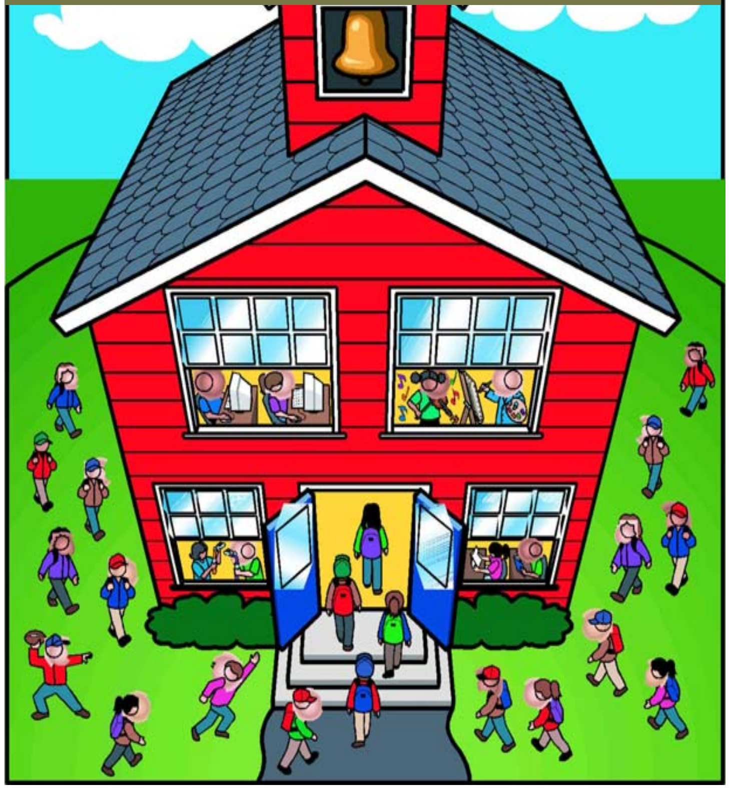
Timescale: *very short*



1 nanosecond
(0.000000001 sec)
a thousandth of a millionth



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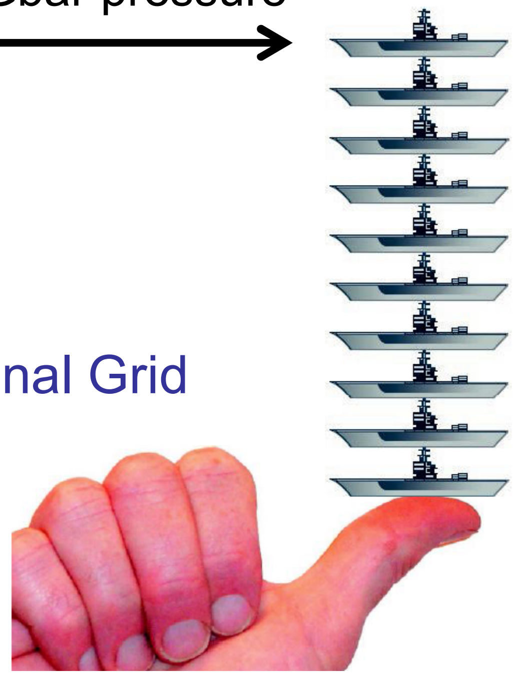
Gbar pressure →



Power (which is simply “energy / time”):
staggeringly large!

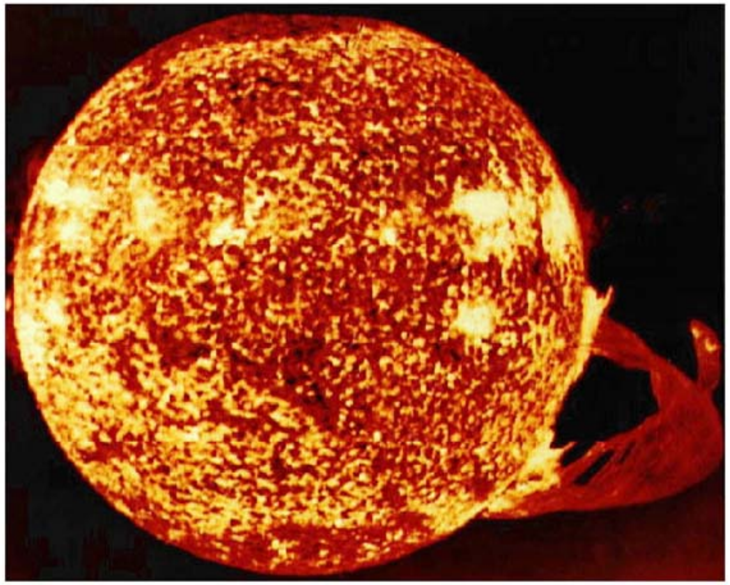
1 Petawatt (1 thousand, million, million Watts)

> > 10,000 times the power of the entire UK National Grid

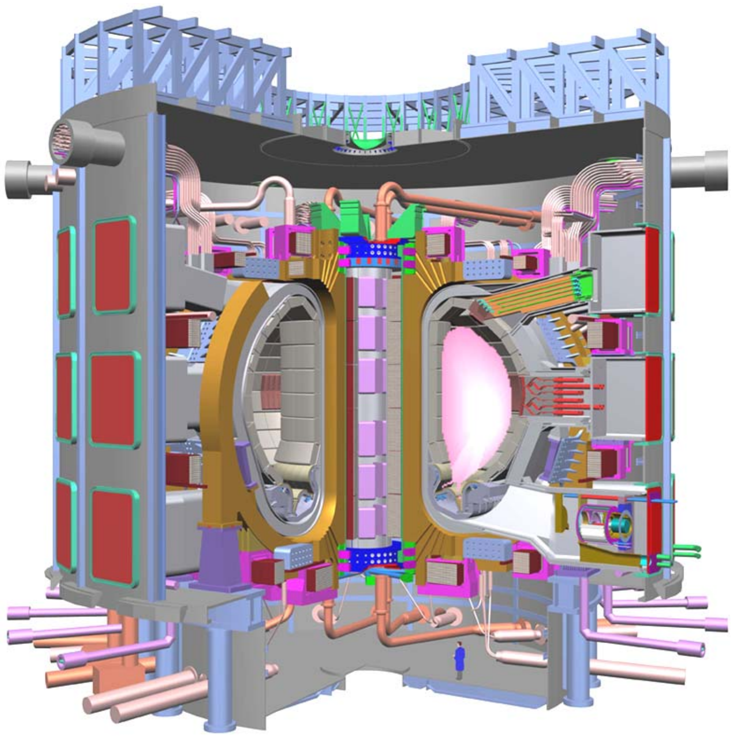
Imagine this power focussed to a spot smaller than the width of a strand of hair…

90,000 london buses stacked on your thumb!

Sun, with eruption



ITER tokamak



HiPER Preparatory phase project

3 main deliverables:

1. Design of the HiPER facility (for the 2 principal options)
2. Establish sufficient level of capability
    - Point designs from self-consistent simulations
    - Integrated experimental validation programme
    - Technology readiness
    - Coordination with international partners
    - Industrial engagement
    - **Confidence in the Fast Ignition route**
3. Legal, financial and governance framework

This work starts <u>now</u> to coincide with anticipated success on NIF, and physics demonstrations for Fast ignition

Coordinated international approach

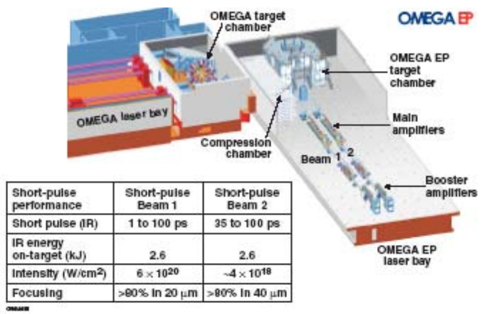
Common strategic theme, with phased facility development in Europe:

– PETAL (France) : Integration of PW and high energy beams

– HiPER : High yield facility

Coordinated scientific and technology development

– Europe + Japan, USA, Canada, S Korea, China



Short-pulse performance	Short-pulse Beam 1	Short-pulse Beam 2
Short pulse (IR)	1 to 100 ps	35 to 100 ps
IR energy on-target (kJ)	2.6	2.6
Intensity (W/cm^2)	6×10^{20}	$\sim 4 \times 10^{18}$
Focusing	>80% in 20 μm	>80% in 40 μm

OMEGA-EP
USA

FIREX
Osaka, Japan

PETAL
France

European Preparatory phase project

This 3 year project has 3 main deliverables:

1. Design of the HiPER facility (options)
2. Mobilising the European laser/plasma community
   - Integrated modelling capability
   - Integrated experimental programme
   - Confidence in the Fast Ignition parameters
   - Readiness of IFE technology
   - Coordination with international partners
3. Legal, financial and governance framework

Result:

Provide the basis for a political decision to proceed

Aligned development strategy

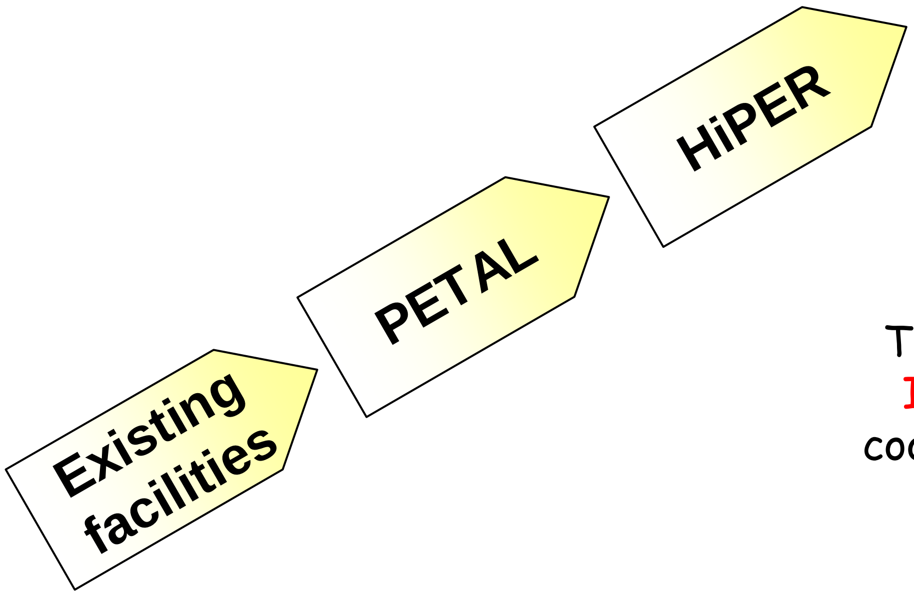
A single approach to IFE within Europe has been established

Common strategic theme, with phased facility development:

– PETAL: Integration of PW and high energy beamlines

– HiPER: High yield facility

Coordinated scientific and technology development between the major European laser laboratories

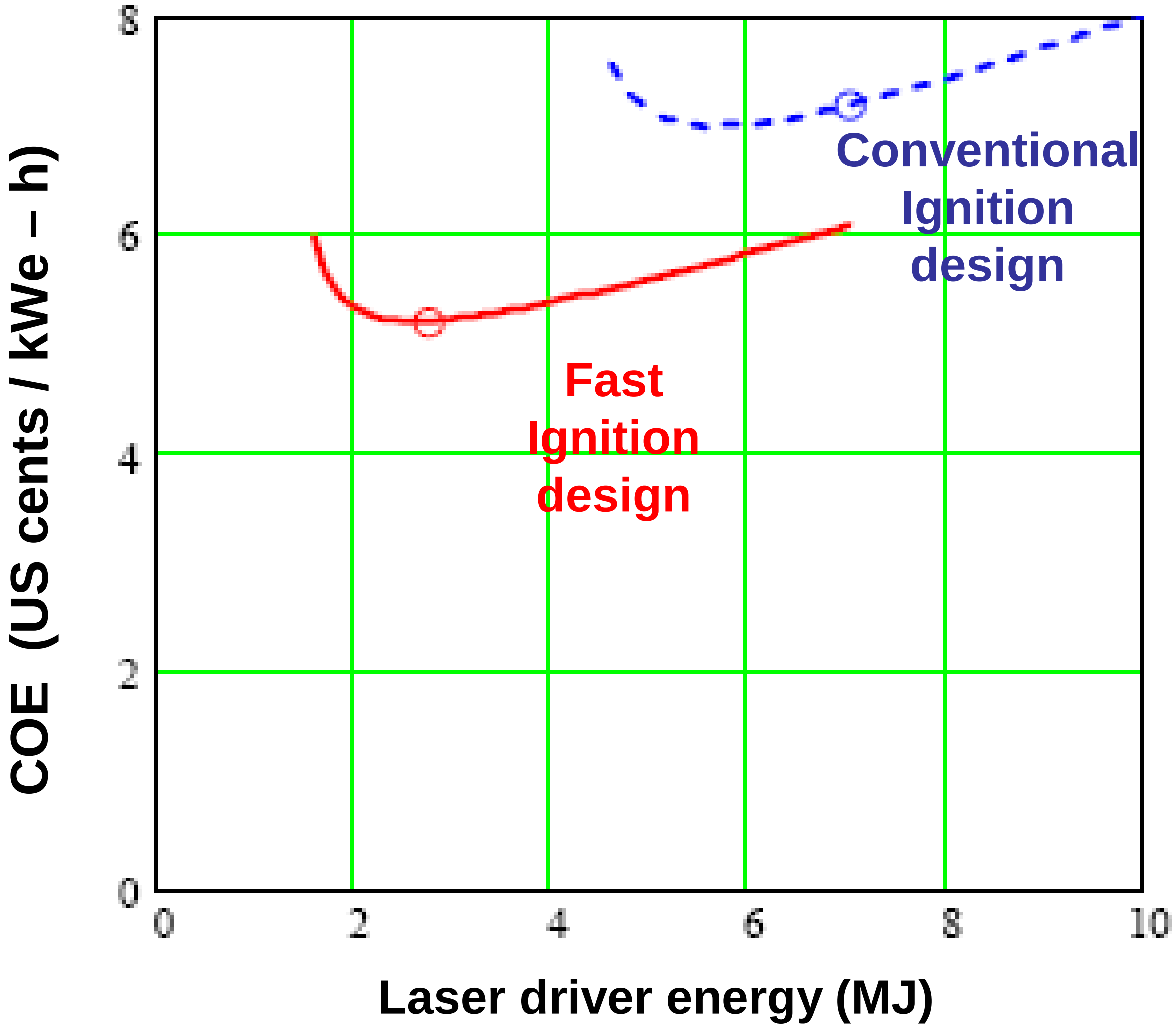


3.5 kJ	60 kJ
0,5 – 10 ps	8 beams
Up to 7 PW	ns , 3ω

The PETAL scientific program is under the Institute Lasers and Plasmas (ILP) which coordinates high intensity lasers activities in France

Predicted Cost of Electricity

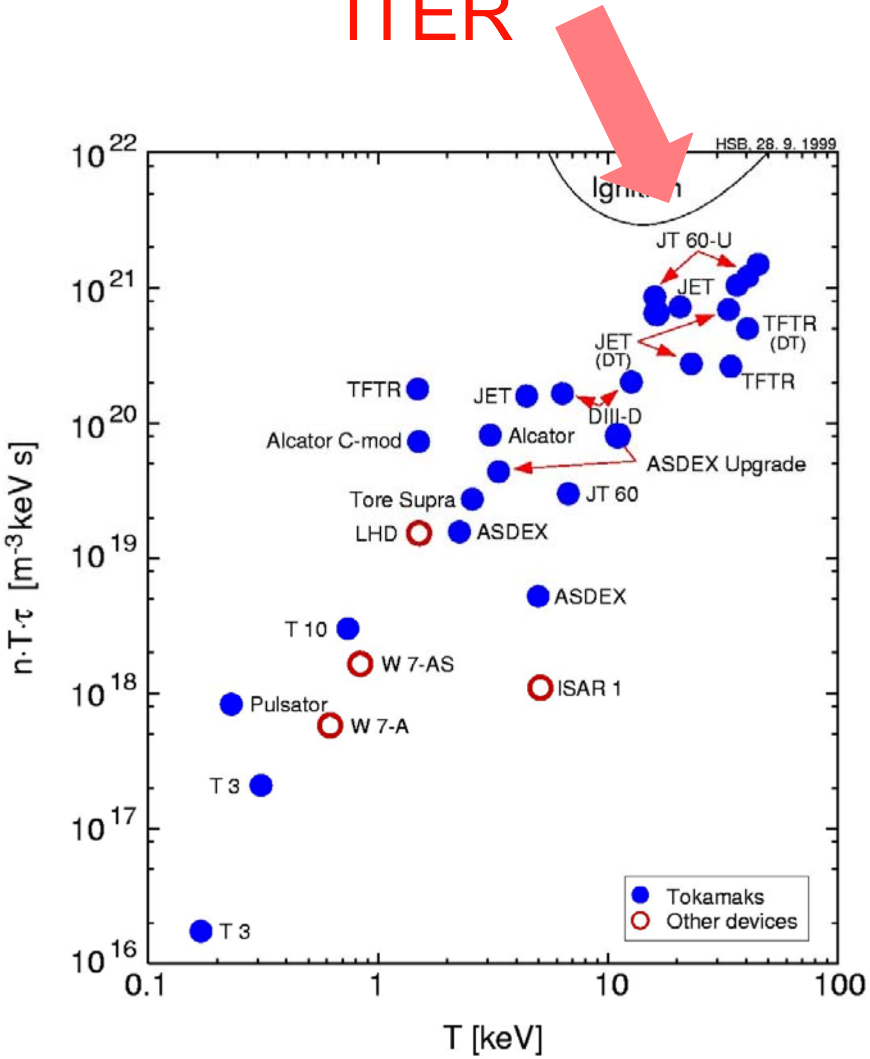
Fast ignition both allows a smaller reactor and cheaper electricity



[Hogan & Meier (LLNL), IFSA 2003]

Status of Fusion Research

ITER



Temperature T: 40 keV achieved

Particle density n achieved

Confinement-time τ_E: a factor 4 is missing

Fusion product $nT\tau_E$: a factor 6 is missing

First scientific goal achieved: Q≈1

DT operation without problems

Fusion power for short time produced: 16 MW

Design of an experimental reactor : ITER

Optimisation concept for stellarators : W7-X

A European project

Partners in the preparatory phase (at the ministerial / national funding agency level):

- UK, France, Spain, Italy, Portugal, Czech Republic, Greece

Other partners in the preparatory phase (at the institutional level):

- Germany, Poland, Russia

International links:

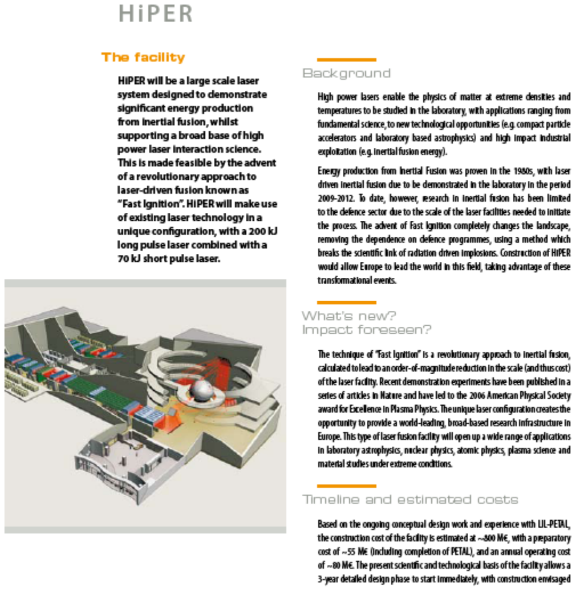
- USA, Japan, China, South Korea, Canada

Included on European roadmap (Oct 06)

UK endorsement – coordinators (Jan 07)

Next phase (EC+MS) (May 07)

Passed assessment (Jul 07)



HiPER

The facility

HiPER will be a large scale laser system designed to demonstrate significant energy production from inertial fusion, whilst supporting a broad base of high power laser interaction science. This is made feasible by the advent of a revolutionary approach to laser-driven fusion known as "Fast Ignition". HiPER will make use of existing laser technology in a unique configuration, with a 200 kJ long pulse laser combined with a 70 kJ short pulse laser.

Background

High power lasers enable the physics of matter at extreme densities and temperatures to be studied in the laboratory, with applications ranging from fundamental science, to new technological opportunities (e.g. compact particle accelerators and laboratory based astrophysics) and high impact industrial exploitation (e.g. inertial fusion energy).

Energy production from Inertial Fusion was proven in the 1980s, with laser driven inertial fusion due to be demonstrated in the laboratory in the period 2009-2012. To date, however, research in inertial fusion has been limited to the defence sector due to the scale of the laser facilities needed to initiate the process. The advent of Fast Ignition completely changes the landscape, removing the dependence on defence programmes, using a method which breaks the scientific link of radiation driven implosions. Construction of HiPER would allow Europe to lead the world in this field, taking advantage of these transformational events.

What's new? Impact foreseen?

The technique of "Fast Ignition" is a revolutionary approach to inertial fusion, calculated to lead to an order-of-magnitude reduction in the scale (and thus cost) of the laser facility. Recent demonstration experiments have been published in a series of articles in Nature and have led to the 2006 American Physical Society award for Excellence in Plasma Physics. The unique laser configuration creates the opportunity to provide a world-leading, broad-based research infrastructure in Europe. This type of laser fusion facility will open up a wide range of applications in laboratory astrophysics, nuclear physics, atomic physics, plasma science and material studies under extreme conditions.

Timeline and estimated costs

Based on the ongoing conceptual design work and experience with LIL-PETAL, the construction cost of the facility is estimated at ~800 M€, with a preparatory cost of ~55 M€ (including completion of PETAL), and an annual operating cost of ~80 M€. The present scientific and technological basis of the facility allows a 3-year detailed design phase to start immediately, with construction envisaged

European Roadmap for new Facilities

Strategic analysis of science facility opportunities for the next 20 years

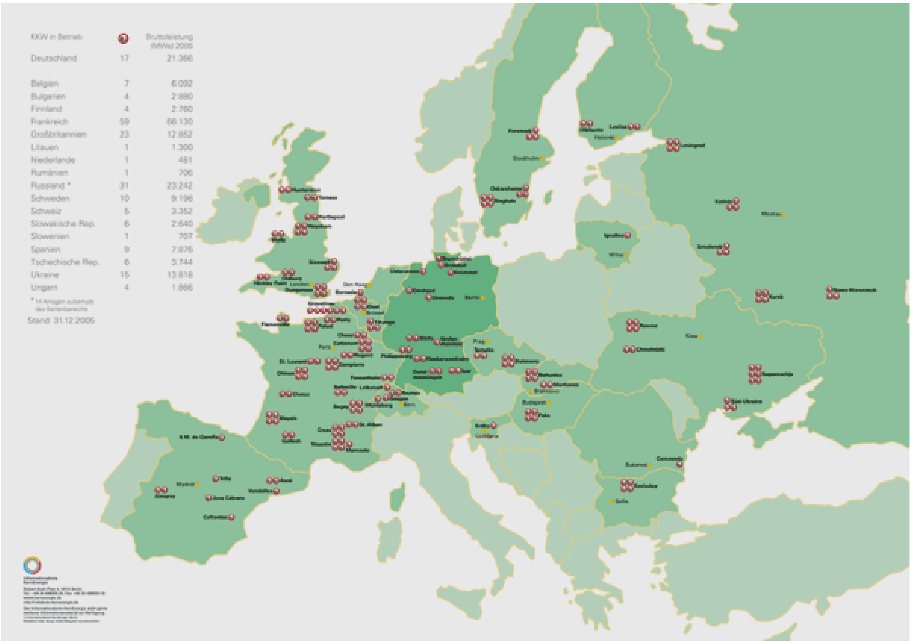
- **35 "Opportunities"**
- **Dedicated EC funding for design**
- **Construction via European Govts**

- **Published October 2006**
- **EC + Governmental funding to pursue these options is now being finalised**

HiPER Flexibility for a broad science programme

- **Material Properties under Extreme Conditions**
  Unique sample conditions & diagnosis
  Non-equilibrium atomic physics tests
- **Laboratory Astrophysics**
  Viable non-Euler scaling & diagnosis
- **Nuclear Physics**
  Access to transient & obscure nuclear states
- **Neutron Scattering**
  PoP for IFE based neutron scattering source
- **Turbulence**
  Onset and evolution in non-ideal fluids
- **Radiation transfer and HED physics**
  Unique sample conditions & diagnosis
- **Development of new particle beam sources**
- **Fundamental strong field science**

Nuclear energy in Europe



Decision on closing existing reactors

- Belgium
- Germany
- Netherlands
- Slovenia
- Spain
- Sweden

Anit-nuclear position by law; no reactors

- Austria
- Denmark
- Greece
- Italy
- Portugal

Plans/approved plans to build new nucl. power plants

- Belarus
- Czech Republic
- Finland
- France
- Lithuania
- Norway (Thorium)
- Poland
- UK

1. generation:
   - systems are based on Silicon waver technology
     - Problem: costs; supply of PV-grade silicon

2. generation:
   - poly-crystalline-, amorphous, low-grade Si; thin-film technology
   - lower costs; no material limits

   - other materials: Gallium-Arsenide, Cadmium-Telluride, Cu-In-Diselenide
     - Chances: cheaper, more abundant

3. generation:
   - dye-sensidized photochemical cells
   - polymer cells
   - molecular organic cells
   - quantum-dots, nano-technology
     - Chances: cheaper, good integration, higher efficiency, high expected potential (to be demonstrated)

Generation I, II, III (EPR, AP1000: more passive safety)

Generation IV: 11 countries cooperate to develop this nuclear system

Major targets:

new concepts

e.g. accelerator driven spallation neutrons into sub-critical reactors

new fuel (Thorium, U^{238})

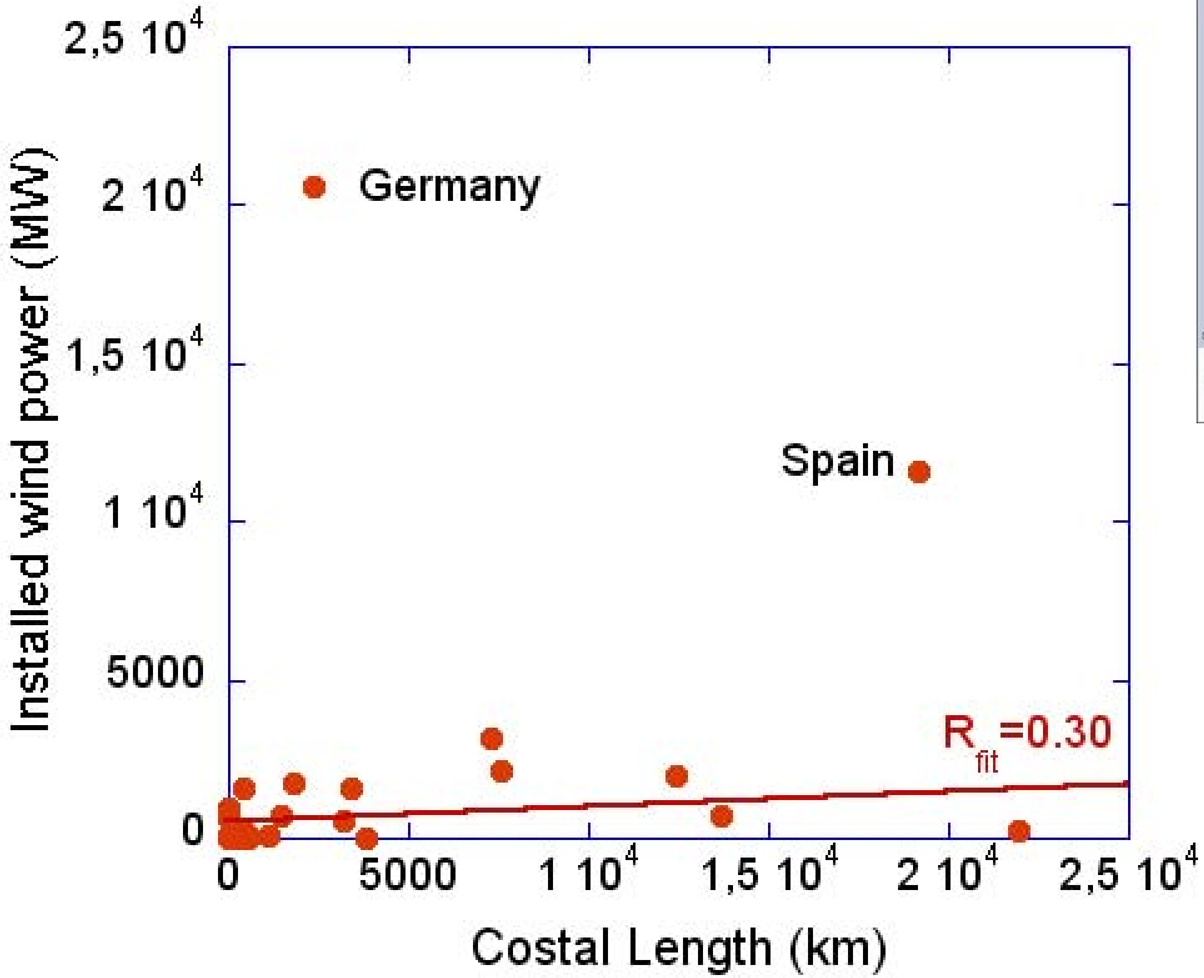
Reprocessing of existing fuel for fuel extension

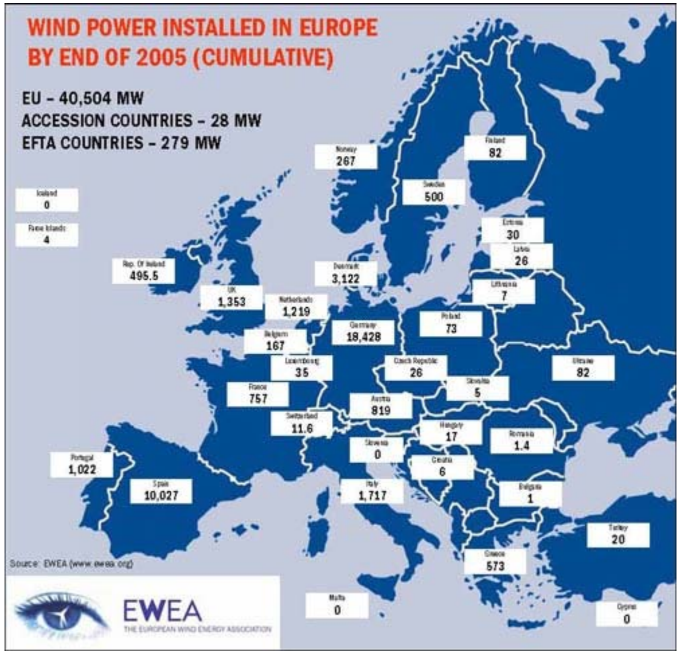
use of the fast neutron spectrum (for breeding)

use of supercritical fluids (no inner surfaces, better thermal features)

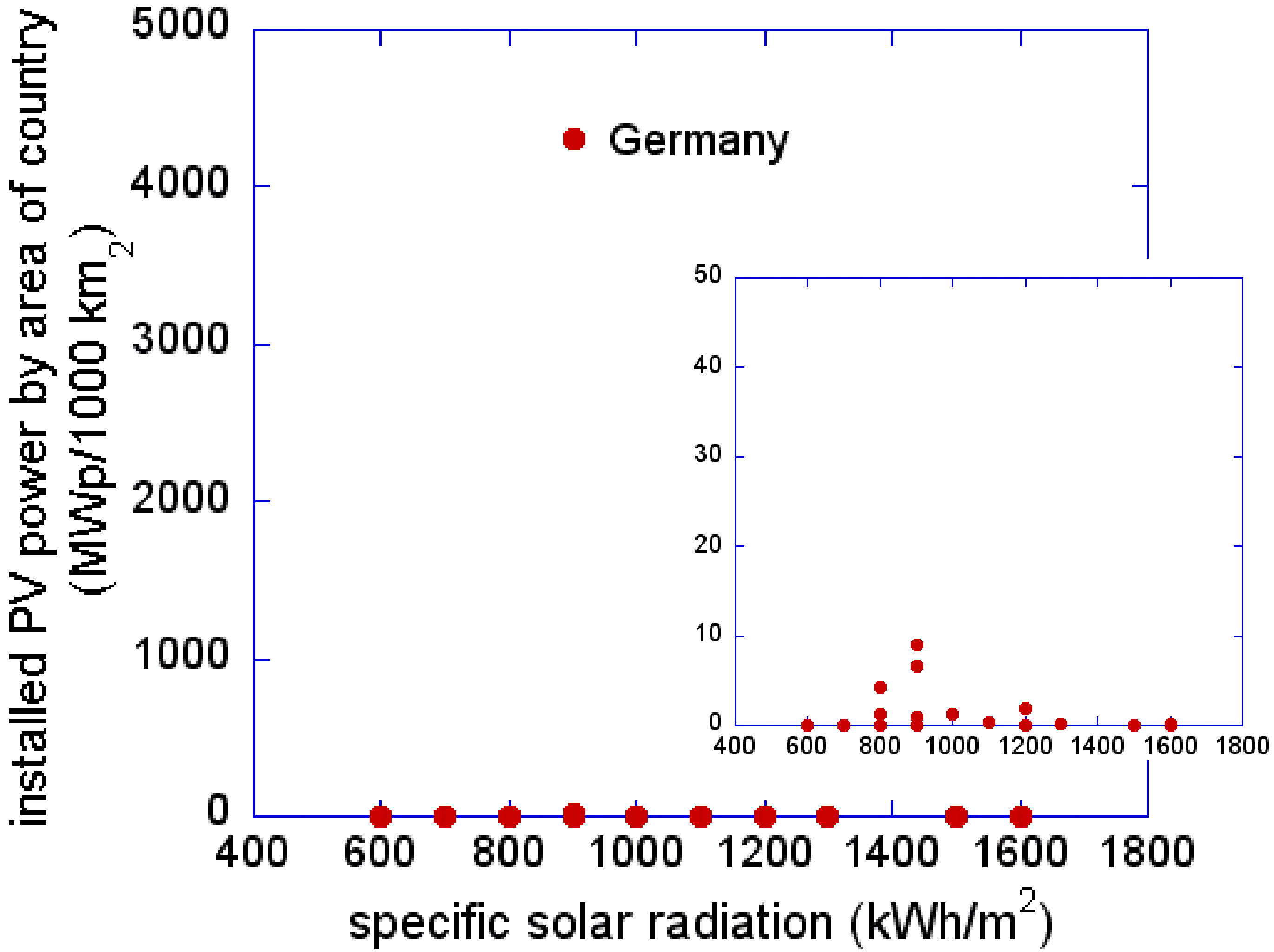
Burn present and future waste by transmutation of Am, Np, Cm

Installed wind power and the correlation to the costal length

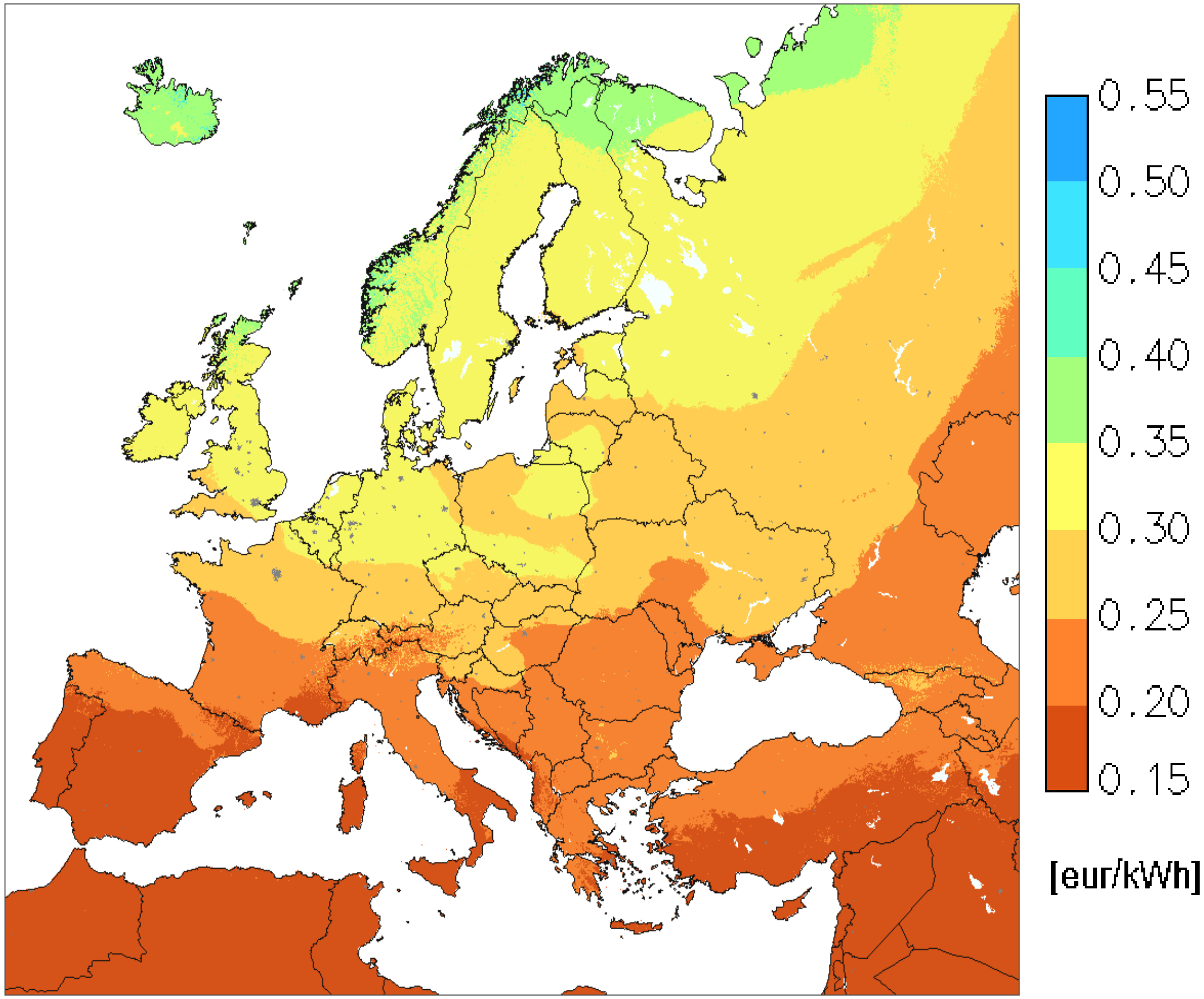




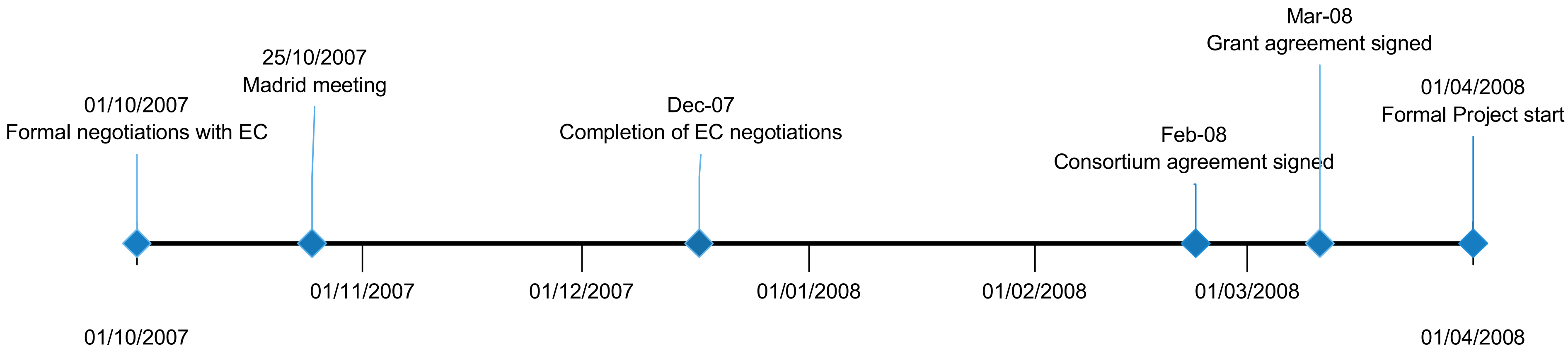
Installed PV power and the correlation to the specific solar radiation

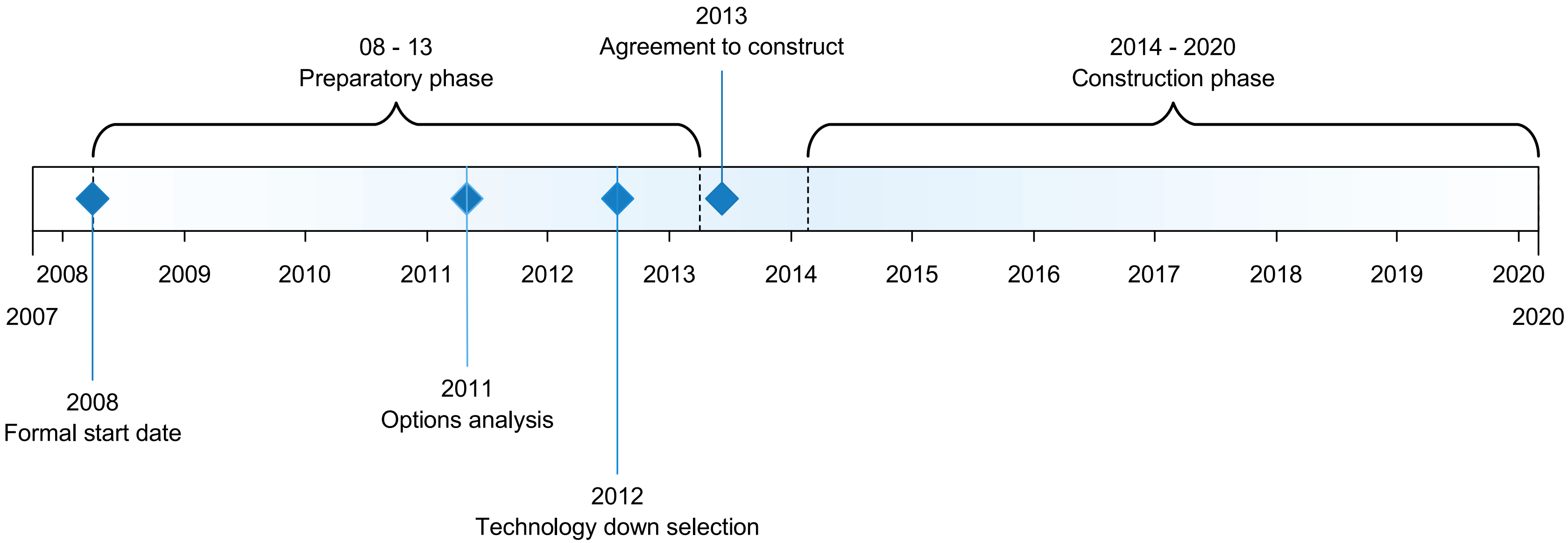


Cost of electricity (€/kWh) from large central PV power station (>1 MWp)



HiPER Project Timeline



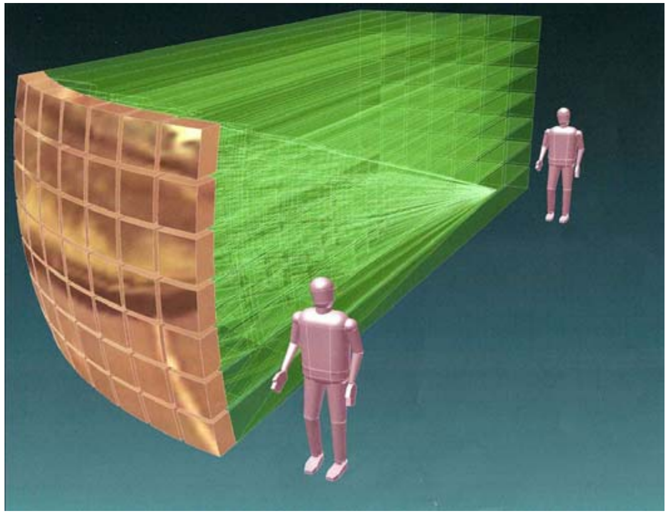


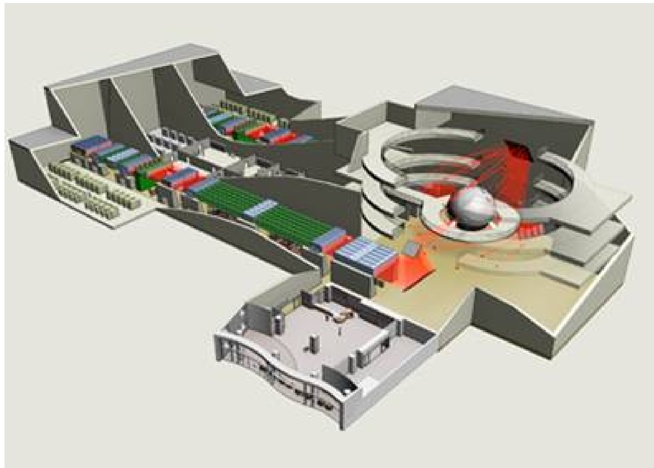
HiPER Laser specification

1. **Implosion laser**
   200 kJ 10ns
   10 m chamber

2. **“Sparkplug” laser**
   70kJ 10ps

3. Parallel development of IFE building blocks
- **Target manufacture**
- **Advanced laser**
- **Reactor designs**





2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015

Feasibility **Detailed design** **Construction phase** **Commissioning**

Science & Technology Facilities Council
Central Laser Facility

Putting laser numbers into perspective

- **Energy**: small

  Vulcan = 500J

4 finger KitKat….
973,000 J

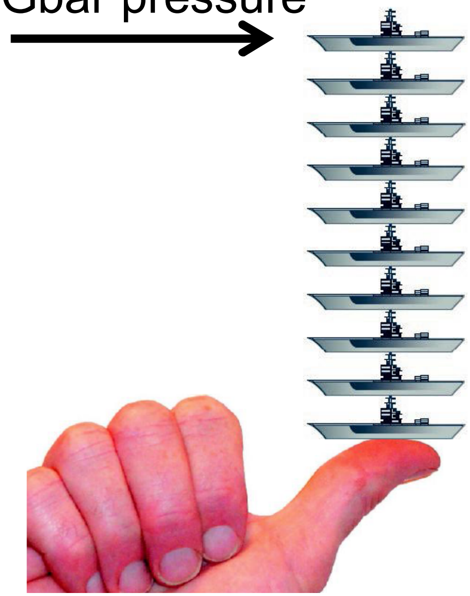
- **Timescale** : very short

  Astra ~ 40 fs (0.00000000000004 s)
  (equivalent fraction to 1 second in 1 million years)

- **Power**: staggeringly large

  1 Petawatt > 10,000x National Grid
  (1,000,000,000,000,000 Watts)

Gbar pressure



Imagine this power focussed to a spot 10x smaller than the width of a human hair…...