The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1953-56

International Workshop on the Frontiers of Modern Plasma Physics

14 - 25 July 2008

Fast ignition and extreme physics.

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Fast ignition and extreme physics.

Prof Bob Bingham

Rutherford Appleton Laboratory, UK

International Workshop on Frontiers in Modern Plasma Physics, ICTP 2008.

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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**

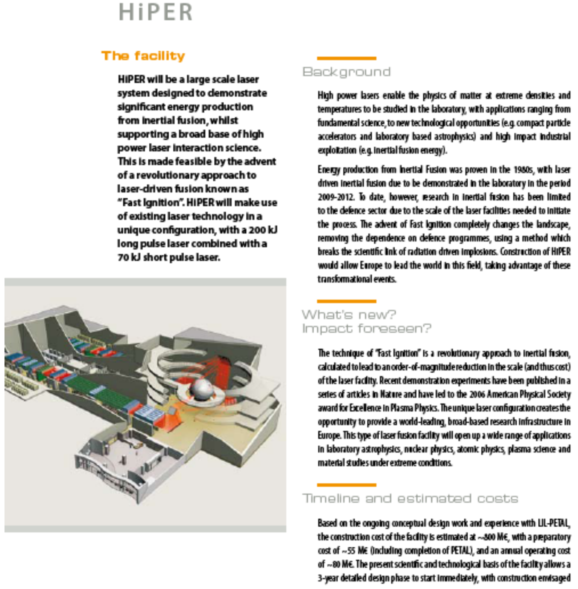
International links:

- **USA, Japan, China, South Korea, Canada**

Included on European roadmap (Oct 06)

UK endorsement – coordinators (Jan 07)

Start programme (Spring 08)



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

HiPER Fusion energy is entering a new era

- **Demonstration of IFE ignition within ~ 5 years**
- **Visibility of fusion via ITER (and IFMIF)**

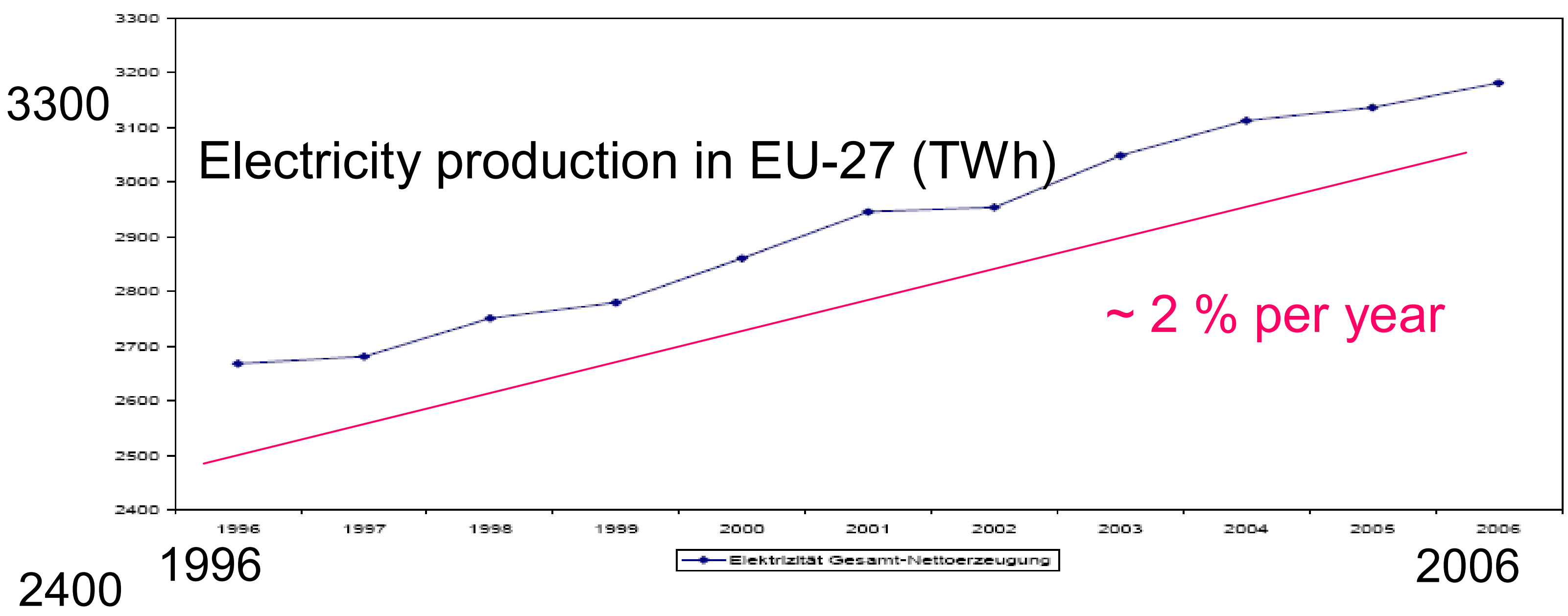
Need to ensure we provide options to move from scientific demonstrations to a commercial fusion energy program

- **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

Ludwig Boltzmann:

“The struggle for existence is the struggle for available energy”

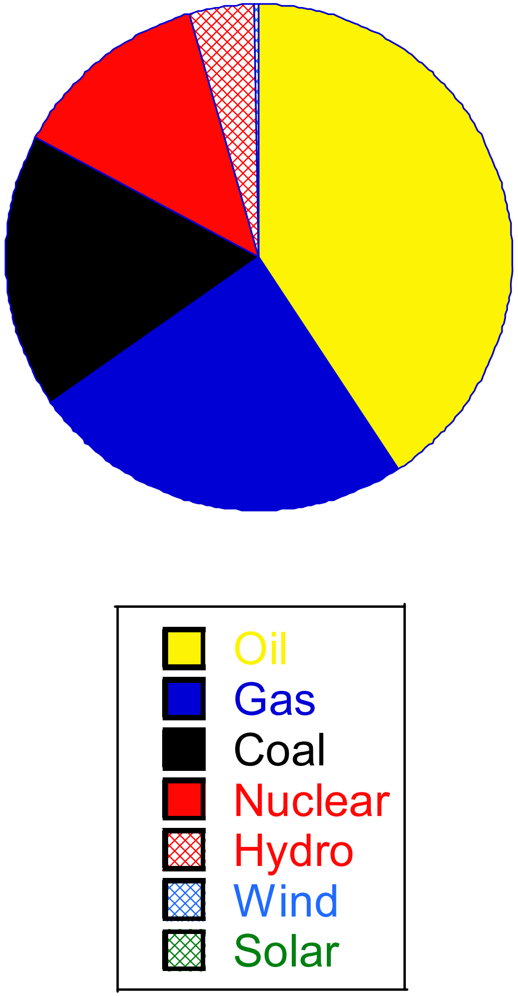
Abbildung 2: Entwicklung der Gesamtnettoelektrizitätserzeugung in EU-27 in TWh zwischen 1996 und 2006



dependence

The overall EU-25 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 %

Conclusions

Share of Renewable Energy in electricity production in EU

The transition from a largely carbon based supply
To one based on Renewable Energy 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 %)

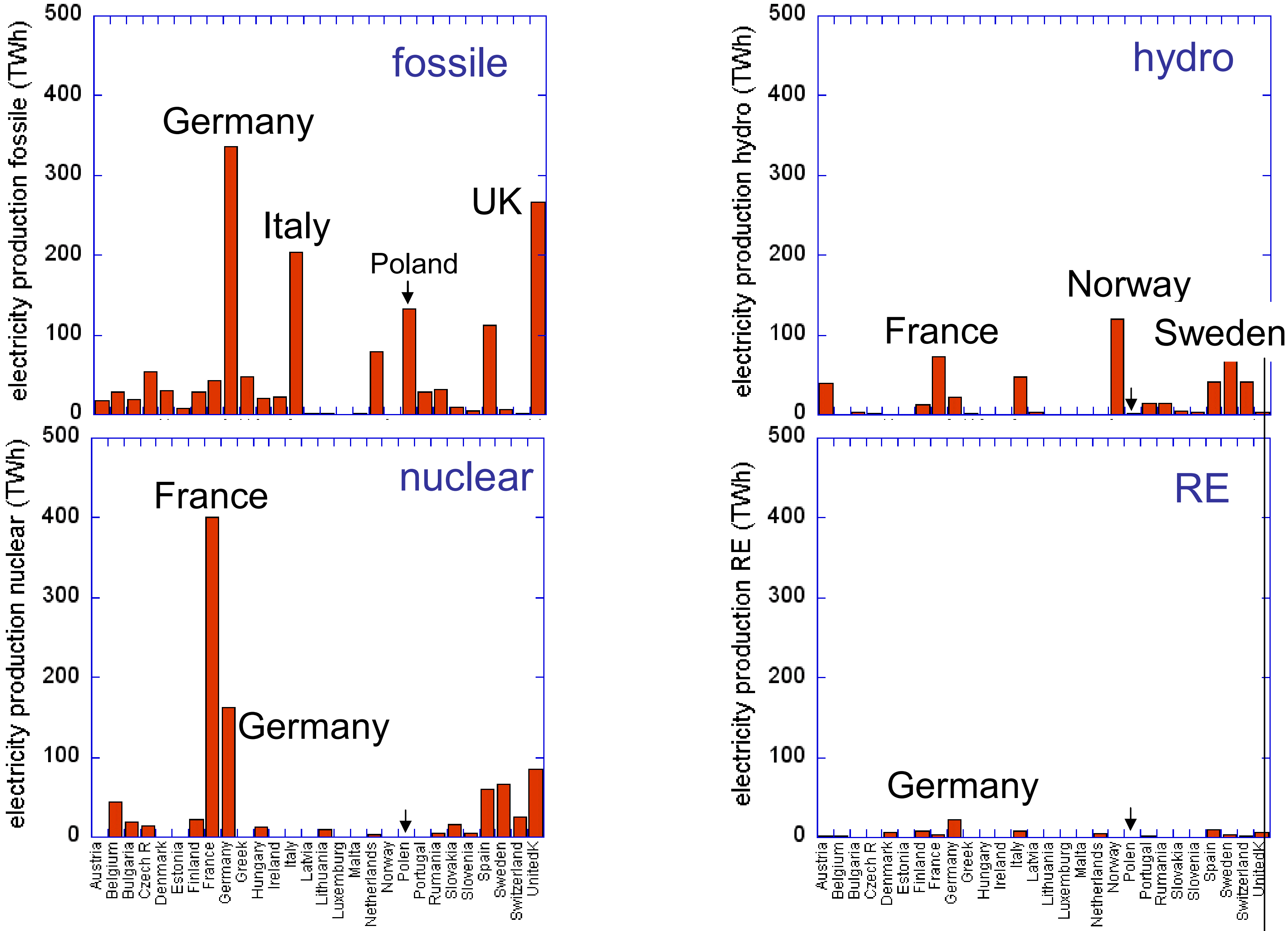
The expansion of Renewable Energy happens at different speeds within Europe.

No other EU country follows Germany in the enforced development of PV energy and wind energy (Spain is 2nd in wind).

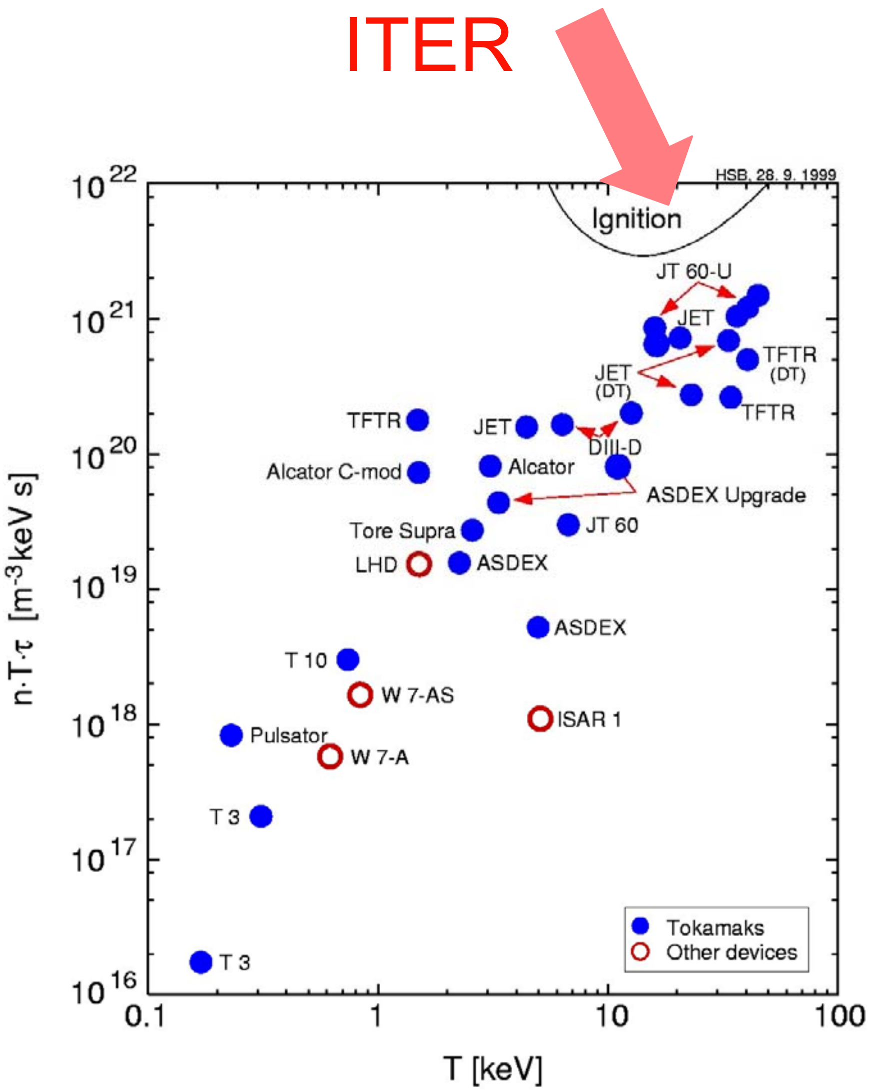
The actual potential of Europe is not used
(Wind at the coast, PV in the south)

The energy diversity of Europe

Electricity production from sources



Status of Fusion Research



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

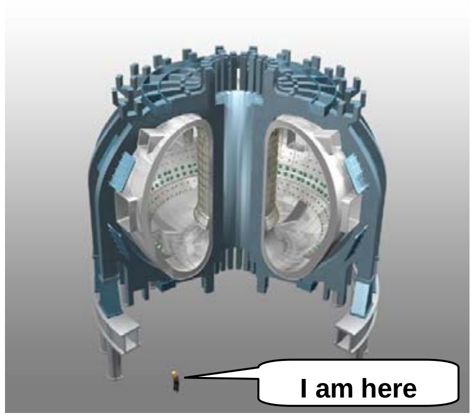
Fusion power for short time produced: 16 MW

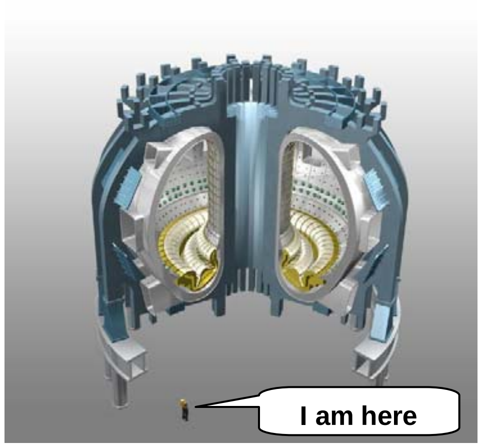
Design of an experimental reactor : ITER

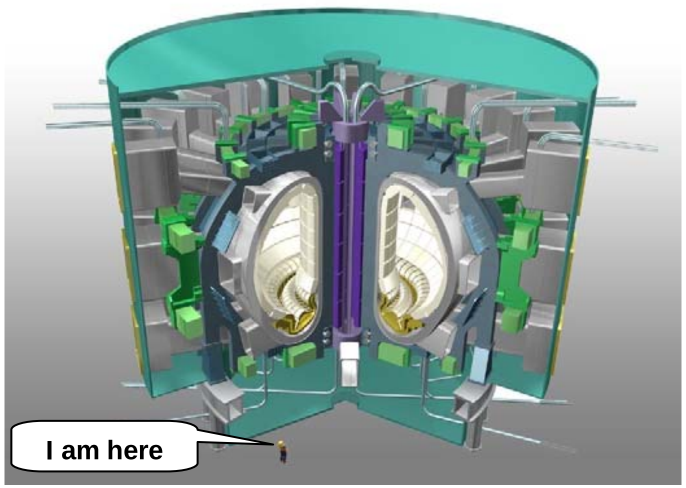
Optimisation concept for stellarators : W7-X

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



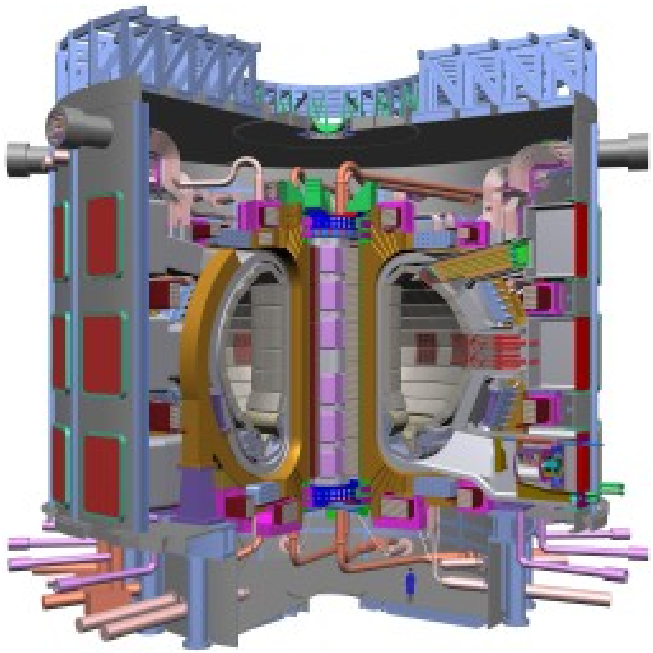




HiPER Fusion: We are entering a new era

- Demonstration of net energy production from laser fusion within **3 to 5 years**
- 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**



Science & Technology Facilities Council
Central Laser Facility

Putting laser numbers into perspective

- **Energy**: small

  Vulcan = 500J

4 finger KitKat….
973,000 J

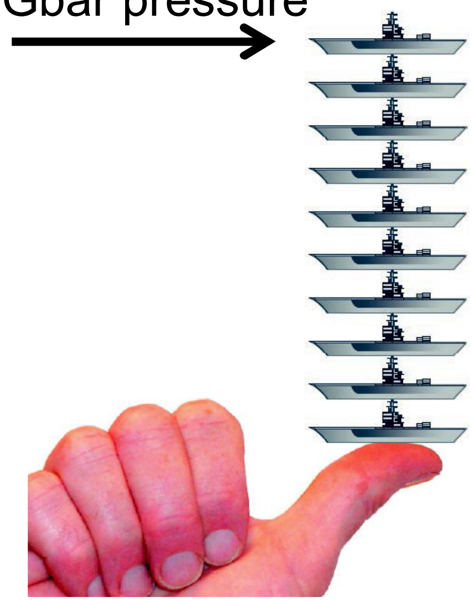
- **Timescale** : very short

  Astra ~ 40 fs

- **Power**: staggeringly large

  1 Petawatt > 10,000x National Grid

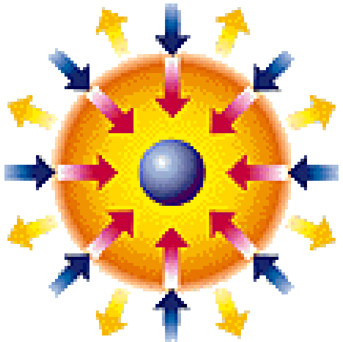
Gbar pressure



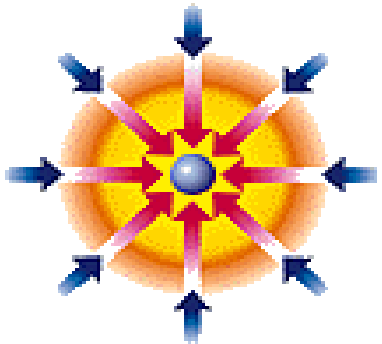
Imagine this power focussed to a spot 10x smaller than the width of a human hair…...

HiPER Conventional approach to IFE

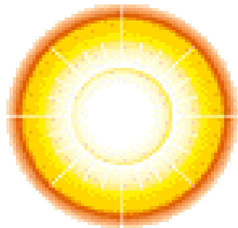
Lasers or X-rays symmetrically irradiate pellet



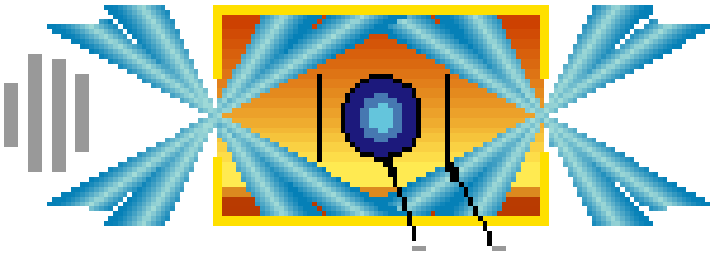
Hot plasma expands into vacuum causing shell to implode with high velocity



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



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



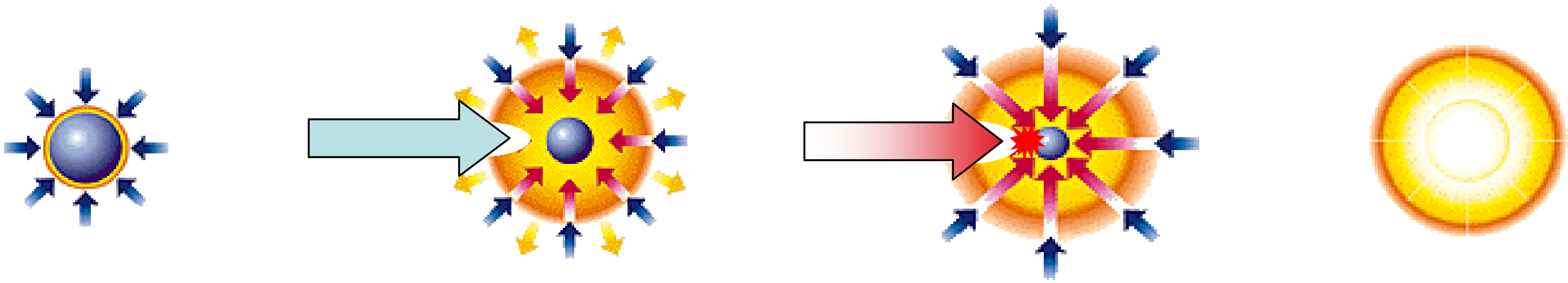
Indirect Drive

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

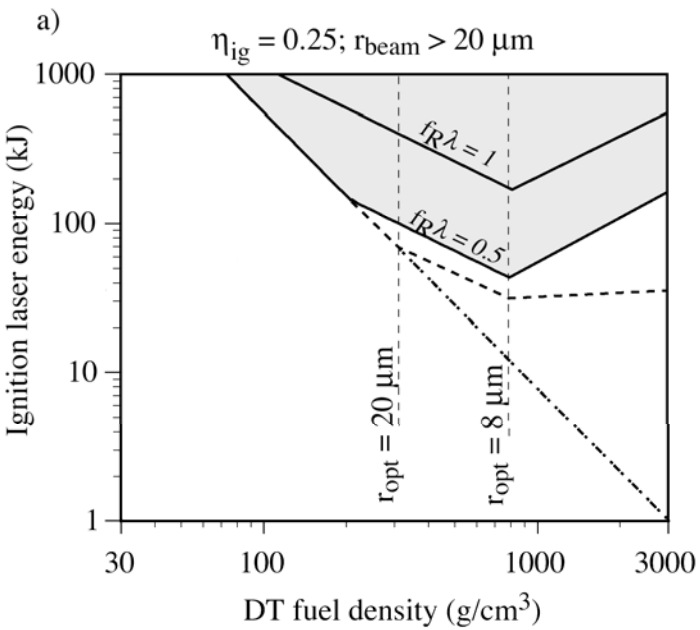
Matter compressed to ~300 gcm^{-3} Guide needed for the PW pulse (via a laser or static gold cone)

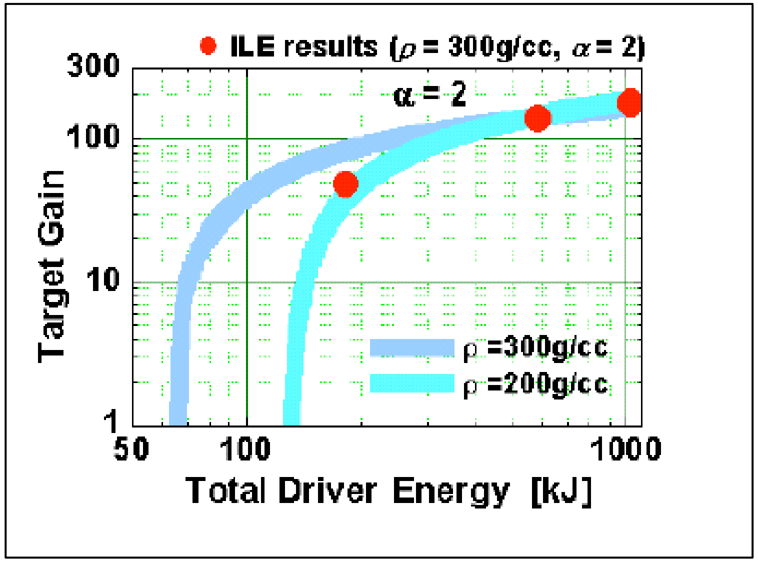
PW laser pulse is launched into channel generating MeV electrons that are stopped in the dense fuel

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

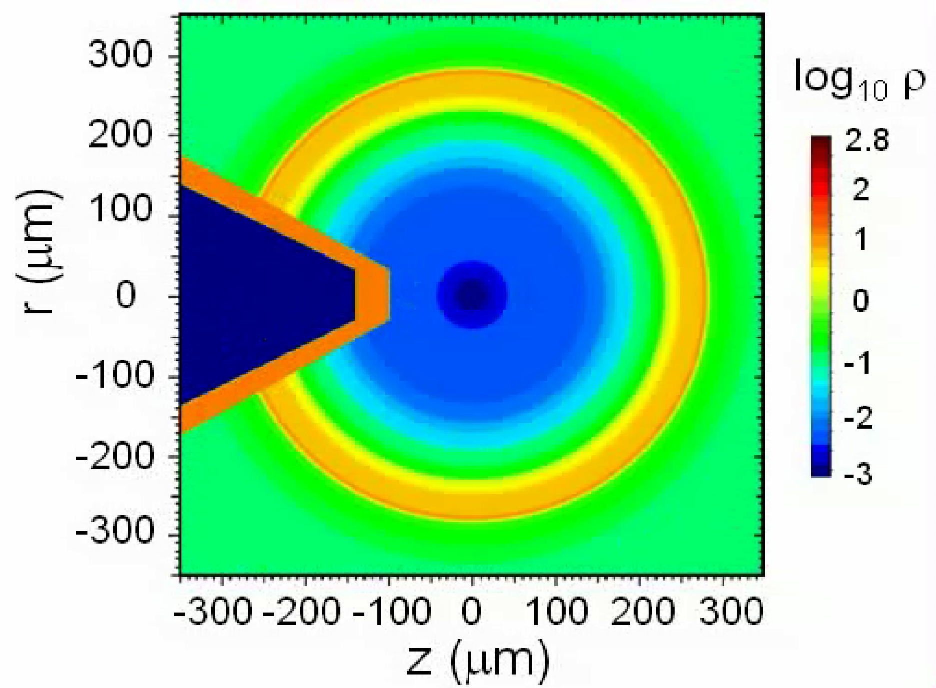


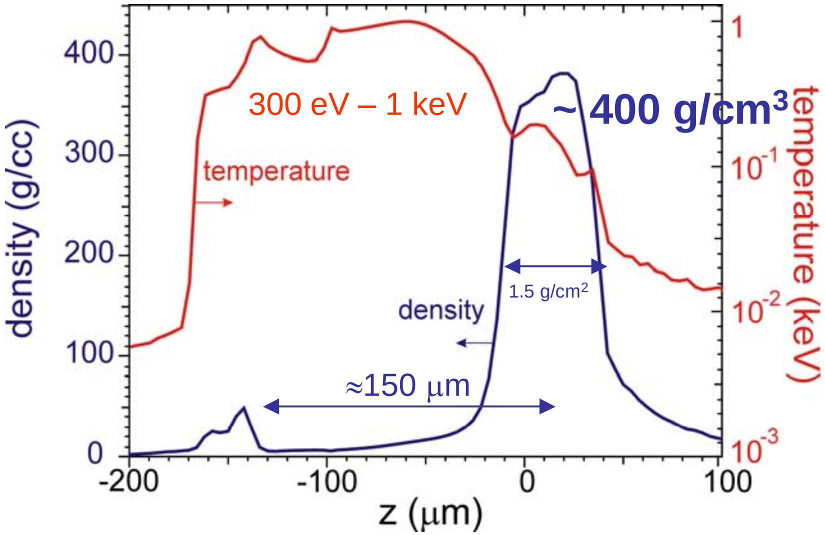


Analytical scaling laws

Specification based on initial modelling

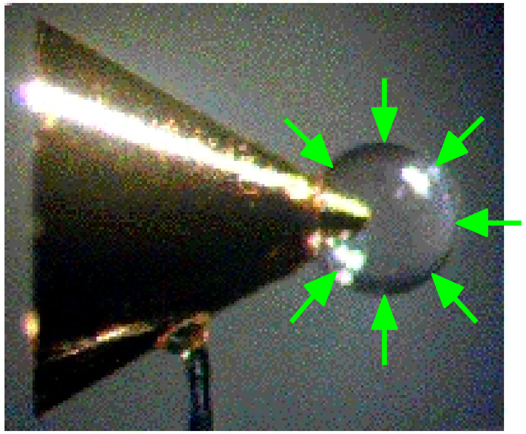
movie



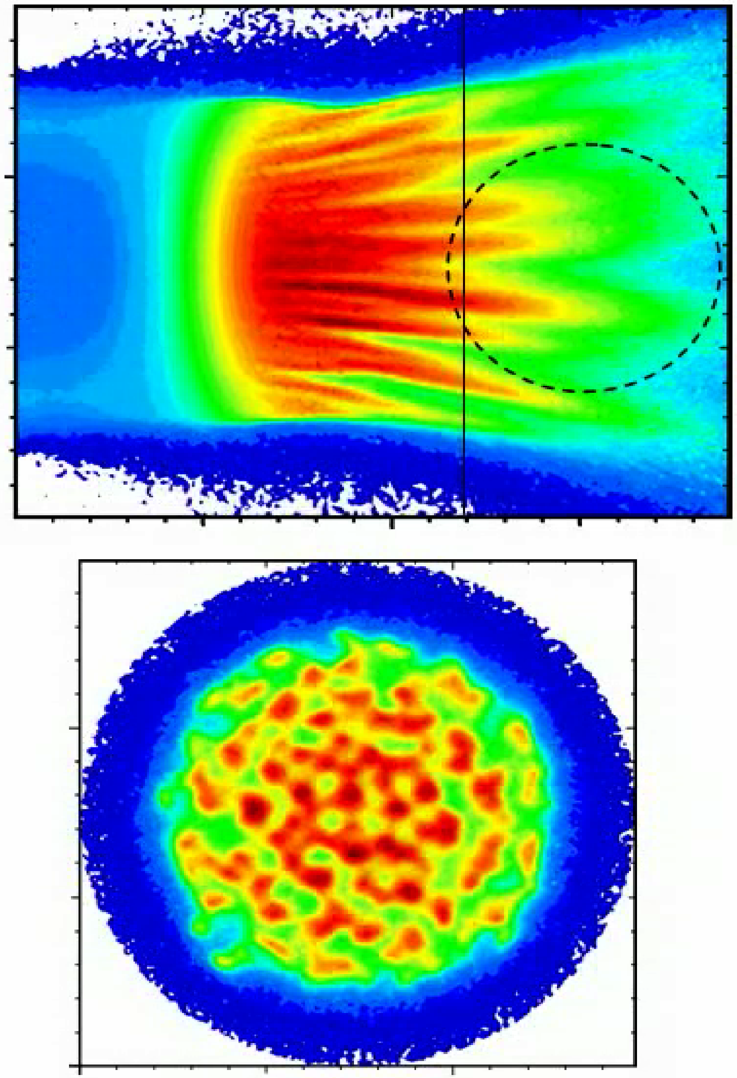


Analytical scaling laws

2D radiation hydrodynamic Implosion simulations



Specification based on initial modelling

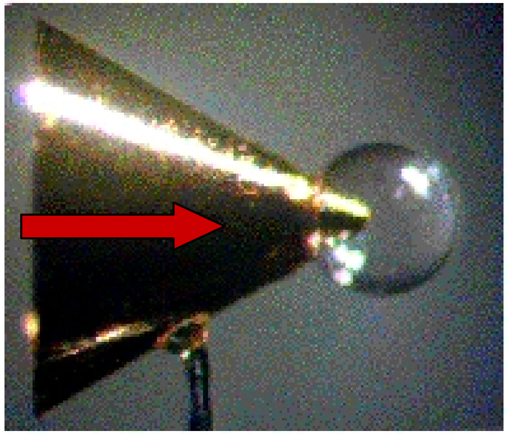


movie

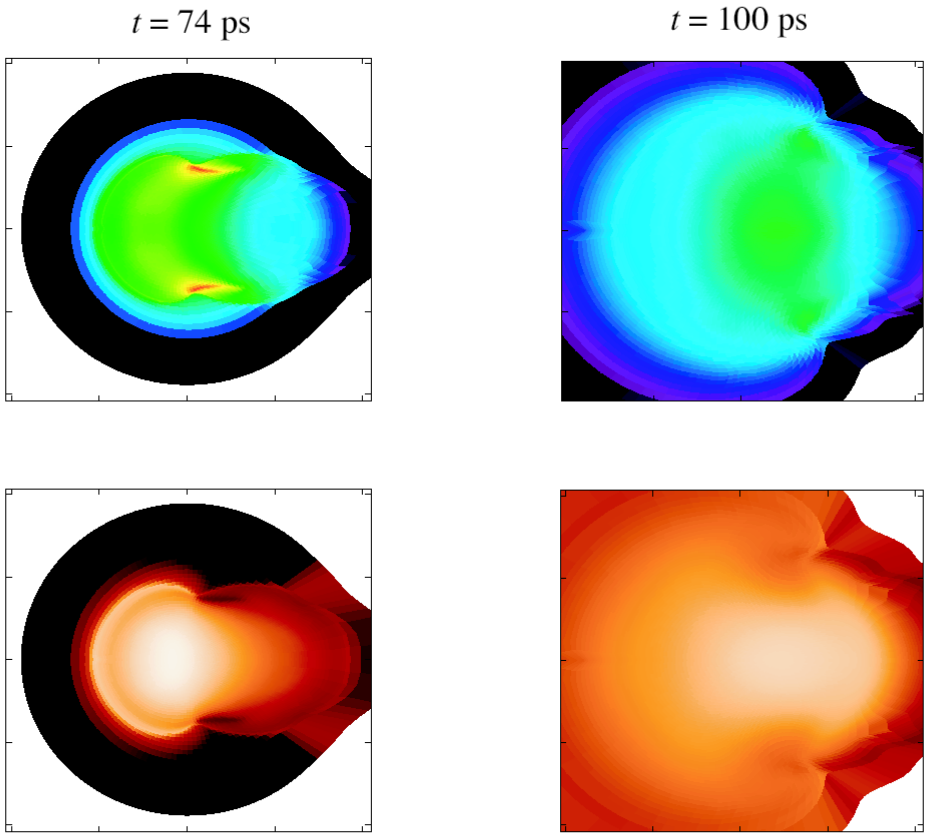
Analytical scaling laws

2D radiation hydrodynamic Implosion simulations

3D hybrid kinetic models of electron transport



Specification based on initial modelling



Analytical scaling laws

2D radiation hydrodynamic Implosion simulations

3D hybrid kinetic models of electron transport

Thermonuclear burn

Energy gains 50 – 100 predicted

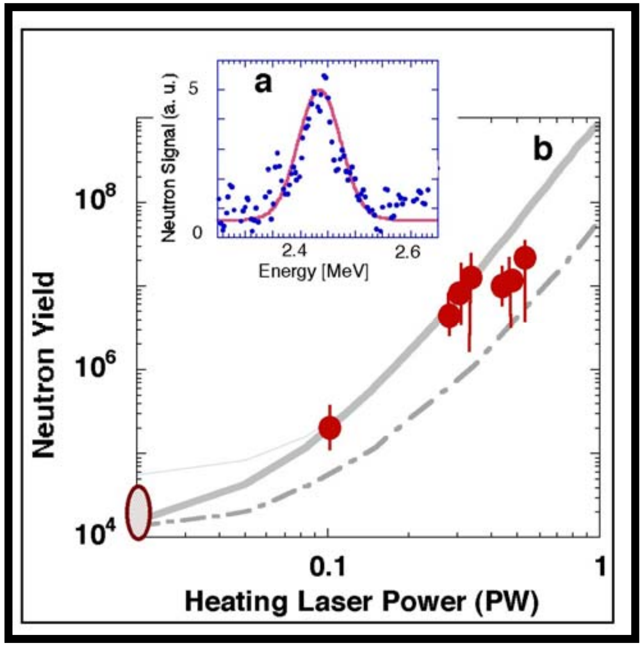
<u>Questions</u>: Are these simulations believable?
Flexibility for other advanced ignition options?

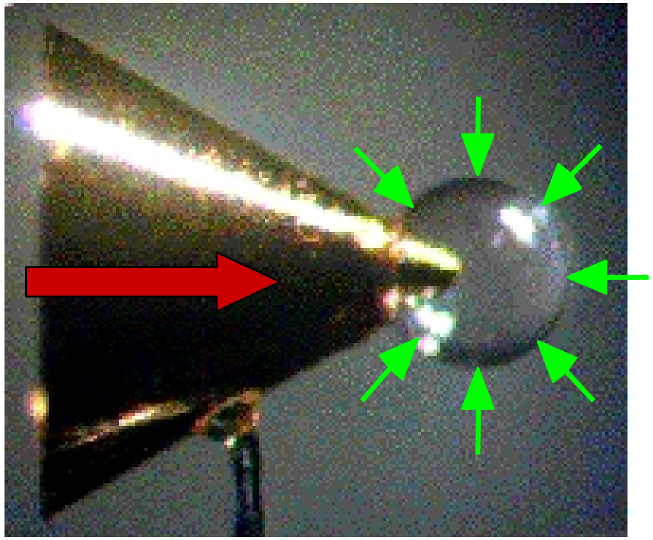
Answer via specific point designs on integrated facilities

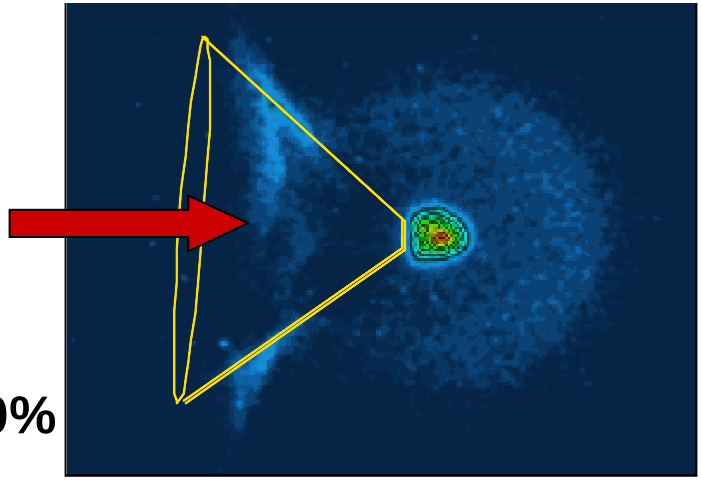
Experiments to date are promising

Cone-guided compression

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



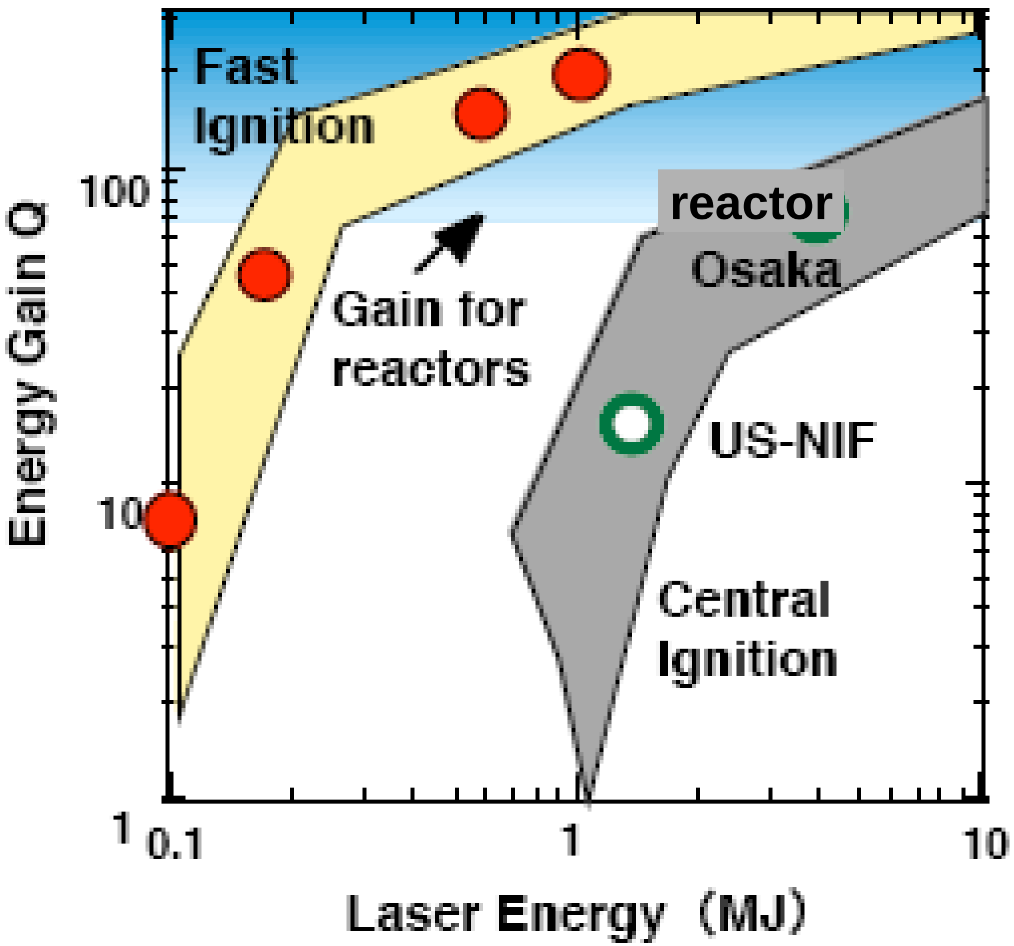




- **Neutron yields increased by factor 1000**
- **Laser to thermal energy conversion 20%-30%**

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

Fast Ignition

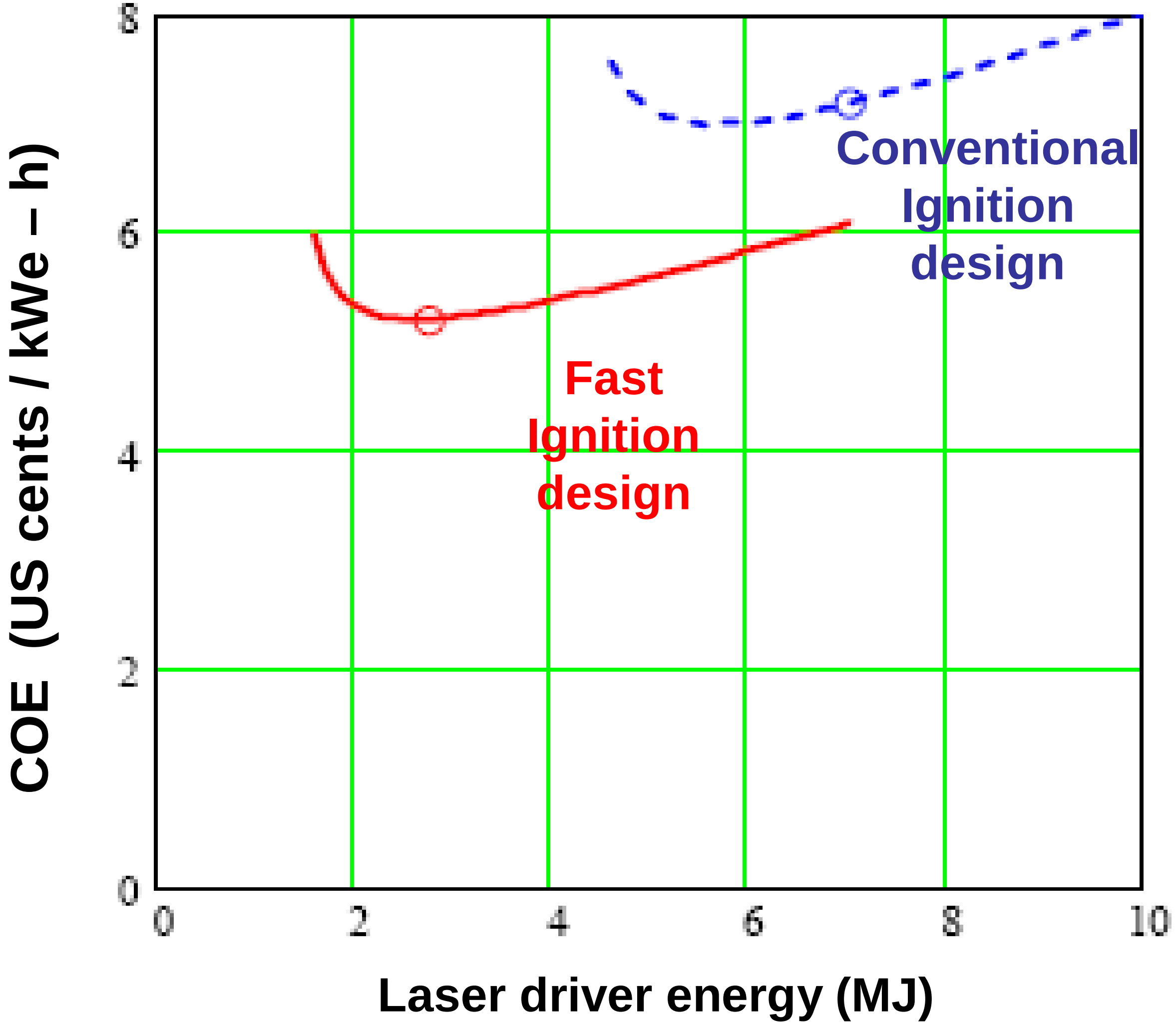


If successful, FI offers:

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

Predicted Cost of Electricity

Fast ignition both allows a smaller reactor and cheaper electricity



[Hogan & Meier (LLNL), IFSA 2003]

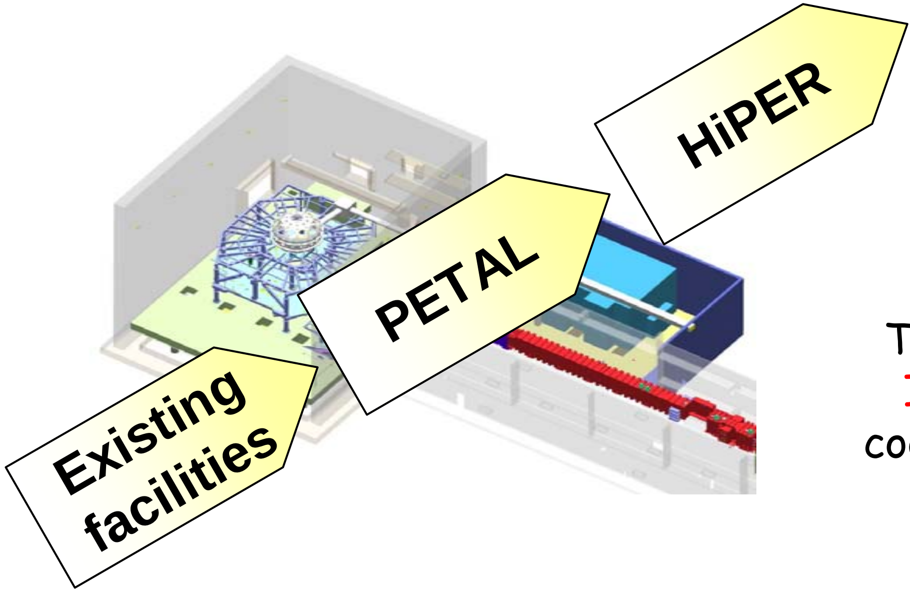
Aligned development strategy

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
0,5 – 10 ps
Up to 7 PW

60 kJ
8 beams
ns , 3ω

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

HiPER Coordinated international approach

Common strategic theme, with phased facility development in Europe:

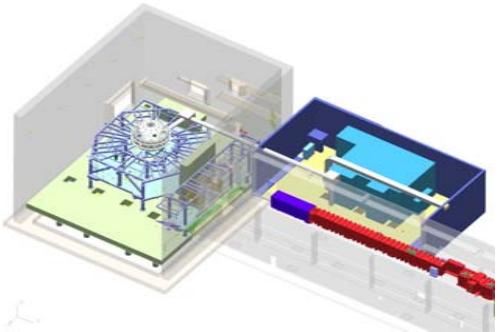
– PETAL (France) : Integration of PW and high energy beams

– HiPER : High yield facility

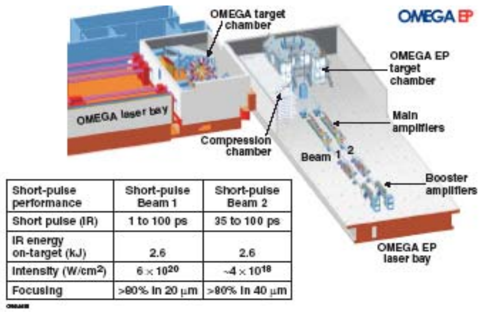
ESFRI

Coordinated scientific and technology development

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



PETAL
France



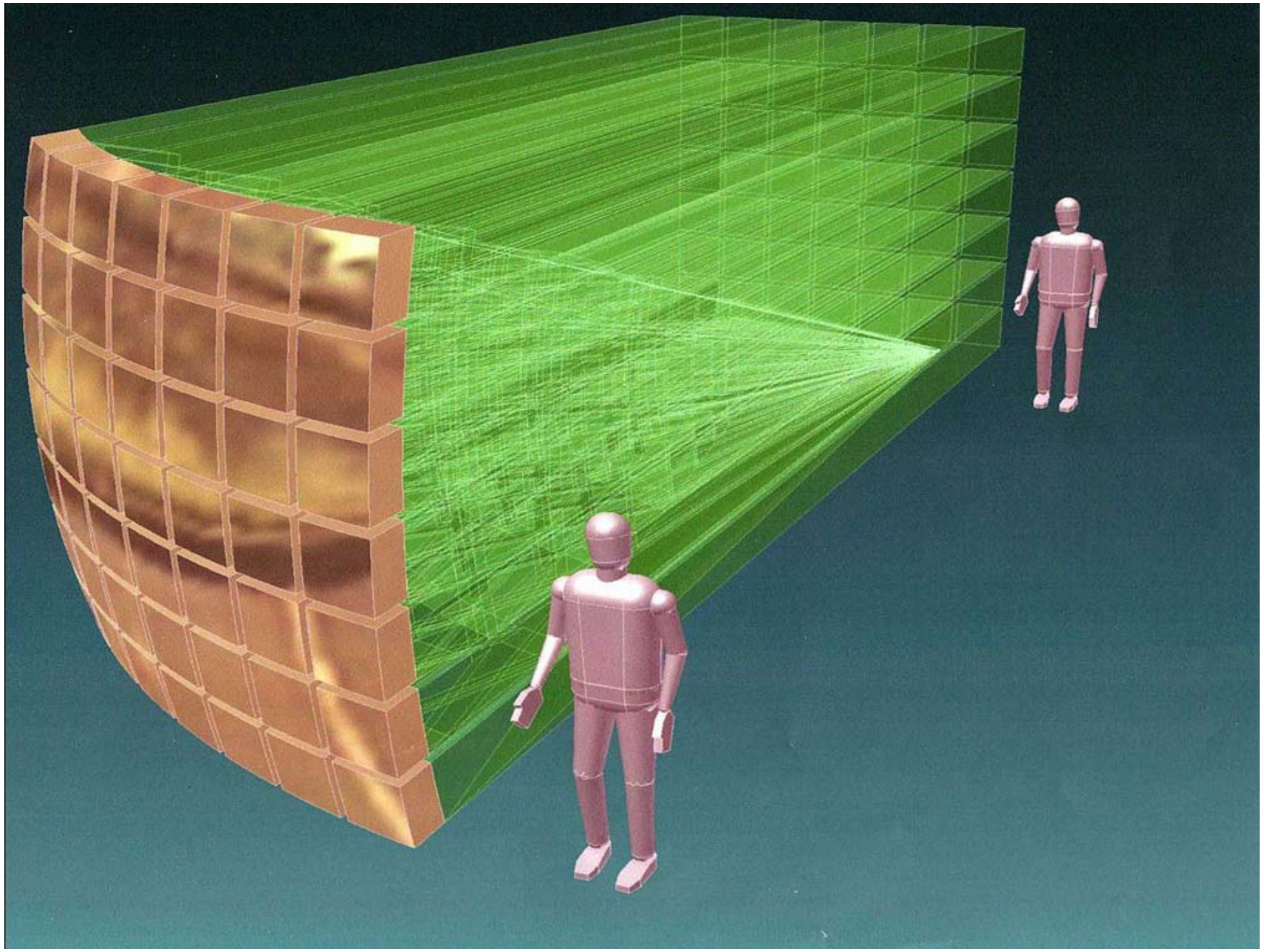
Short-pulse performance	Short-pulse Beam 1	Short-pulse Beam 2
Short pulse (IR)	1 to 100 ps	35 to 100 ps
IR energy on-target (kJ)	2.6	2.6
Intensity (W/cm^2)	6×10^{20}	$\sim 4 \times 10^{18}$
Focusing	>80% in 20 μm	>80% in 40 μm

OMEGA-EP
USA

FIREX
Osaka, Japan

Baseline laser specification

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



Baseline laser specification

2. “Sparkplug” laser
   70kJ, 10ps, 2ω

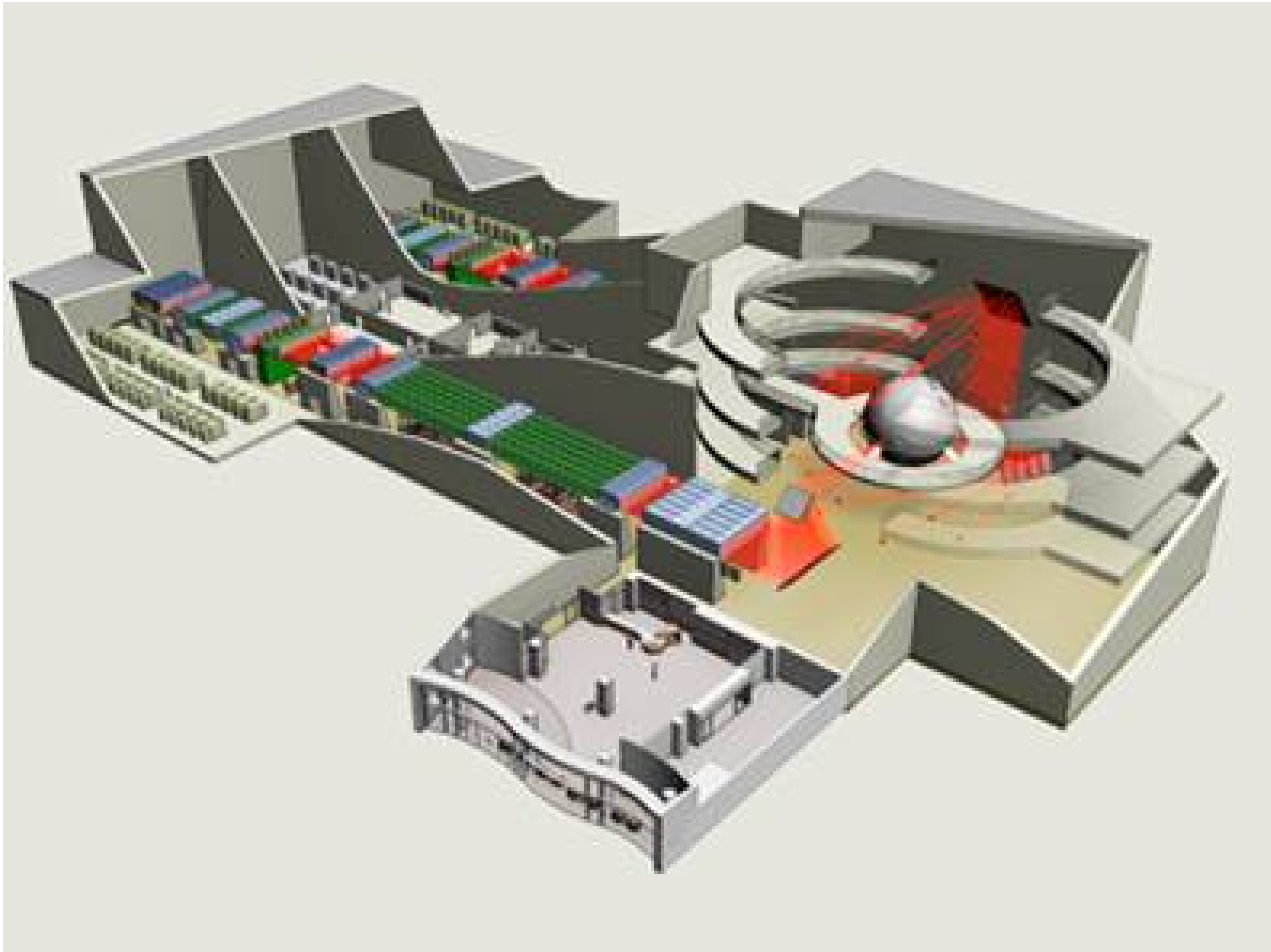
Baseline laser specification

3. Parallel development of IFE building blocks

Target manufacture

DPSSL laser

Reactor designs

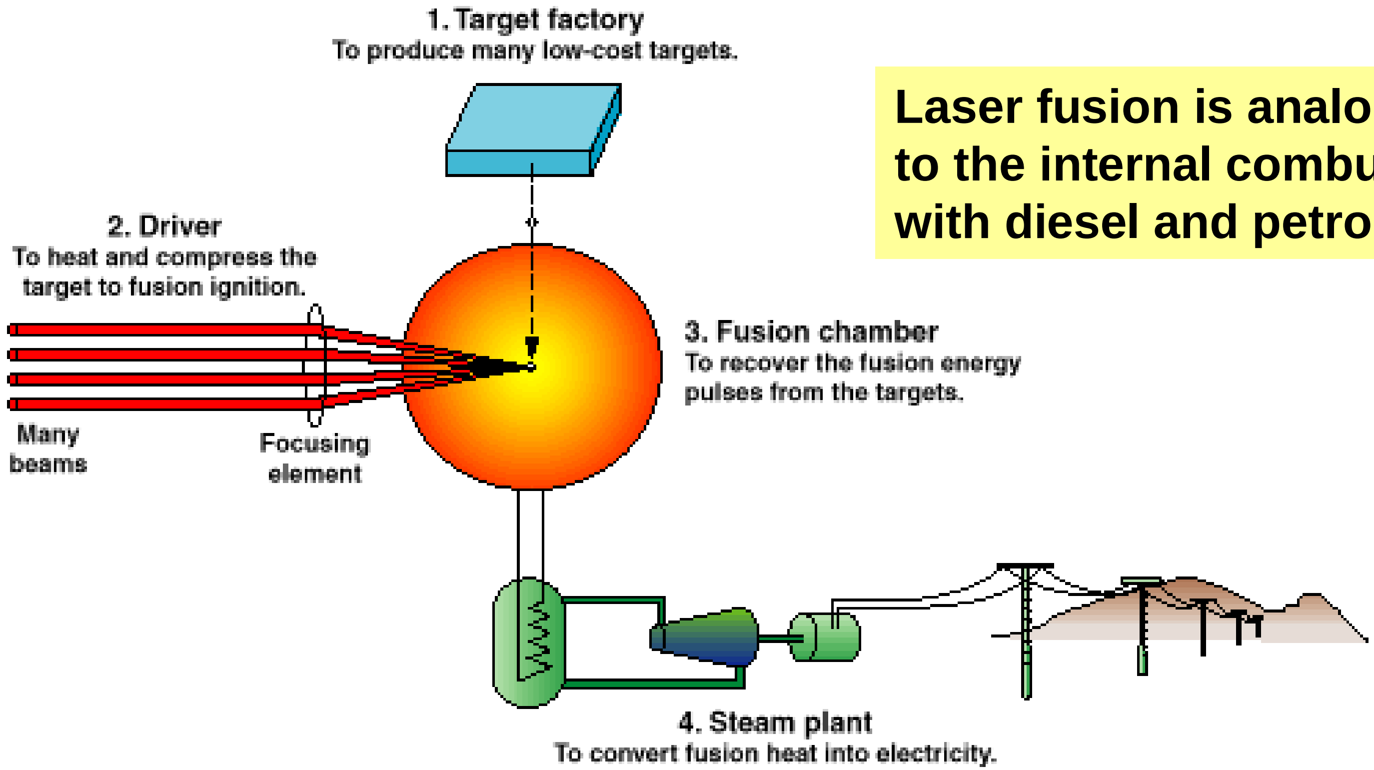


HiPER Inertial Fusion Power Plant

- **Complementary approach - scale of the problem demands multiple options**

- **Inertial fusion has been proven to work (1980s)**

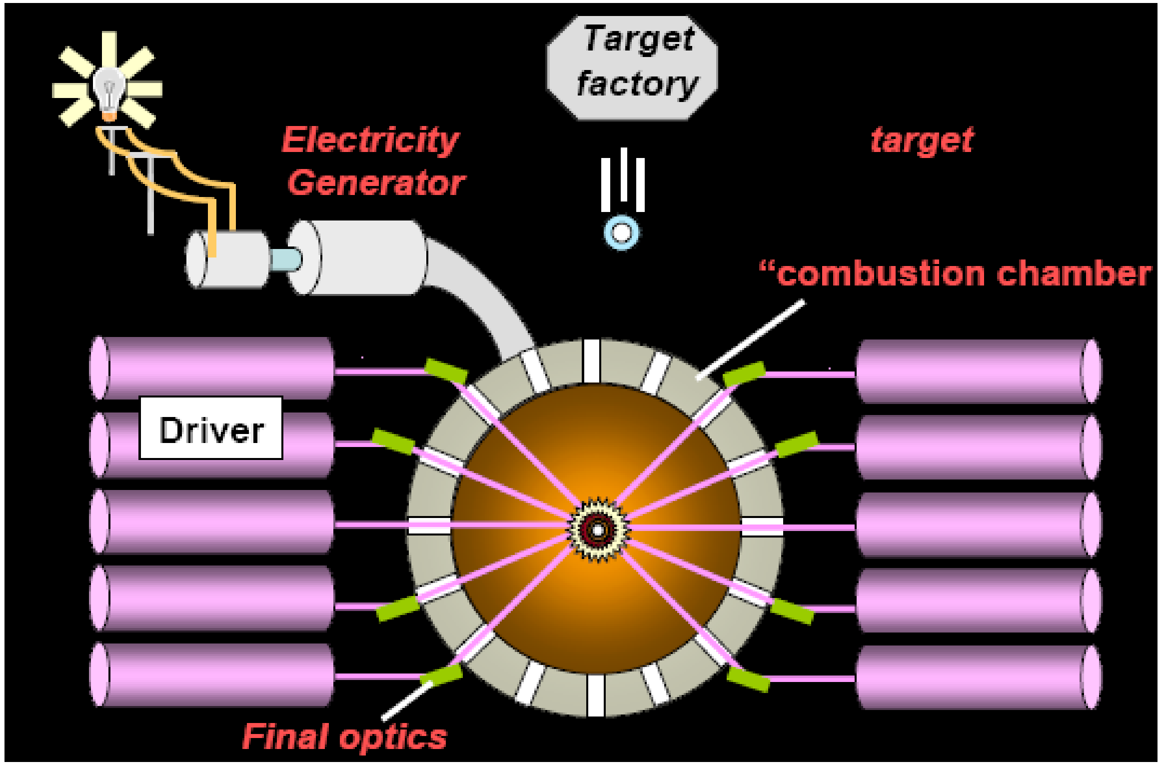
- **What now remains is to achieve this in the laboratory (2010) and define the route to a commercially viable power plant**



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

Inertial (Laser) Fusion

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

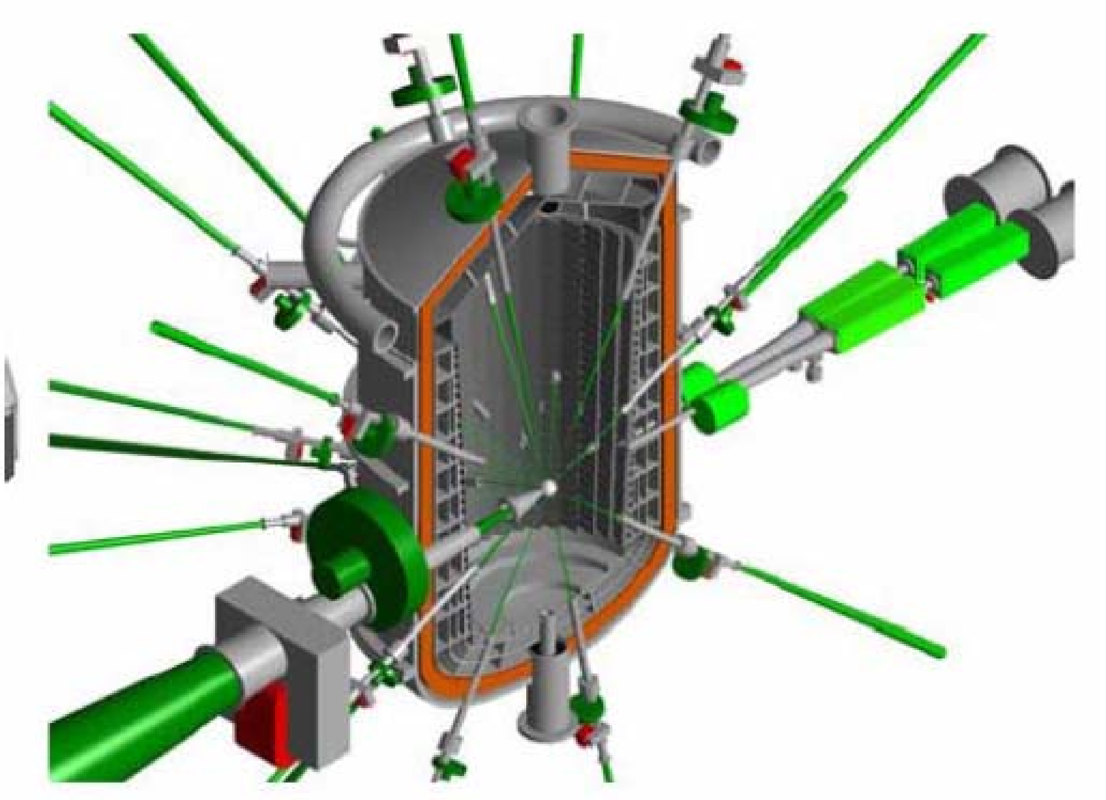


Laser fusion is analogous to the internal combustion engine: with diesel and petrol variants!

- **Complementary approach - scale of the problem demands multiple options**
- **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**


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

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 (2010-2012) and define the route to commercial and scientific exploitation**

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

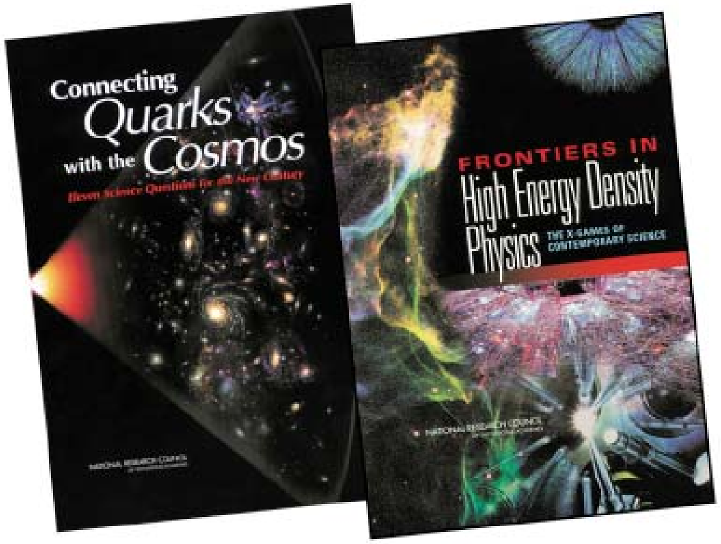
HiPER

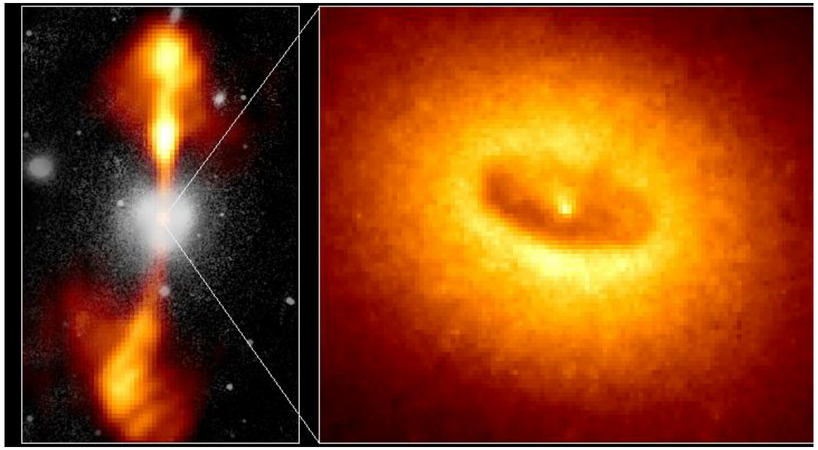
Summary

- 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

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**





HiPER Flexibility needed for a broad science base

- **Material properties under extreme conditions**

Planetary core studies

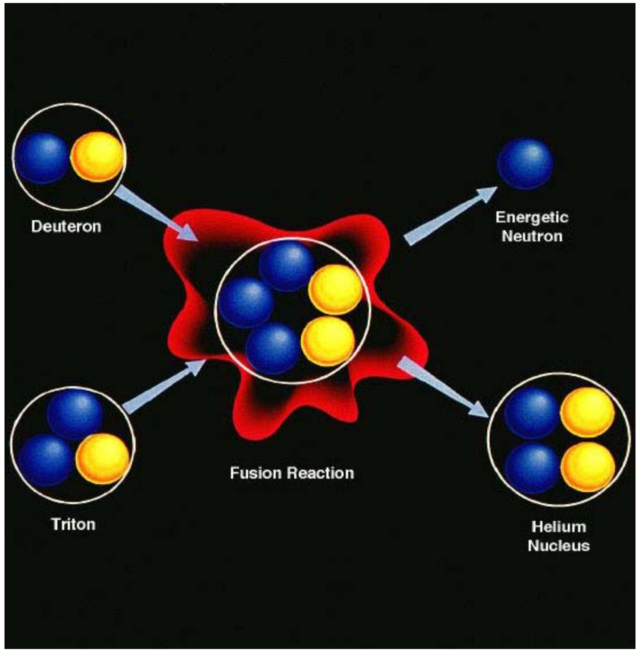
LTE and non-LTE Atomic physics

Warm Dense Matter research

Flexibility needed for a broad science base

• **Material properties under extreme conditions**

• **Nuclear Physics & Neutron Scattering**



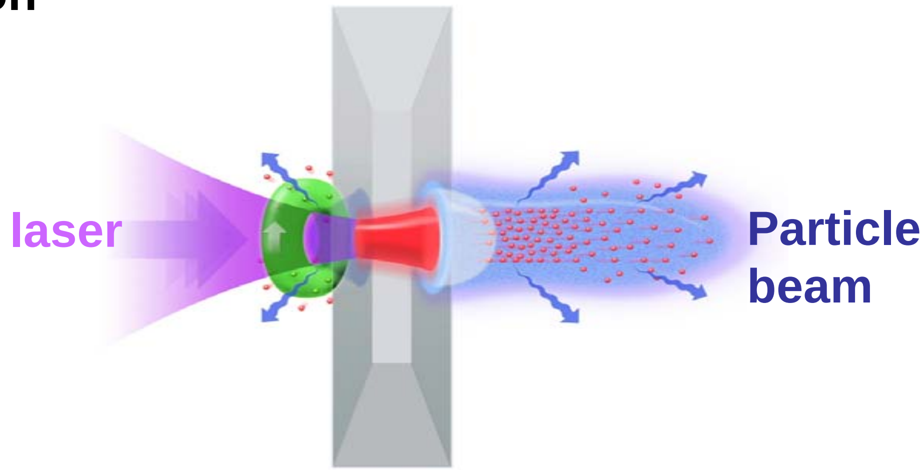
Synthesis of trans Fe nuclei (multi n0 capture)

Access to transient nuclear states

IFE based neutron scattering science

Flexibility needed for a broad science base

- Material properties under extreme conditions
- Nuclear Physics & Neutron Scattering
- **Ultra-Relativistic Particle acceleration**



Ultra-relativistic Plasma Physics

High energy electron, proton, ion … sources

Novel diagnostic tools

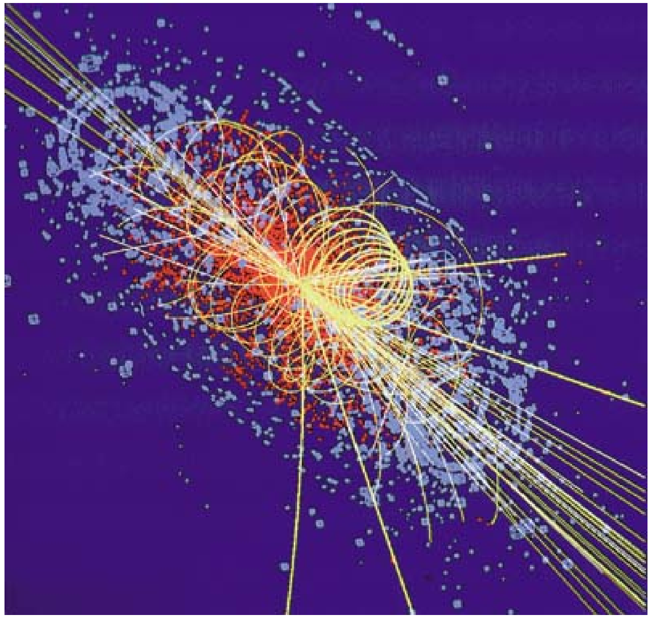
Flexibility needed for a broad science base

- Material properties under extreme conditions
- Nuclear Physics & Neutron Scattering
- Ultra-Relativistic Particle acceleration
- **Laboratory astrophysics**

Recreation of stellar cores and coronal plasma
He to C burning stars
Supernovae explosion dynamics
Interstellar jet dynamics
Planetary Nebulae
Gamma ray burster mechanisms
Neutron star atmospheres
Giga-Gauss magnetic fields
Landau Quantisation of states
Planetary Cores - metalisation
"Large" Volume Experiments @ GBar pressures

HiPER Flexibility needed for a broad science base

- Material properties under extreme conditions
- Nuclear Physics & Neutron Scattering
- Ultra-Relativistic Particle acceleration
- Laboratory astrophysics
- **Extreme field physics**



Non-linear Quantum Electrodynamics

Pair production directly from the vacuum

Production of Pion, Muon beams

Vacuum Polarisation studies

Gravitational & Quantum Field Theory

Gravitational Equivalence

Unruh (Hawking) Radiation?

High energy accelerator physics

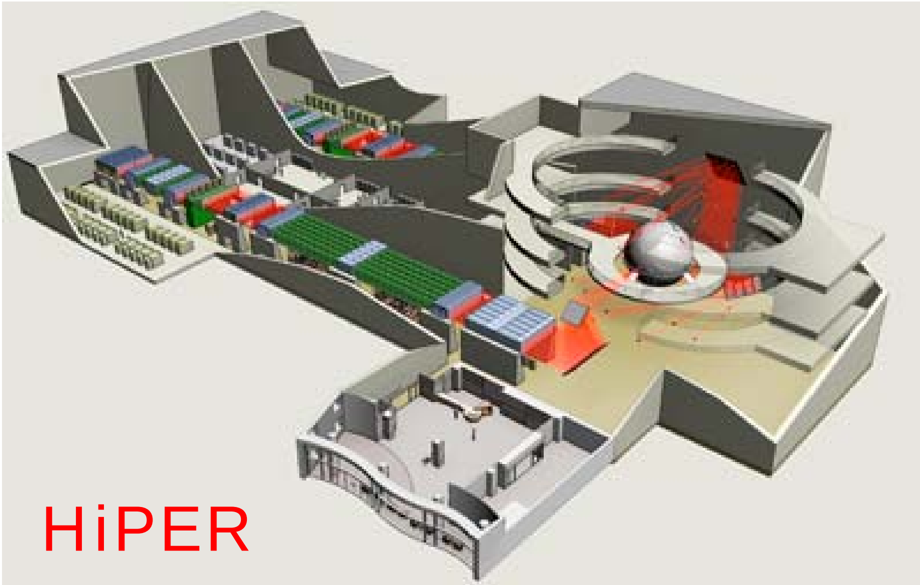
TeV e - e and g – g effects

GeV / nucleon ion acceleration

HiPER High Power Lasers

- Gemini - 2 Beam 1 PW 3 shots/min
  15 J, 30 fs/beam
- Vulcan - 1 Beam 1 PW
- Vulcan upgrade – 10 PW OPCPA system
- Future
  - HiPER, ELI

$I > 10^{24} – 10^{25}$ W/cm^2



HiPER Quantum Vacuum Fluctuations

- Electromagnetic vacuum QED
- Chromodynamic vacuum QCD
- Gravitational vacuum QGD?
- QED
  - Intense E and B fields interrogate the electromagnetic vacuum.
  - Laser projects such as HiPER and ELI will be able to experimentally investigate the vacuum.
  - Lamb Shift (1947) – verified.
  - Casimir Effect (1949) – verified.
  - e^+e^- creation (only in presence of matter)
  - Photon-photon scattering …
  - Unruh radiation …

- QGD? – Planck scale physics. $E_p = 10^{19}$ GeV
  - Matter creation
  - Hawking radiation
  - Possible to detect using atom/matter beams.

QED – Electron's Anomalous Magnetic Moment

$$\frac{1}{2} g_{\exp t} = 1.0011596521\;8085\;(76)$$

- Measured in 2006
  - Incredible precision 1:10^{12}
  - Freeman Dyson sent a letter of congratulations
  - "We thought of QED as a jerry-built structure. We didn't expect it to last more than 10 years before a more solidly built theory replaced it. But the ramshackle structure still stands. The revealing discrepancies we hoped for have not yet appeared. I'm amazed at how precisely Nature dances to the tune we scribbled so carelessly 57 years ago, and at how the experimenters and theorists can measure and calculate her dance to a part in a trillion."

Freeman J. Dyson (1923–)

- Landau Quantization
  - Quantization of electron motion transverse to magnetic field
  - Important if electron energy is less than energy between Landau levels

$$k_B \le \hbar\omega = 11.6 B_{12} \ \text{kev}$$

- For neutron stars $B \sim 10^{10} - 10^{12}\, G$
- Magnetars $B \sim 10^{14} - 10^{15}\, G$
- White dwarfs $B \sim 10^{6} - 10^{9}\, G$
- Lab. Max. field so far is in laser plasmas.

$$B \sim 10^{9}\, G$$

HiPER Electron quantization

- Electron energy

$$E = m_e c^2 \left[1 + 2nb + \left(\frac{p_z}{m_e c} \right)^2 \right]^{1/2}$$

[Pavlov & Gnedin, 1984]

- *n* = 0, 1, 2, …   is the number of Landau levels
- p_z is the parallel momentum
- *b* parameter is due to quantum recoil
- If photon energy $\hbar\omega$ is comparable to the electron energy *E*, must include quantum recoil.

$$\hbar\omega_B = \hbar \frac{eB_c}{m_e c} = m_e c^2 \qquad B_c = \frac{m_e{}^2 c^3}{\hbar e} = 4.4 \times 10^{13} G.$$

Quantum Electrodynamical Processes in Strong Fields

- Relativistic effects are important for large B of the order B_c, i.e.
  - in neutron star magnetospheres
  - Electron-positron pair creation
  - Vacuum polarization
  - Photon splitting
- Single photon pair creation is a forbidden process in a field free region.
- e^+e^- creation:-

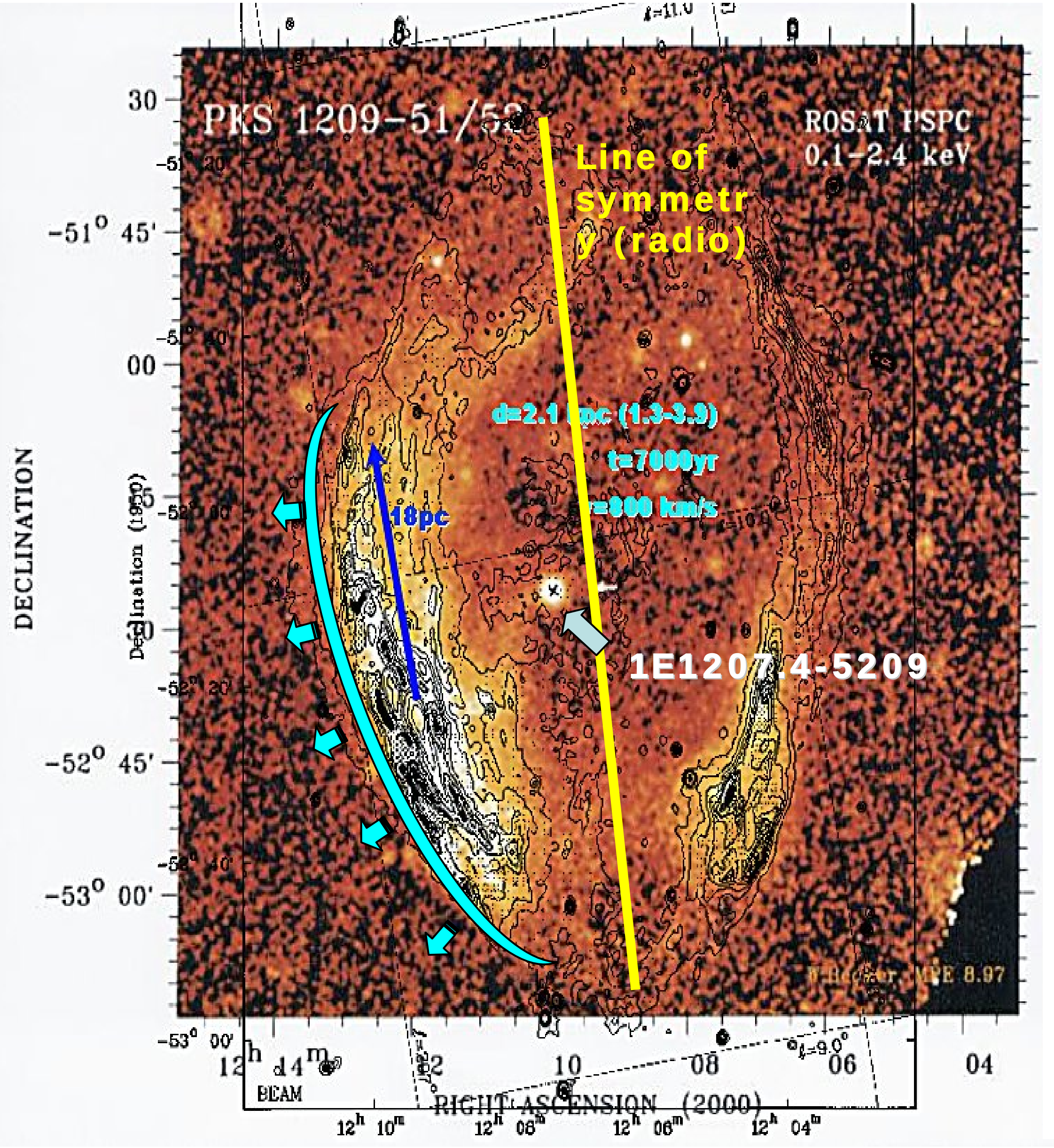
$$\hbar\omega\sin\theta > m_e c^2\left[1+\left(1+{2B}/{B_c}\right)^{1/2}\right]$$

- Vacuum polarization
- Propagation of radiation in a magnetized vacuum
  - Like an ordinary anisotropic medium (i.e. plasma)
- For $B \approx B_c$

$$n_{1,2} = 1 + \frac{1}{90\pi}\frac{e^2}{\hbar c}\left(\frac{B\sin\theta}{B_c}\right)^2 F_{1,2}$$

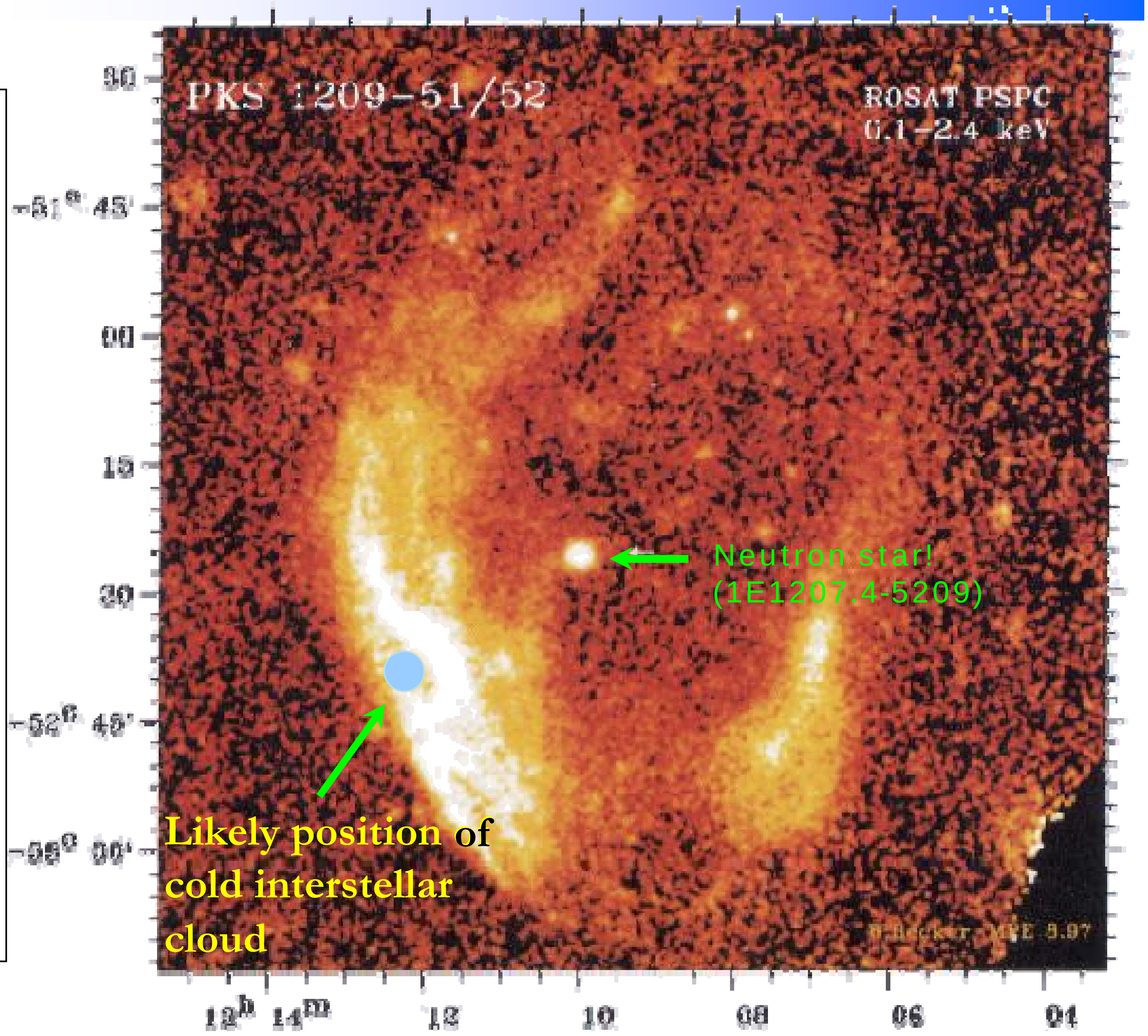
- where 1,2 represent different polarizations.

PKS1209-52 & 1E1207.4-5209

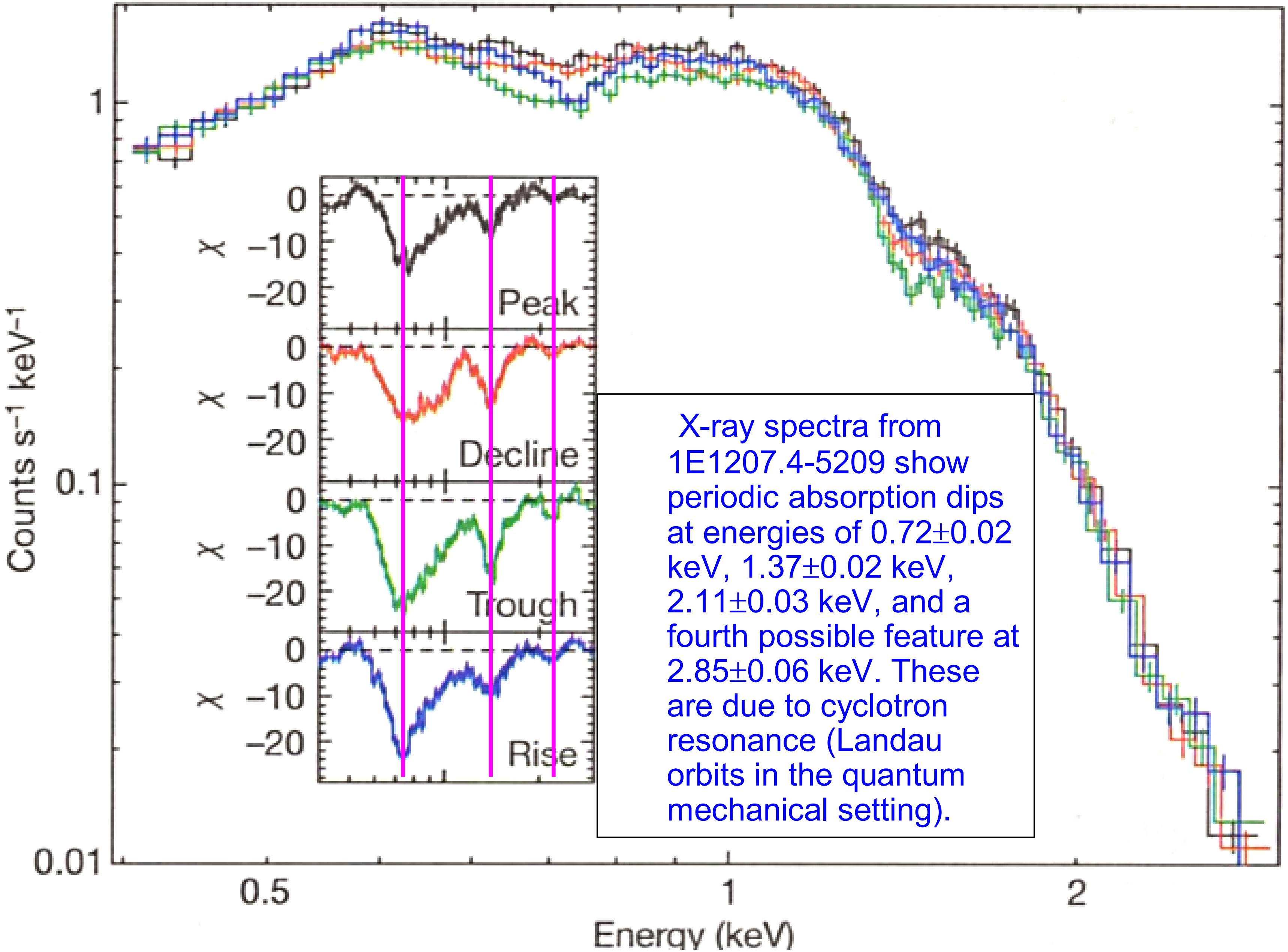


PKS1209-52 Supernova

The supernova remnant PKS 1209-51/52 has an expansion of about 150 light years and its age is estimated to be 10,000 years. Its structure is attributed to an axially symmetrical ejection of matter of the exploding star. Near the geometric centre of the remnant there is a compact X-ray source (marked by the arrow) which is neither detected in optical light nor at radio frequencies. With a high probability, it is a neutron star created by the same explosion; its surface temperature of three million degrees is so hot that it is emitting exclusively X-rays.



HiPER Cyclotron Absorption Features



X-ray spectra from 1E1207.4-5209 show periodic absorption dips at energies of 0.72±0.02 keV, 1.37±0.02 keV, 2.11±0.03 keV, and a fourth possible feature at 2.85±0.06 keV. These are due to cyclotron resonance (Landau orbits in the quantum mechanical setting).

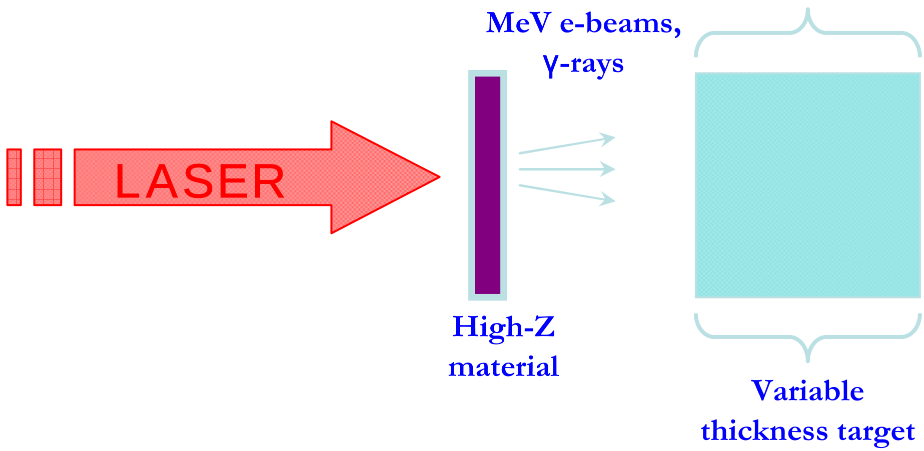
Positron, γ-ray Production
(Heitler, 1954)

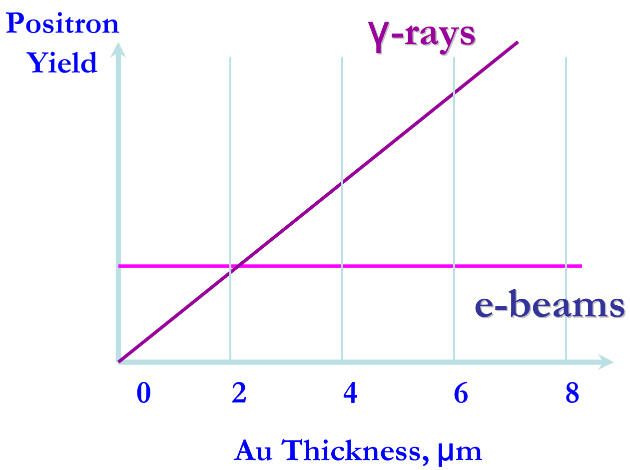
a) electron-beam ⇨ positrons

$$e^- + Z \Rightarrow 2e^-e^+ + Z$$

b) γ-ray ⇨ positrons

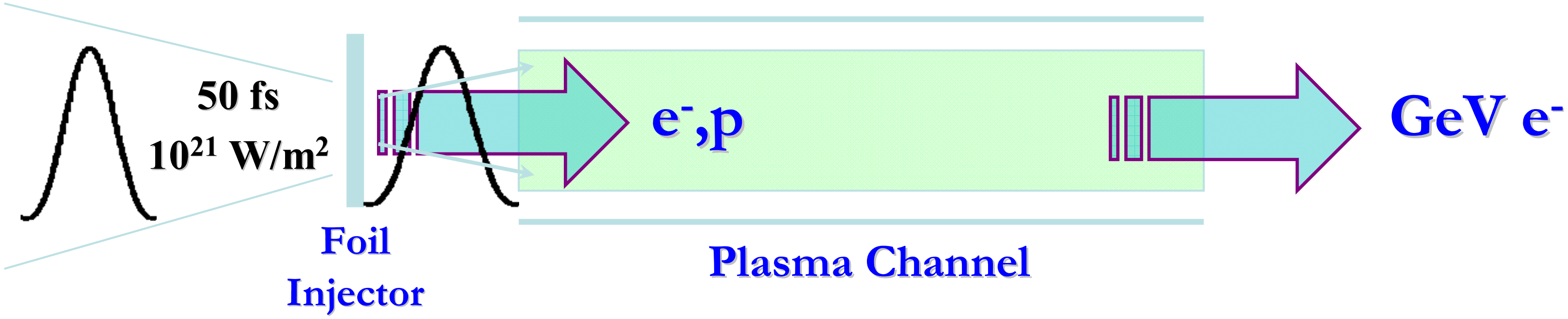
$$\gamma + Z \Rightarrow e^-e^+ + Z$$



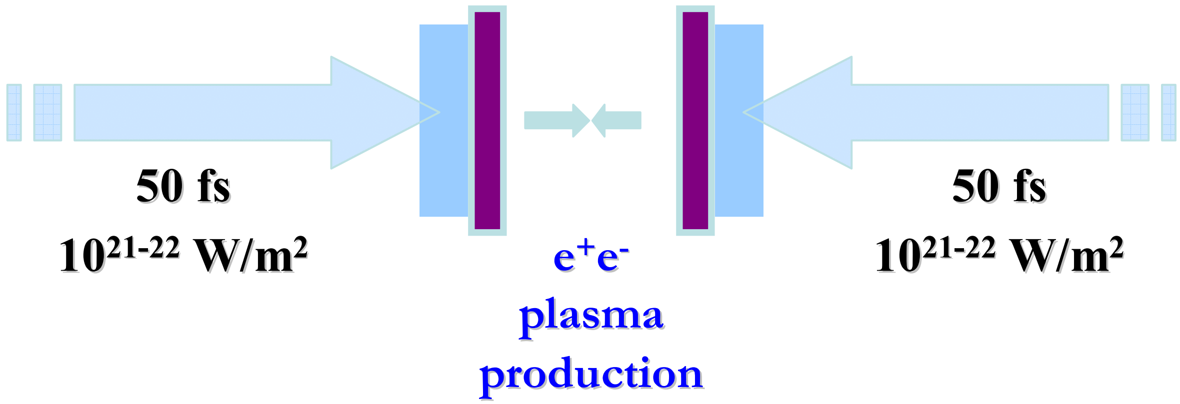


HiPER Experiments

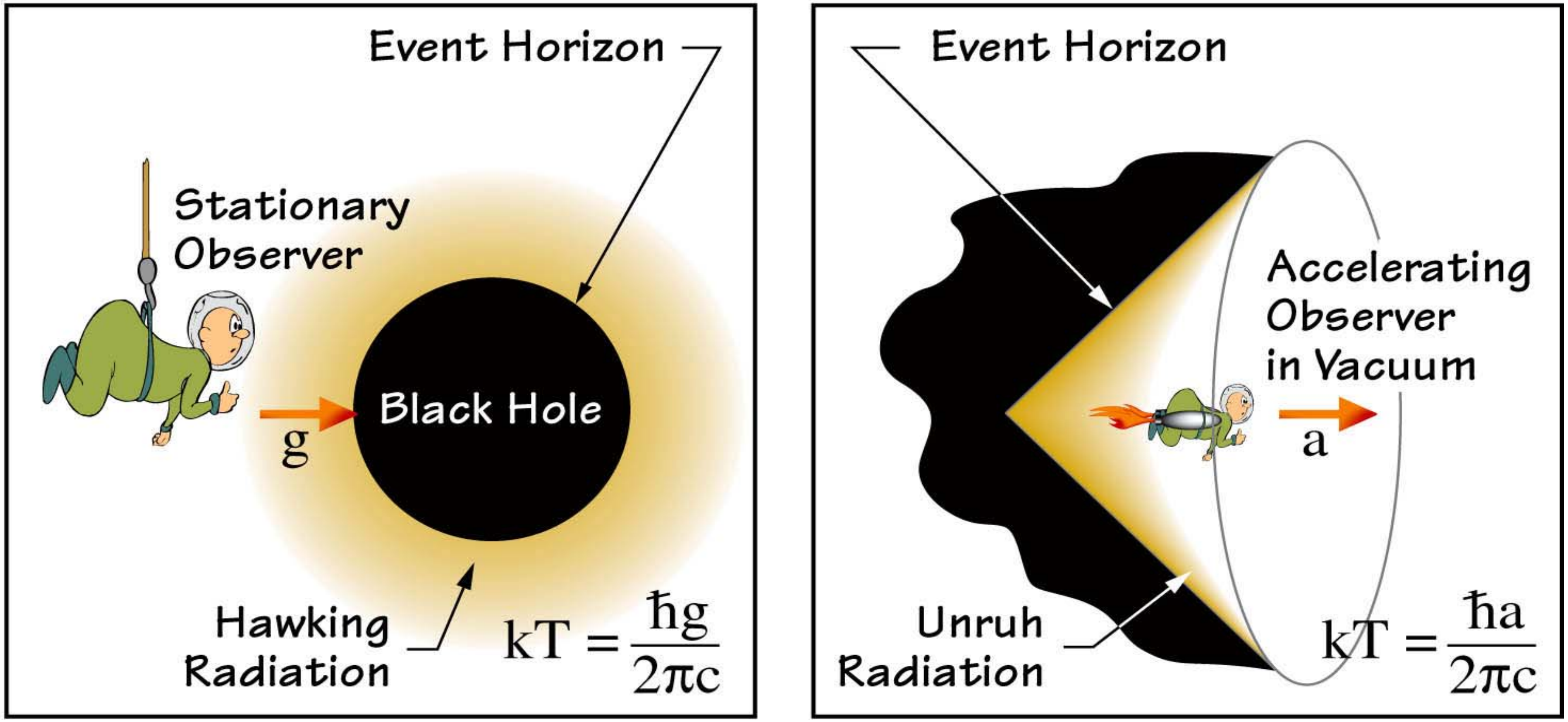
- ## 2-Stage Accelerator



- ## 2-Foil Experiments

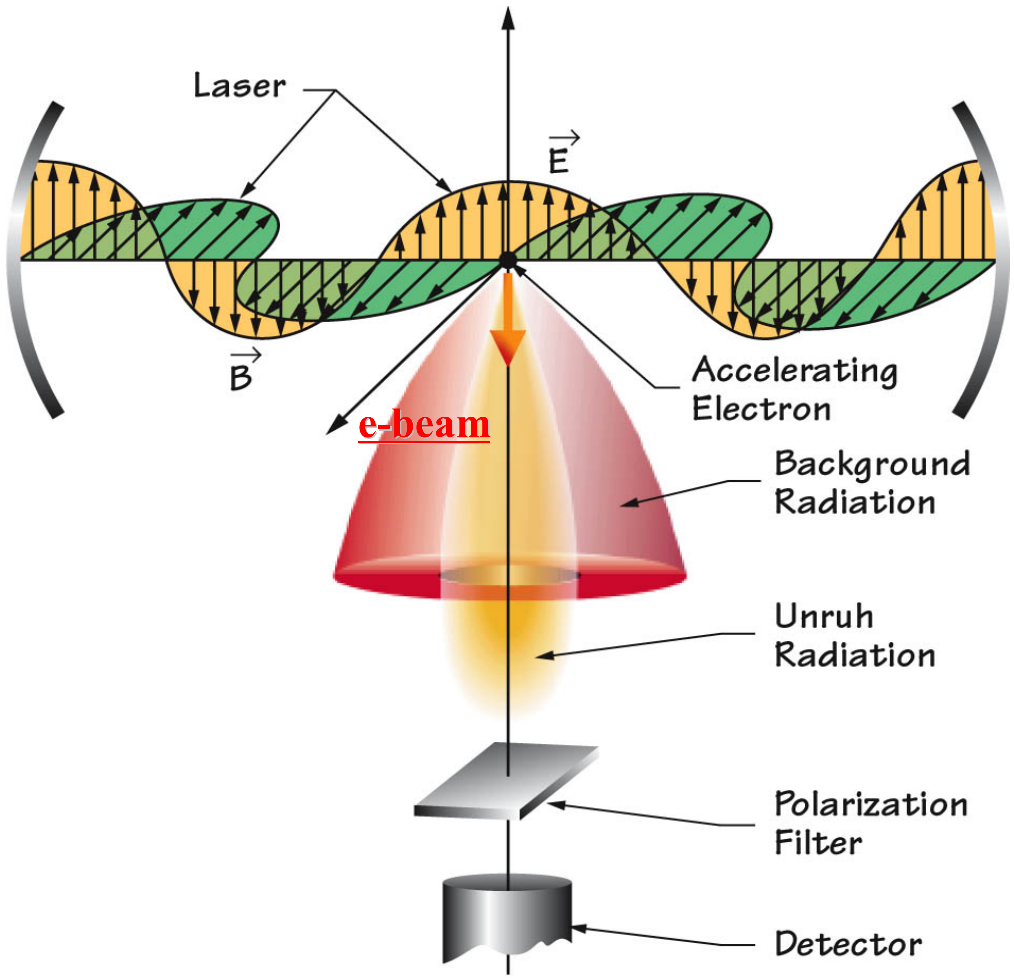


EVENT HORIZONS: From Black Holes to Acceleration



A stationary observer outside the black hole would see the thermal Hawking radiation.

An accelerating observer in vacuum would see a similar Hawking-like radiation called Unruh radiation.



Schematic Diagram for Detecting Unruh Radiation

Two experimental signatures:

1. Far-field Unruh radiation
2. Acceleration in intense radiation field.

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**

Conclusions

- HiPER provides a new approach to fusion.
- Unlocks the door to extreme physics.
- The future looks bright.

Thank you.

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

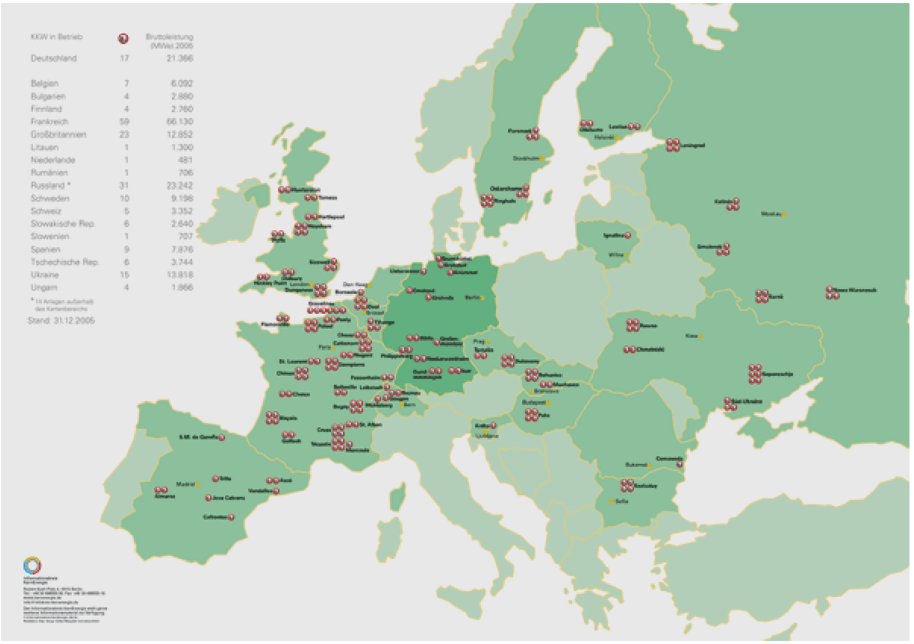
Preparatory phase project

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

Nuclear energy in Europe



Decision on closing existing reactors

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

Plans/approved plans to build new nucl. power plants

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

Anit-nuclear position by law; no reactors

- Austria
- Denmark
- Greece
- Italy
- Portugal

Conclusions

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 RE

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

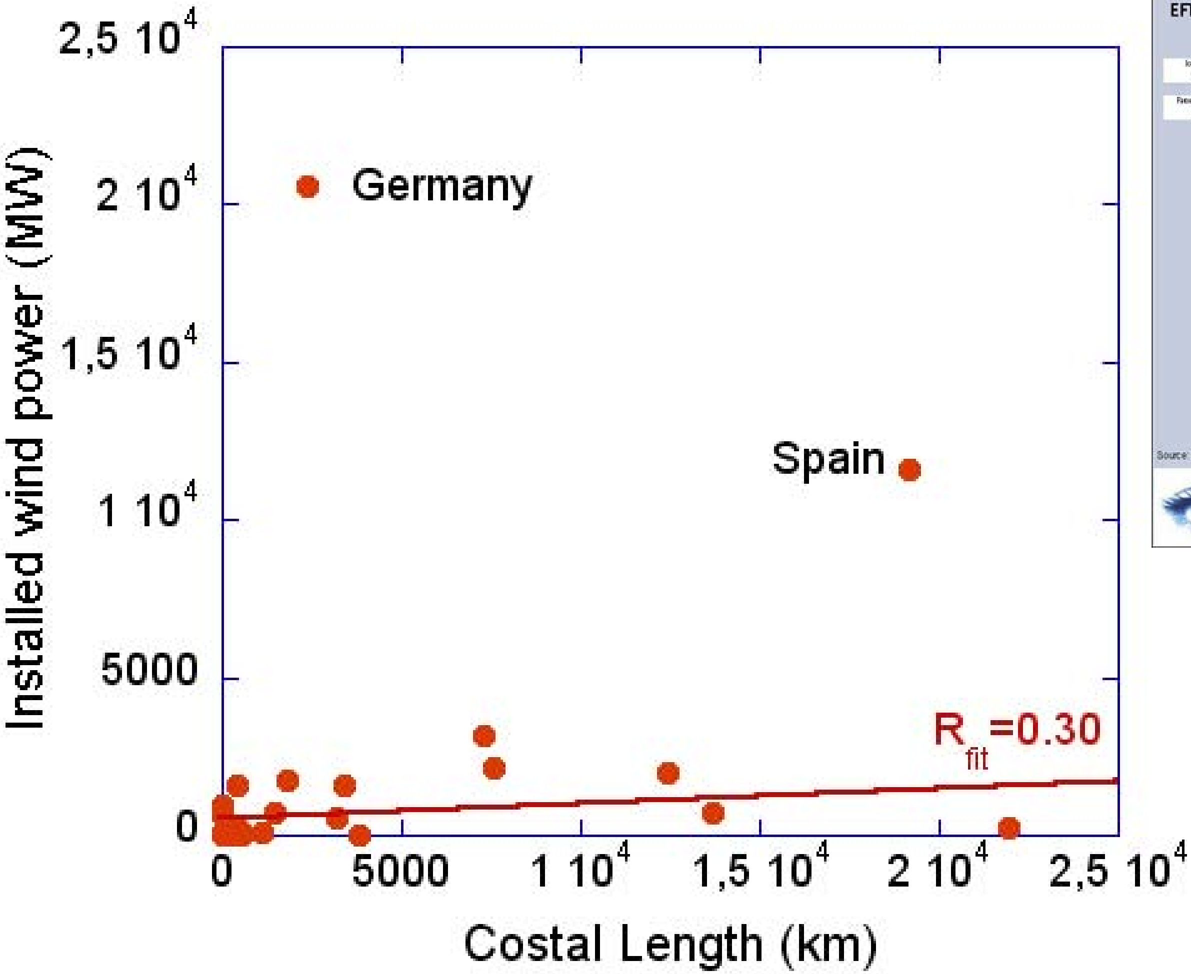
electricity saving	2
electricity distribution	
conventional technology	2
HT-superconductor	3
electricity storage	
conventional measures	2
hydrogen	2
HT-superconductor	3
conversion into electricity	2

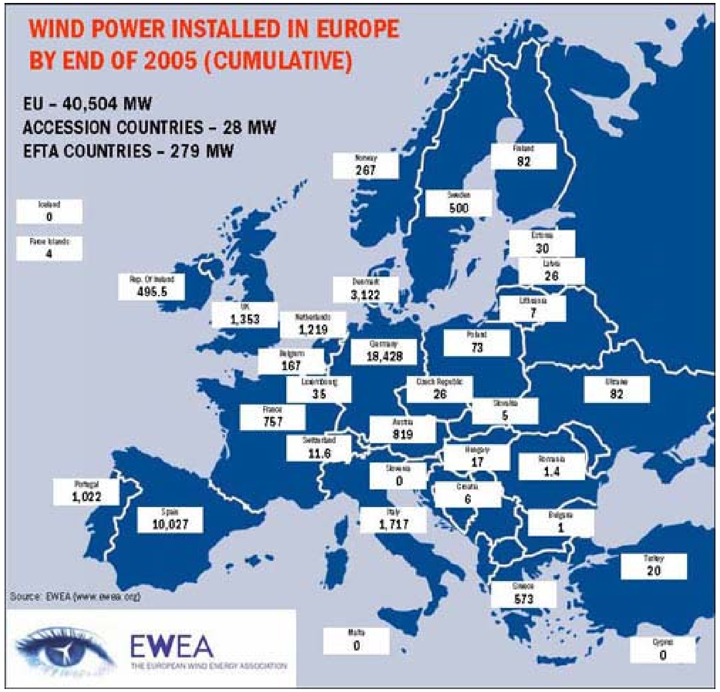
Fusion in the laboratory is imminent …

NIF (USA) and LMJ (France) due to demonstrate laser fusion "ignition" (i.e. energy gain) within the next 5 years

How will we respond to this transformational event?

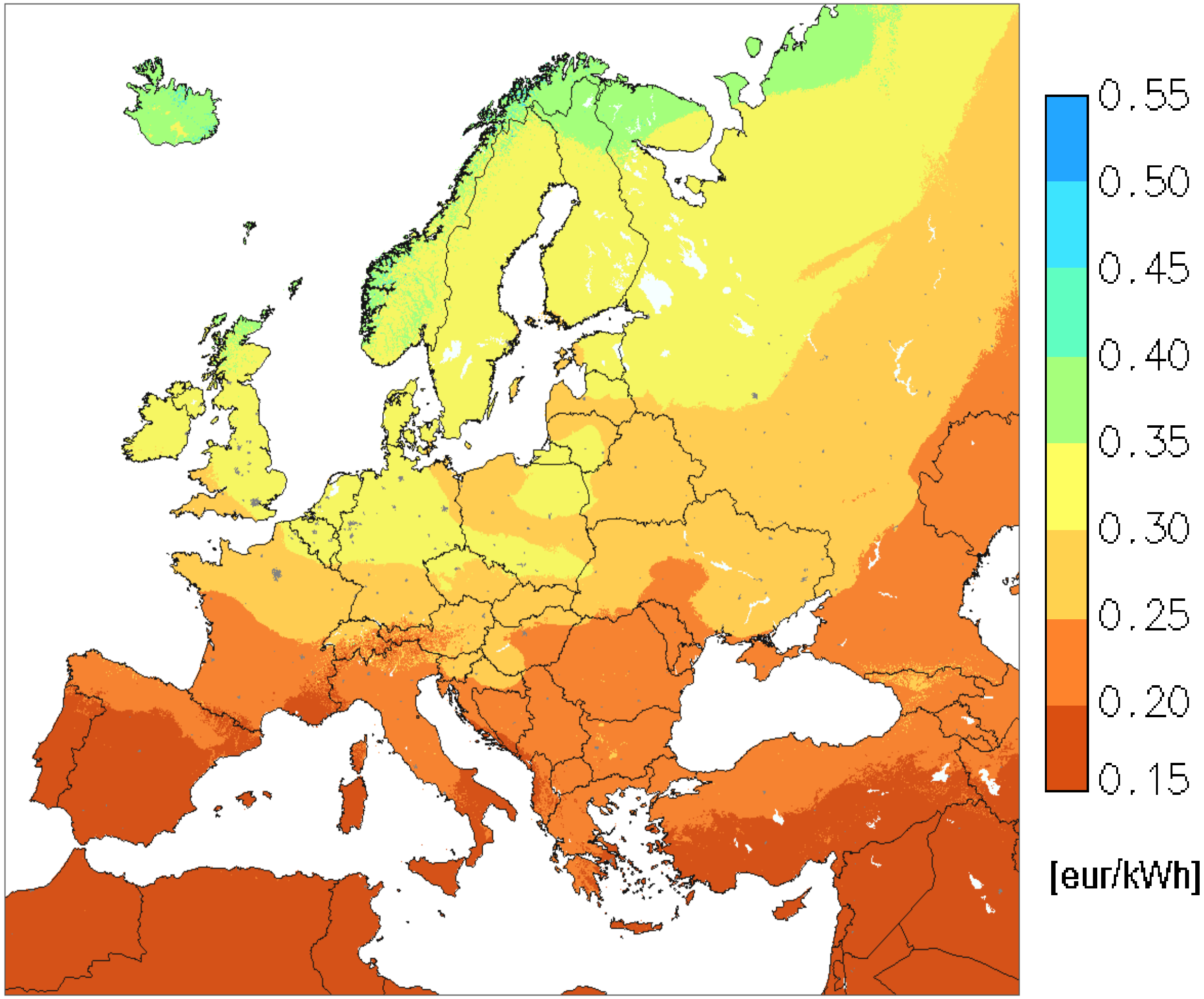
Installed wind power and the correlation to the costal length



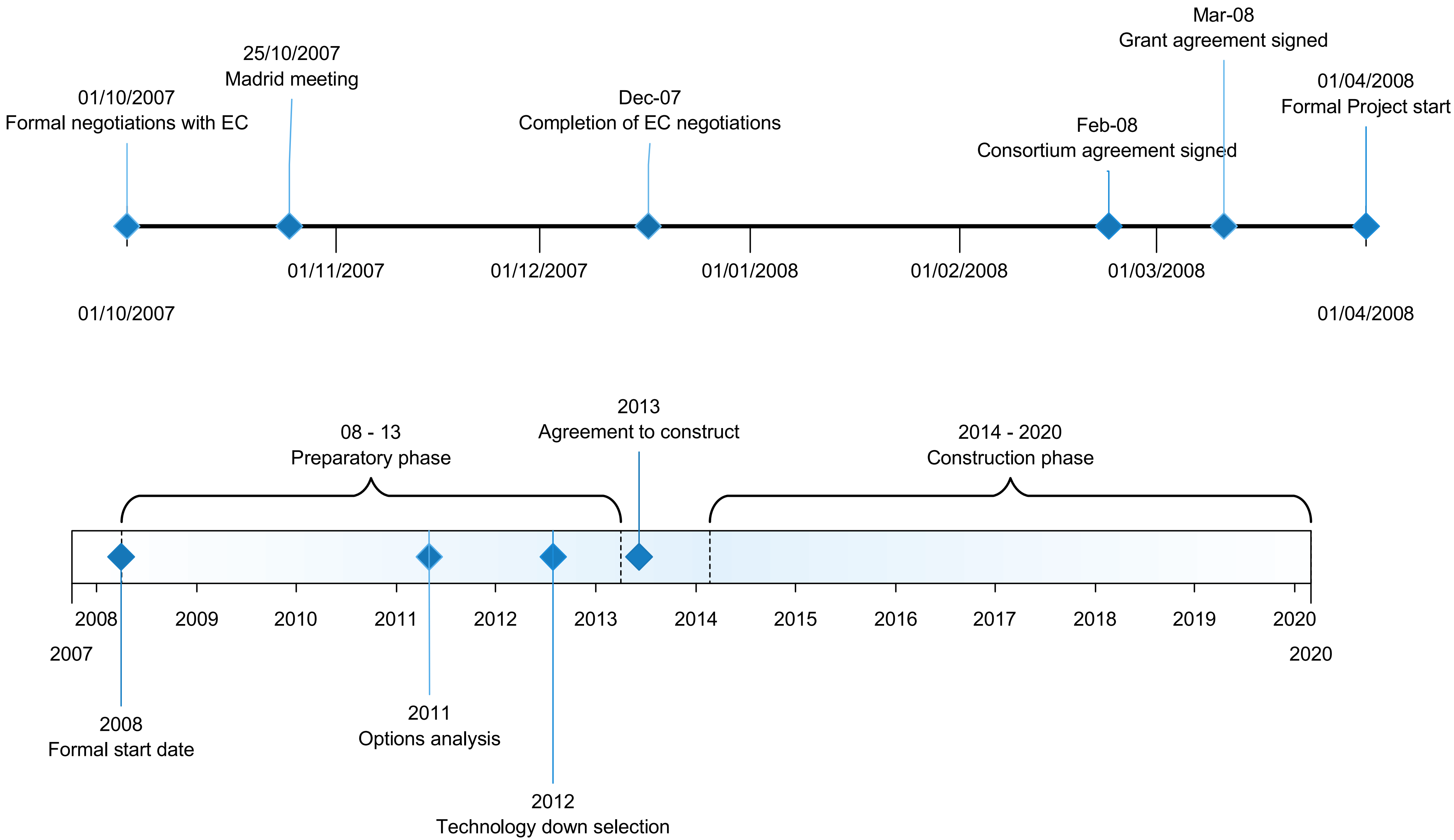


Distribution of solar energy in Europe

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



Project Timeline



HiPER 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**

Energy Future

Europe is strongly dependent on energy import.

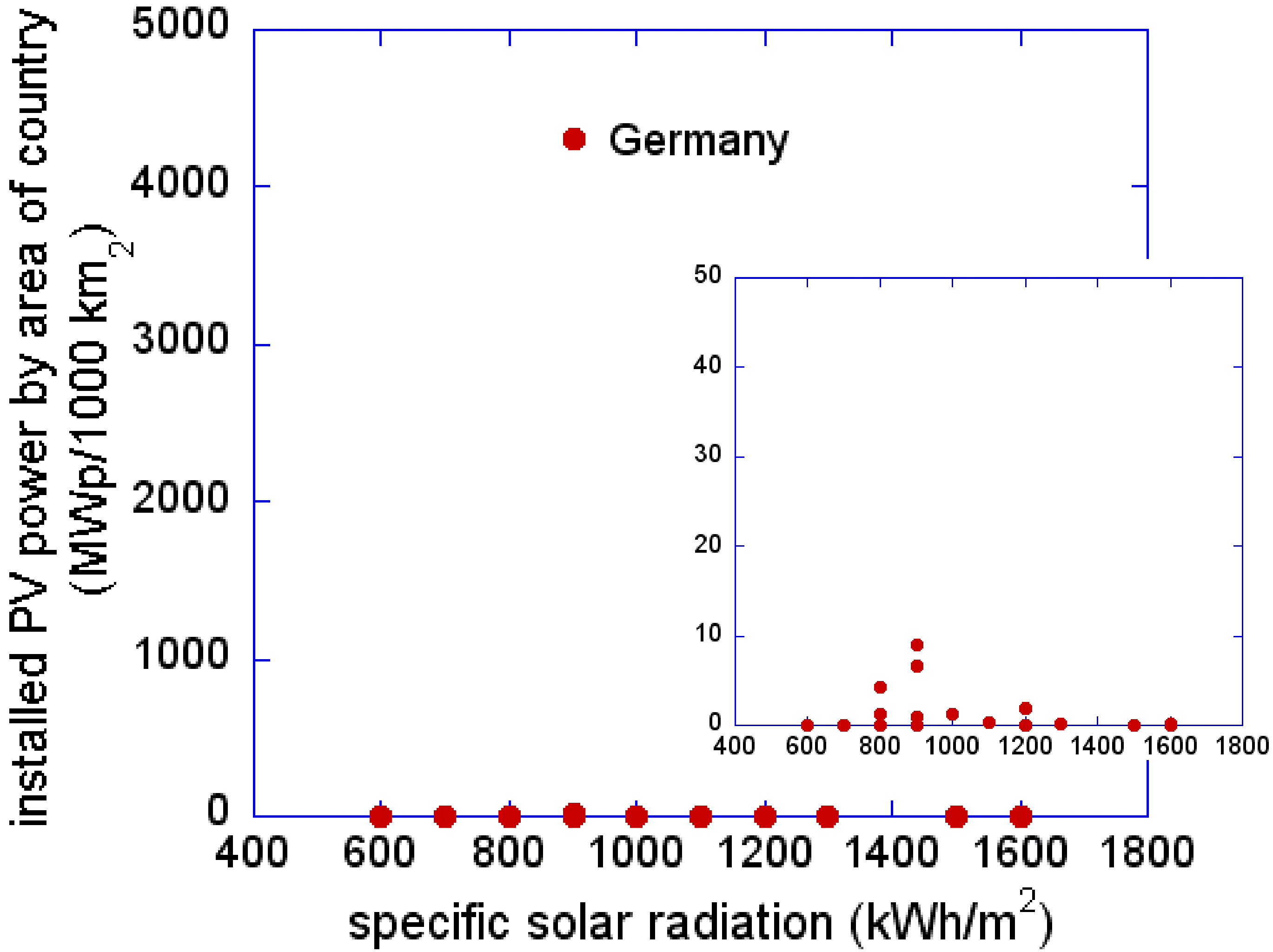
This dependence will grow and will be specifically serious for the gas market.

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.

Installed PV power and the correlation to the specific solar radiation



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)

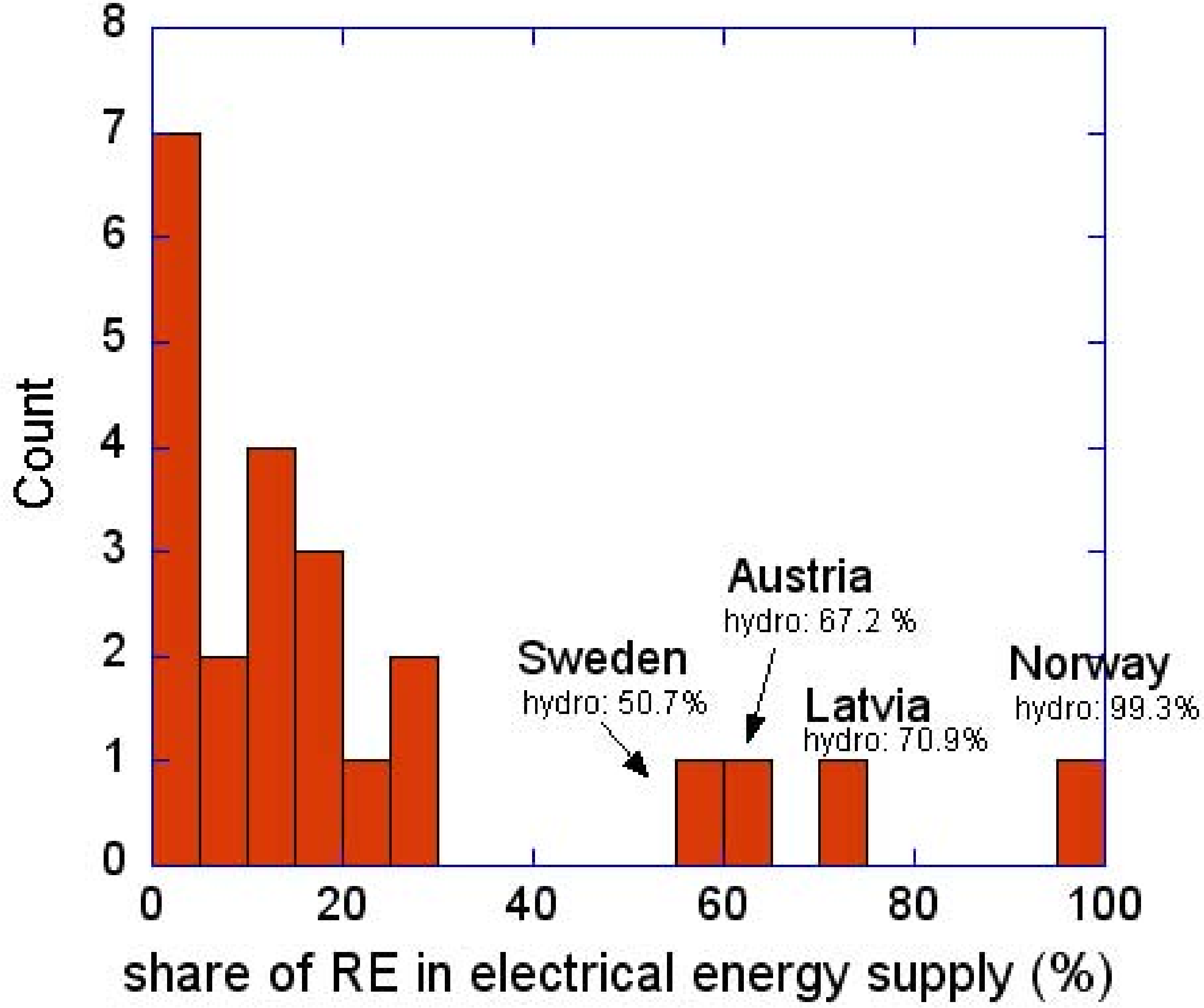
Generation IV: 11 countries cooperate to develop this nuclear system

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

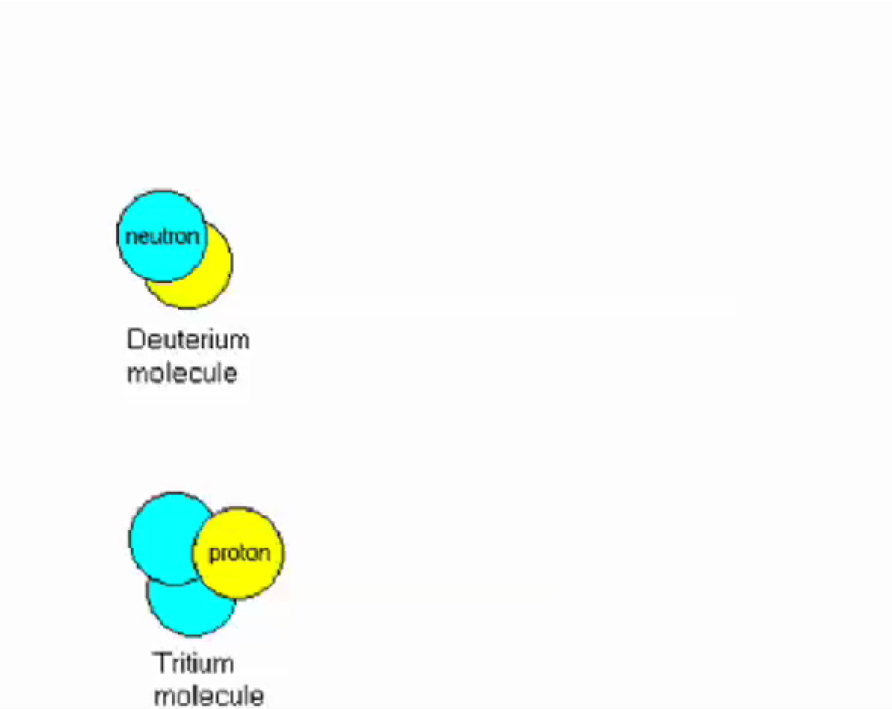
Distribution of RE in EU countries

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



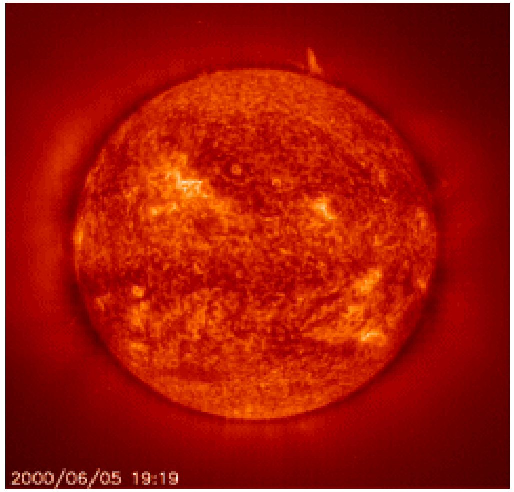
Fusion: energy for the future

movie



The Sun: a natural fusion reactor

movie

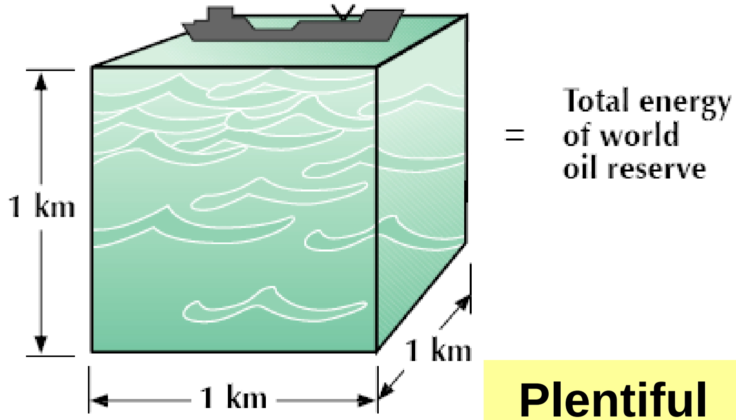


$$D + T \rightarrow He + n$$

$$3.5 + 14.1 \text{ MeV}$$

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

$$E = m c^2$$



Plentiful fuel

Fusion

Sun: 4 p $\Rightarrow$ He^4 + 27 MeV

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

technical: d+t $\Rightarrow$ He^4+n+ 17.6 MeV

t from breeding reaction:

n + ^7Li $\Rightarrow$ ^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

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

T=15 keV; $n \approx 2\ 10^{20}\ m^{-3}$

$\tau_E > 2$ sec

τ_E is energy confinement time

The potential of fusion

Deuterium

Lithium

electricity for a family per year

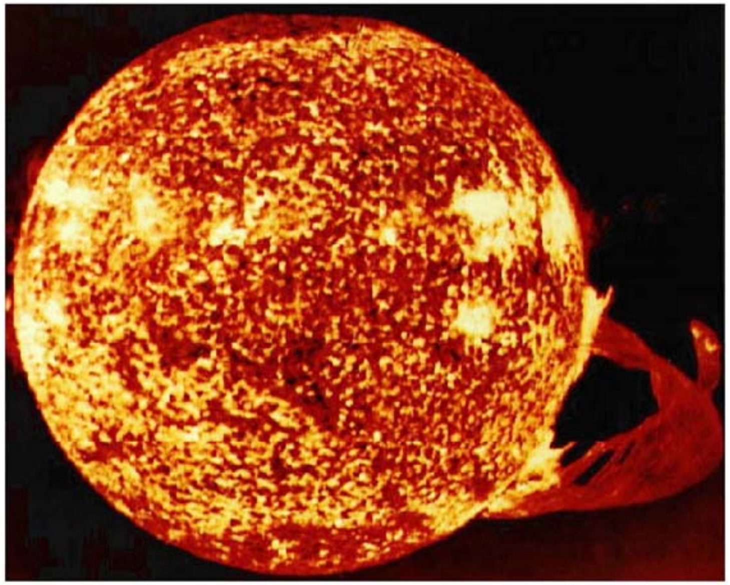
The case for fusion energy

- **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)

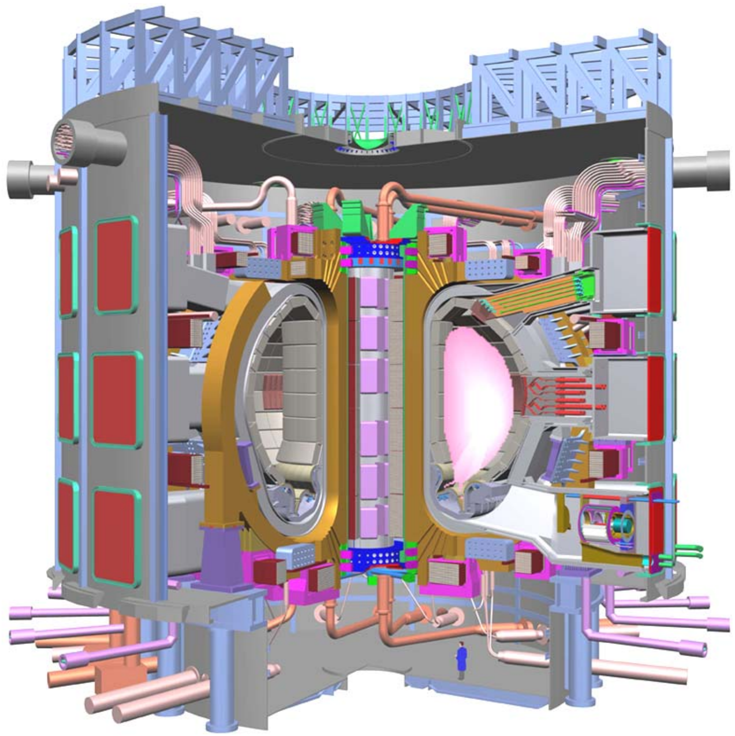
A 100 ton (4200 Cu ft) ***COAL*** hopper runs a 1 GWe Power Plant for ***10 min***

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

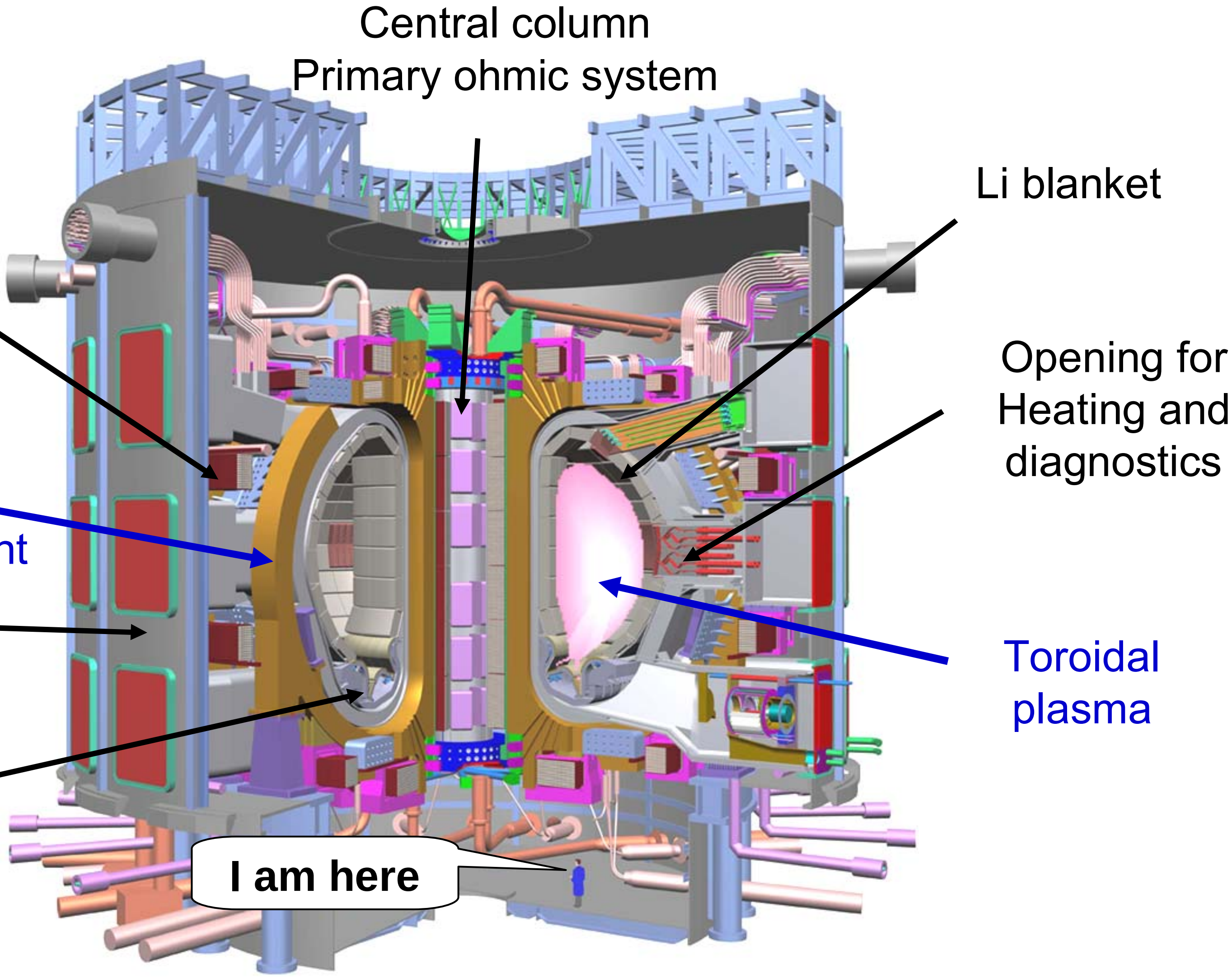
Sun, with eruption



ITER tokamak

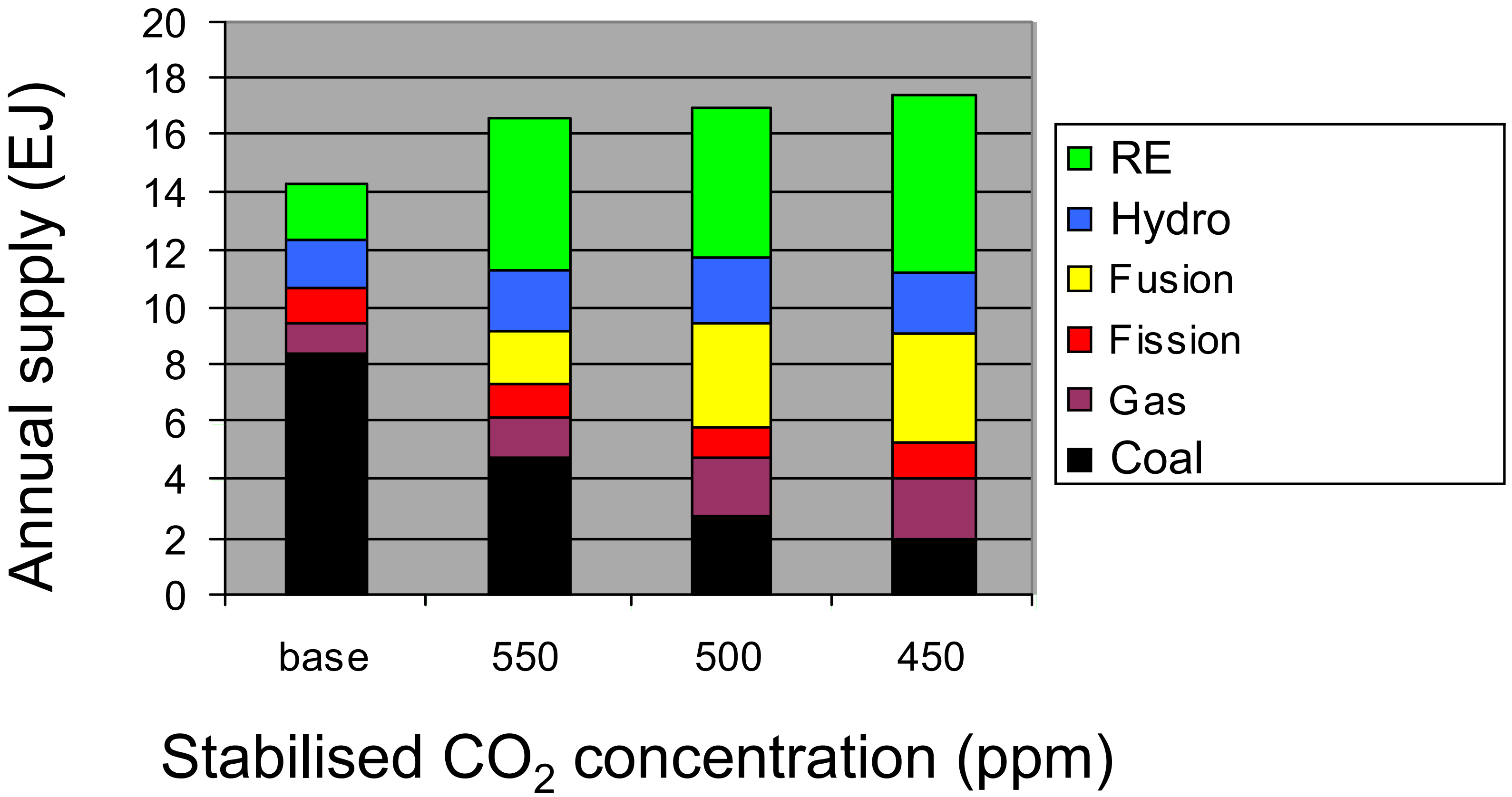


ITER:



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

Energy scenario with fusion

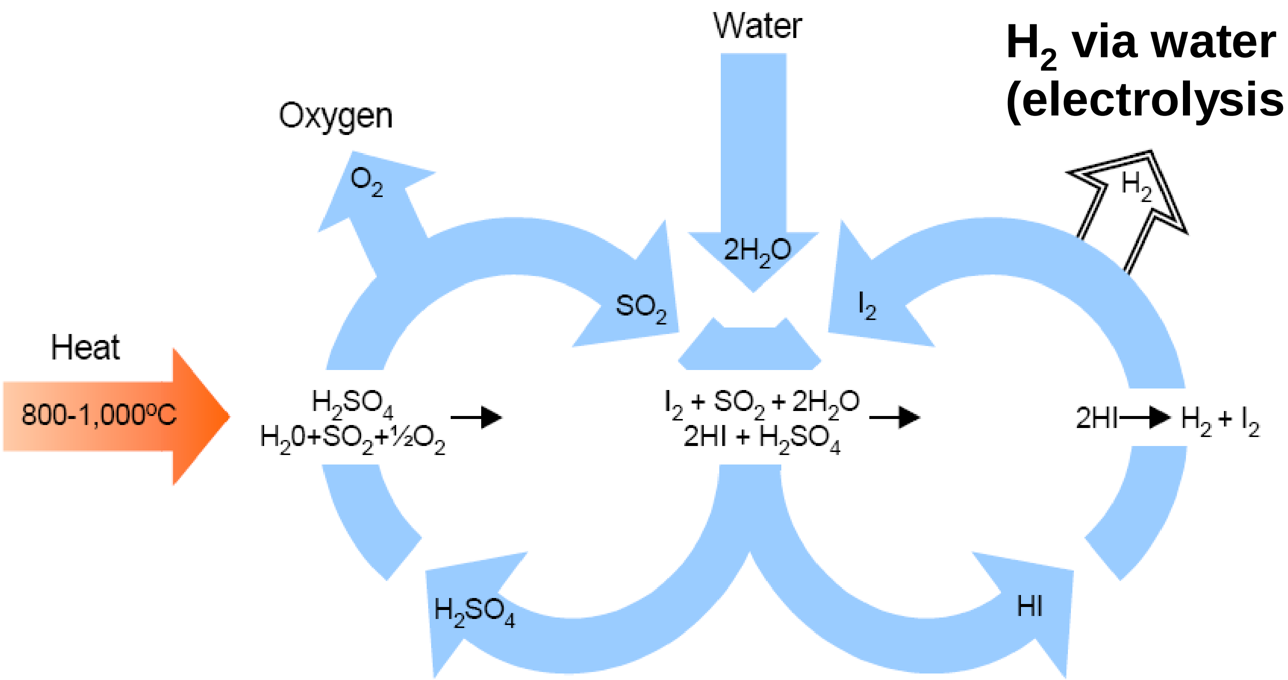


Why pursue fusion energy?

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

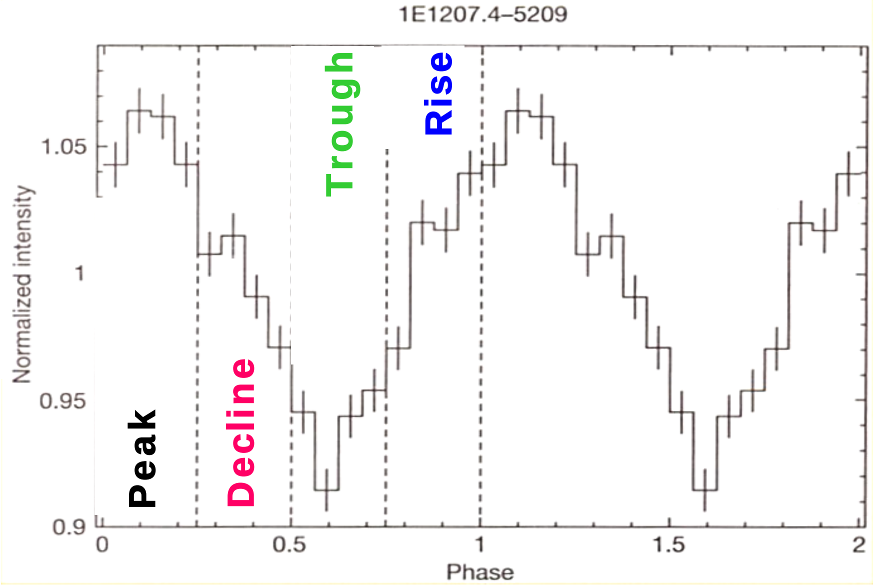
- **Would provide a source of Hydrogen (high temperature environment)**
- **Advanced H_2 cycles do not suffer from CO_2 by-product**

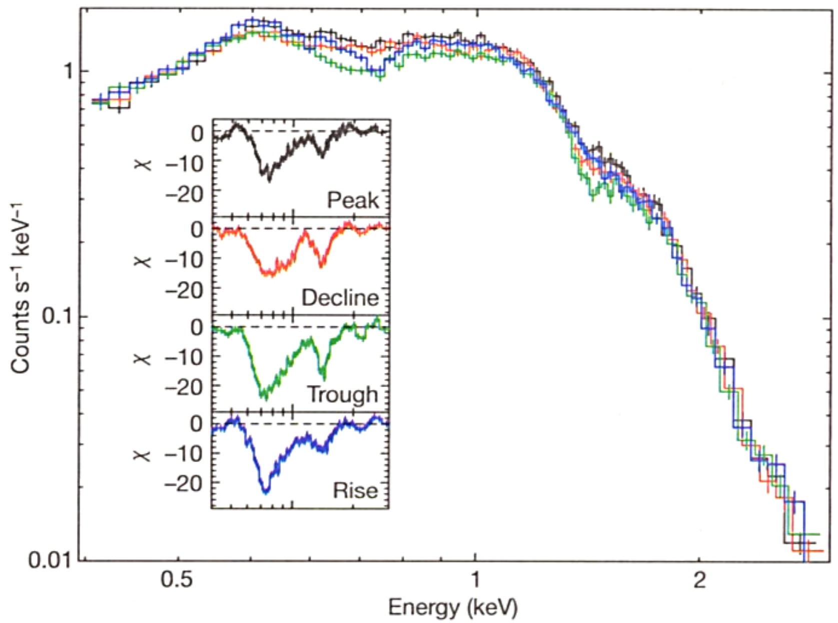
H_2 via water decomposition (electrolysis + chemical cycle)



HiPER 1E1207.4-5209

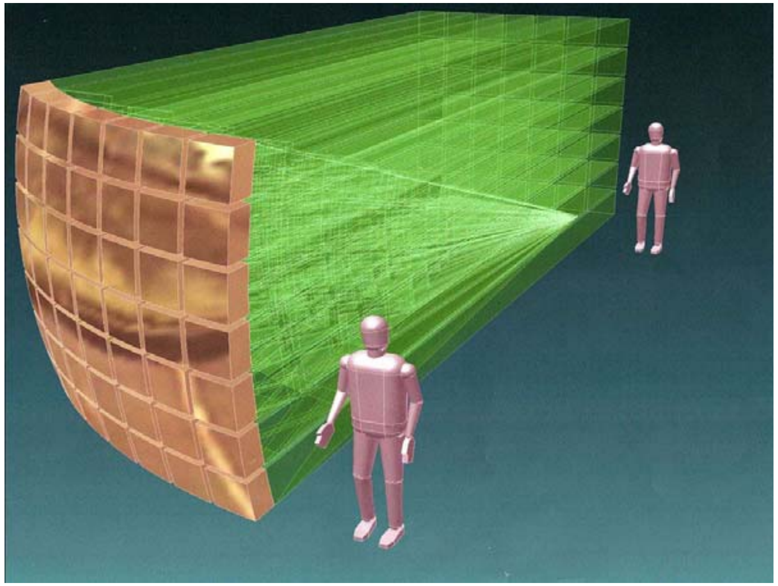
- First X-ray spectrum was taken by EXOSAT.
- Kellett *et al*. (1987) first suggested that this source was the actual neutron star remnant of the original star that exploded to create the supernova remnant PKS 1209-52 (~7000 yr old).
- Recently, XMM observed the pulsar (0.4241 second period – shown top-right) for ~250,000 seconds (Bignami *et al*., 2003).
- XMM PN and MOS spectra clearly reveal absorption features in the spectrum (PN spectrum shown in right-bottom).
- Detailed analysis of these absorption dips shows them to have energies of 0.72±0.02 keV, 1.37±0.02 keV, 2.11±0.03 keV, and a fourth possible feature at 2.85±0.06 keV.
- These features are consistent with cyclotron absorption at the fundamental (0.7 keV) and the first, second and third harmonics.
- 1E1207.4-5209 is unique among isolated neutron stars to show these features although they have been seen before for old neutron stars in mass accreting binary systems.
- The derived magnetic field strength is 8×10^{10} G – which is about x30 LESS than expected for this pulsar (to explain the observed spin-down period).





Laser specification

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

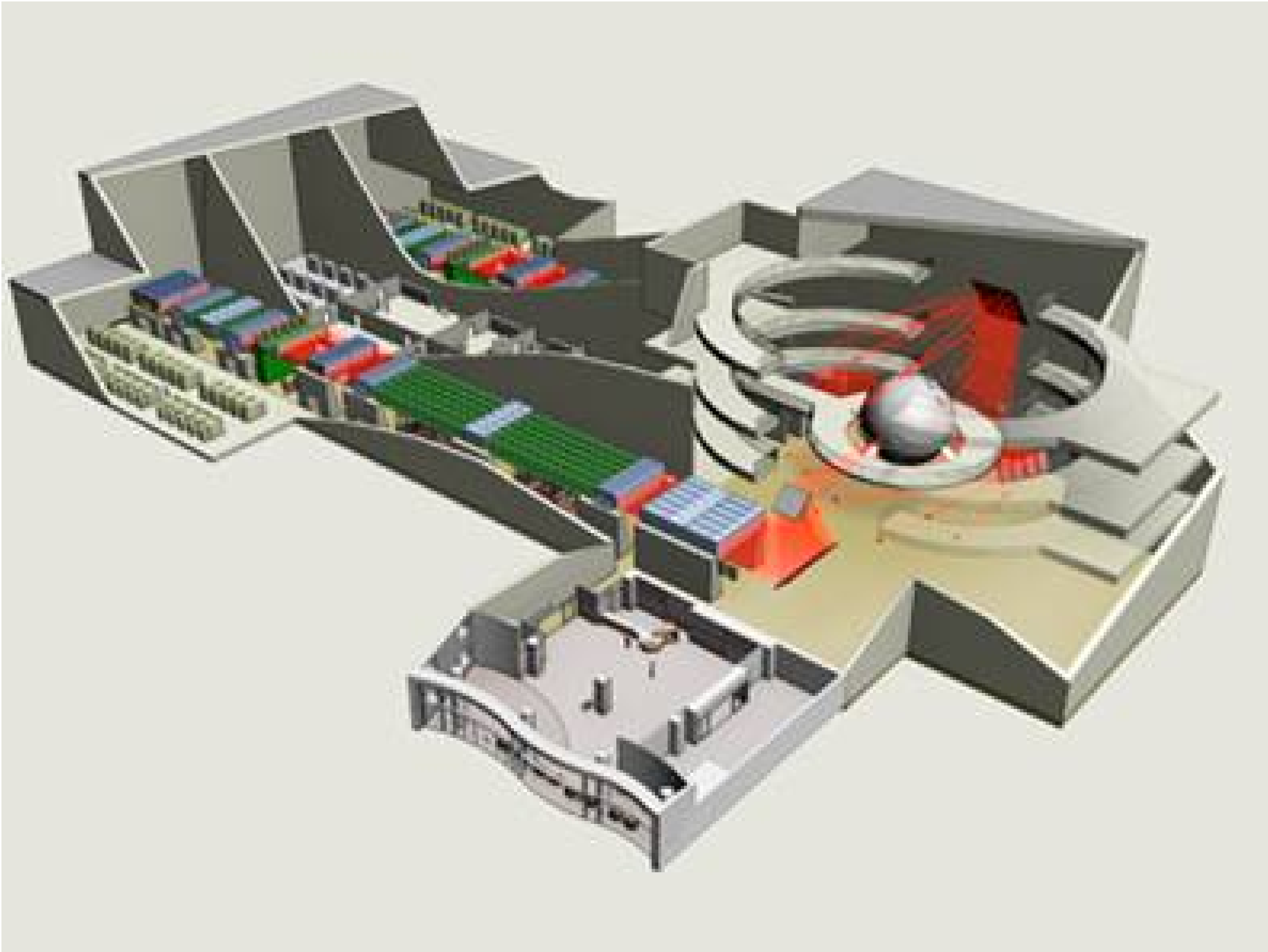


Feasibility **Detailed design** **Construction phase** **Commissioning**

Laser specification

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