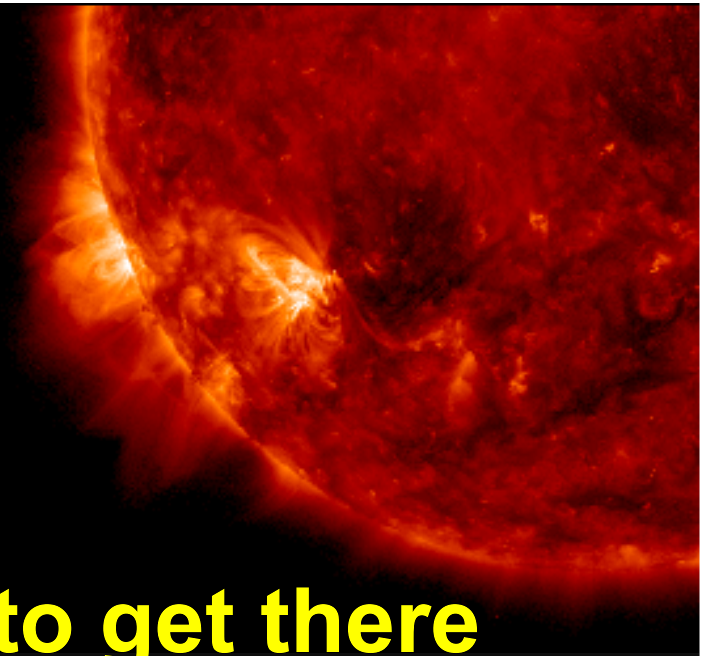
Fusion electricity

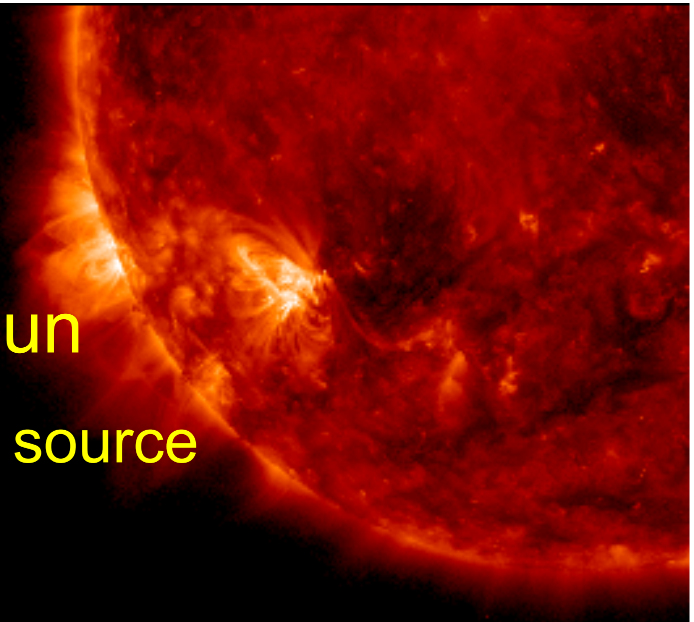
- the basics and the roadmap to get there



Jan Scheffel

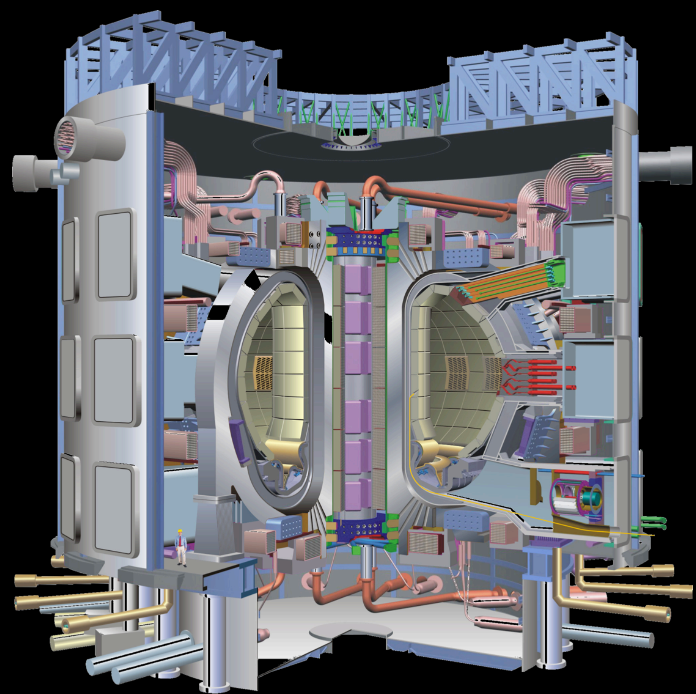
Fusion Plasma Physics, KTH

Background

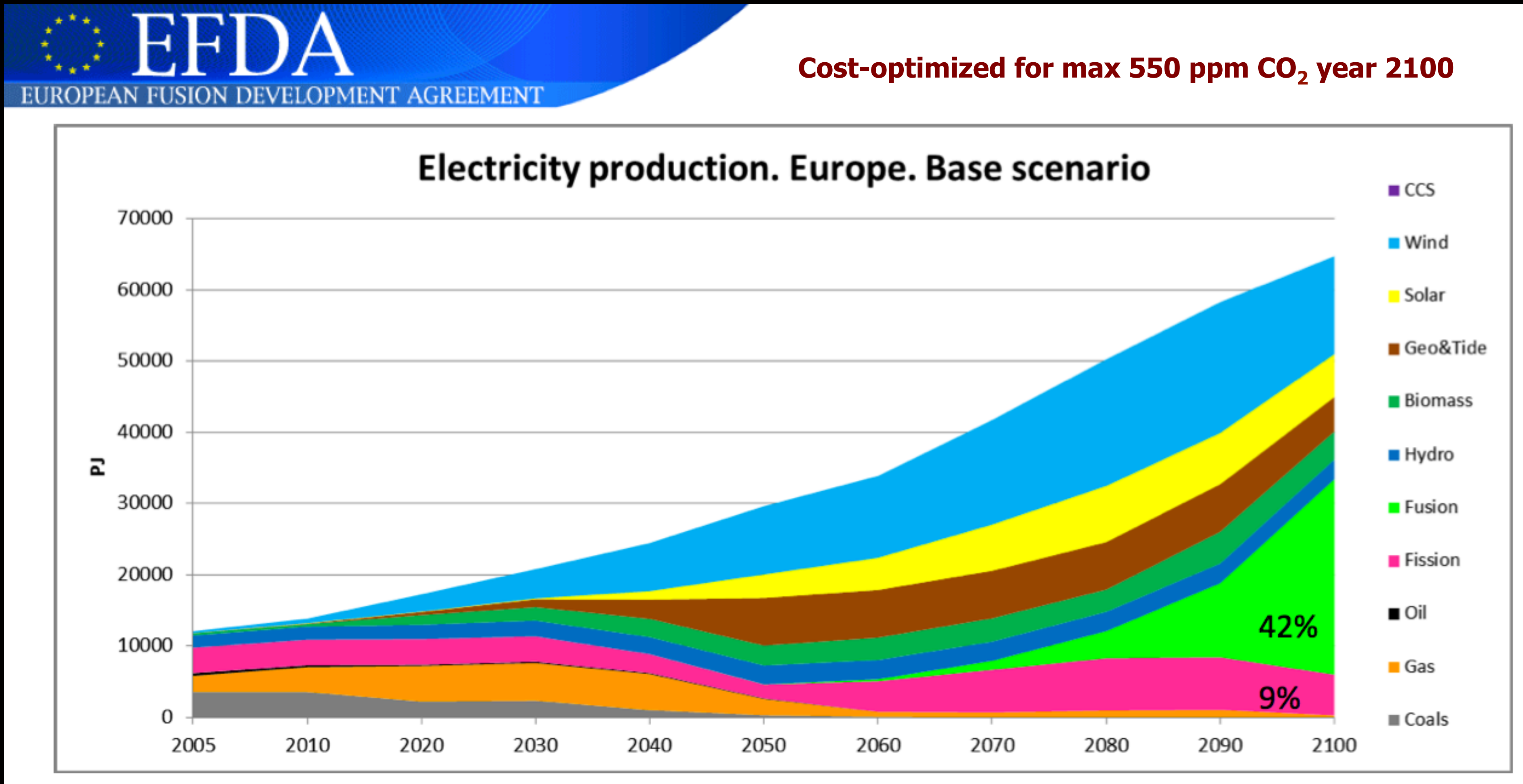


- Fusion is the energy source of the Sun
  - On earth – a sustainable, clean energy source
  - But – a great technical challenge!

- Today we build ITER – the first reactor to produce more energy than it consumes !
- How do we move from ITER to commercial power stations?
- Is fusion safe?



Fusion energy is needed in future energy mix



Development of fusion energy

Jan Scheffel, jans@kth.se
Professor, Fusion plasma physics
Deputy Head, Swedish Fusion Association
Alfvén Laboratory, KTH, Stockholm
www.alfvenlab.kth.se

CONTENTS

- What is fusion energy?
- Do we need fusion?
- How can we develop fusion?
- What are the costs?
- Conclusions

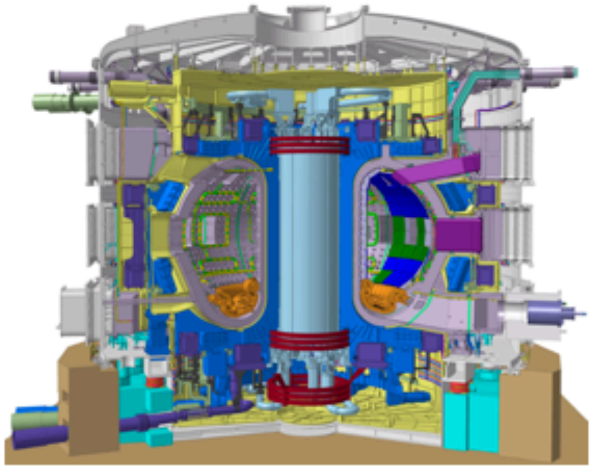
The Swedish Fusion Association
EURATOM – VR

COURSE

Energy and Fusion Research

ENERGY AND FUSION RESEARCH - AN INTRODUCTORY COURSE

This introductory course will present the state of today's fusion research and provide insight into the physics and technology of fusion.

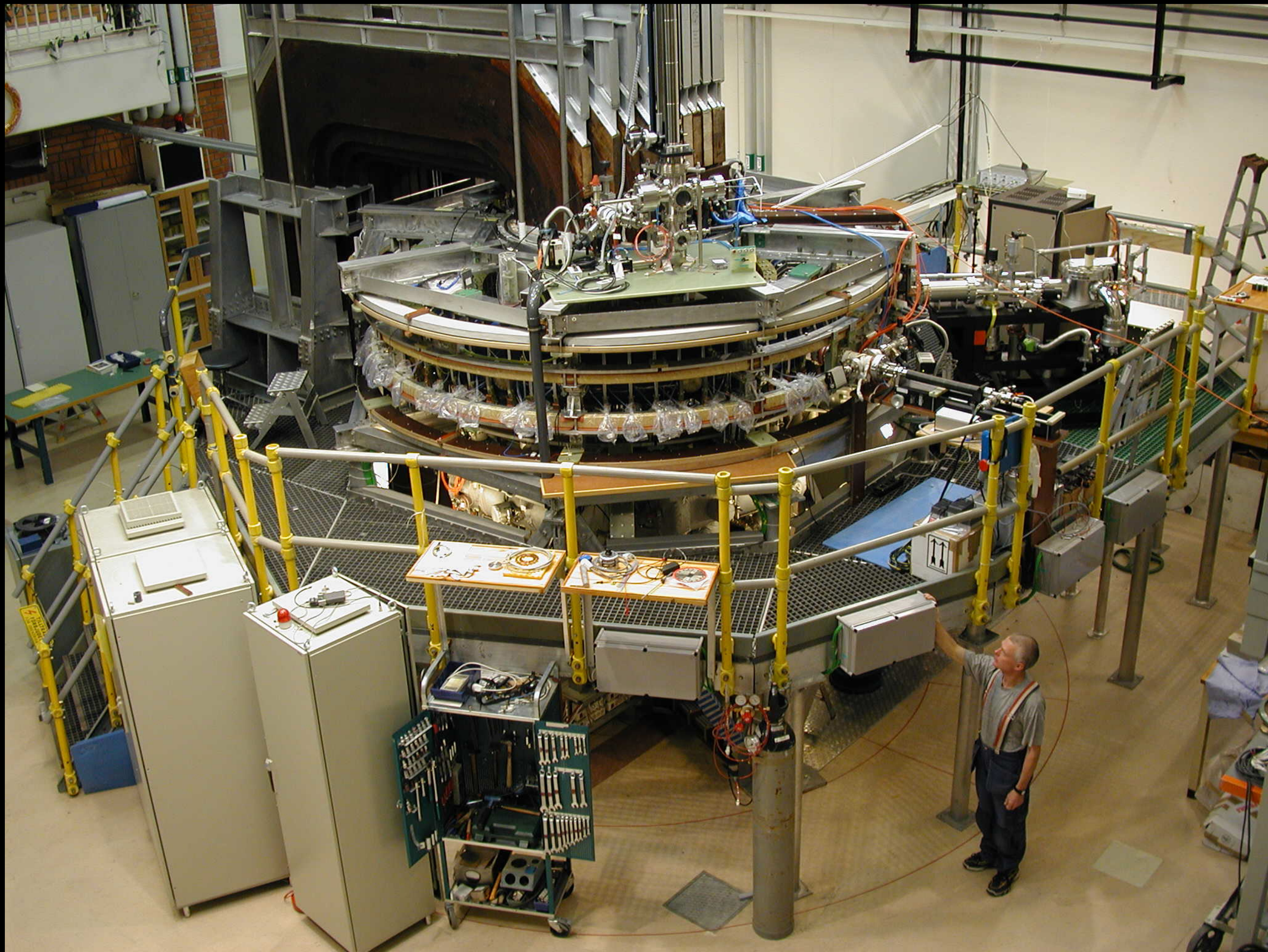


The development of fusion has now reached a state when it may be said that fusion power will indeed be realized. In this course, different solutions to "the greatest technological challenge ever pursued" will be presented.

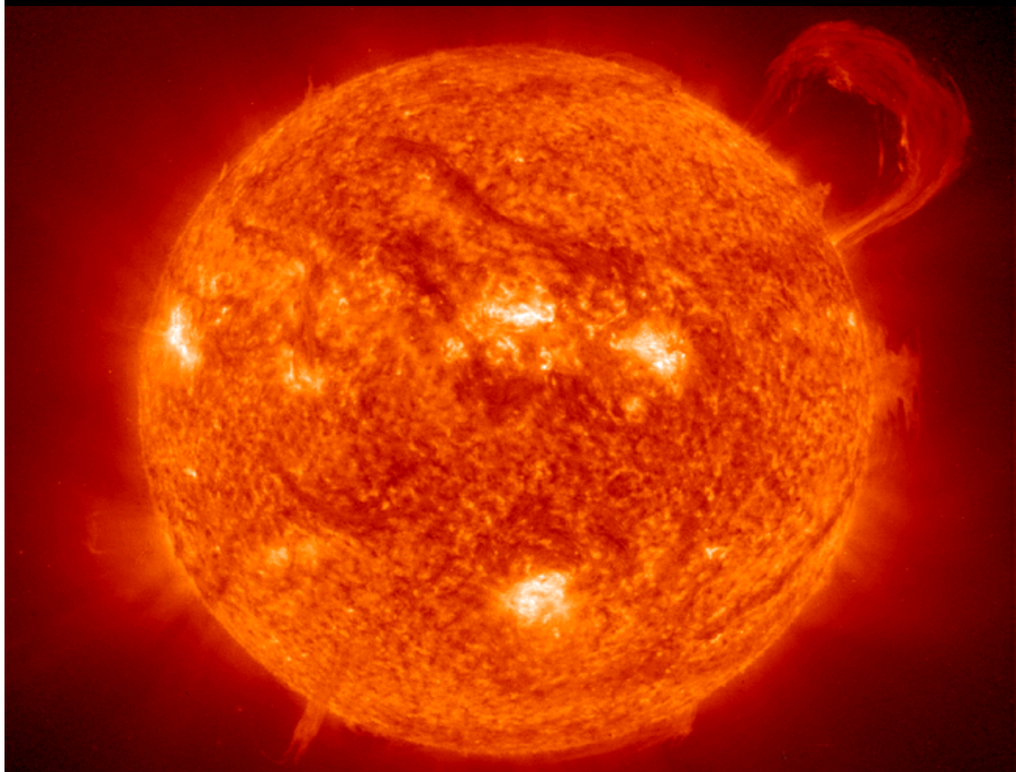
As a background, we will discuss the energy problems that threat to become critical towards the mid-century, unless new energy sources are developed. Comparisons with the non-fossil energy sources that are known today will be made.

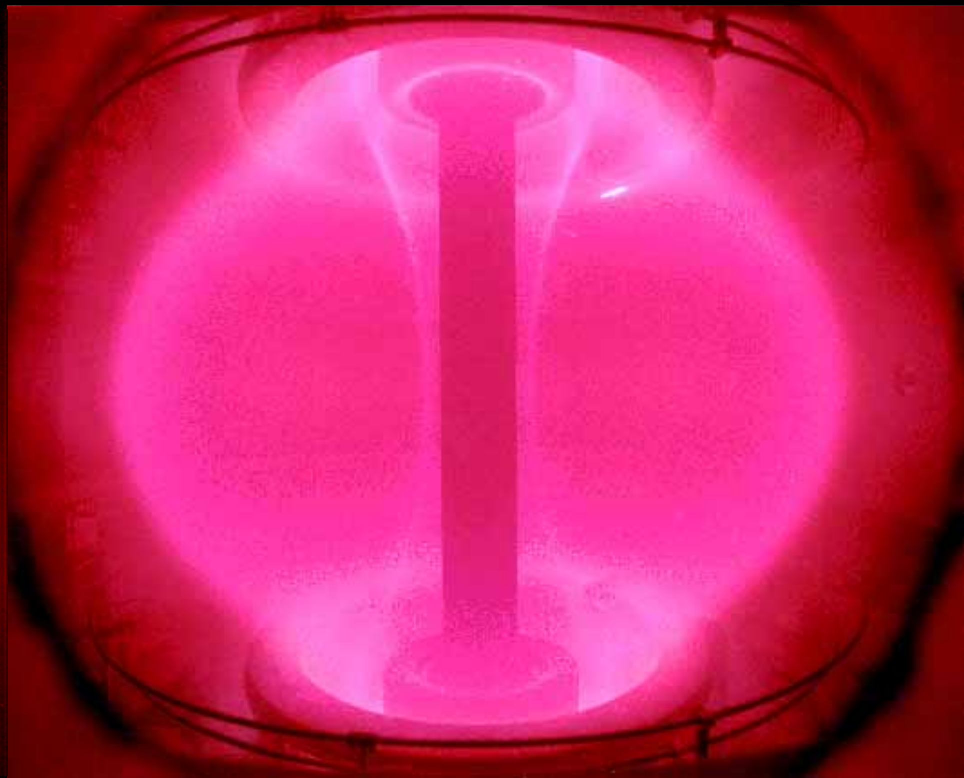
EXTRAP T2R, Alfvén Laboratory, KTH

Scandinavia's only fusion experiment – a reversed-field pinch



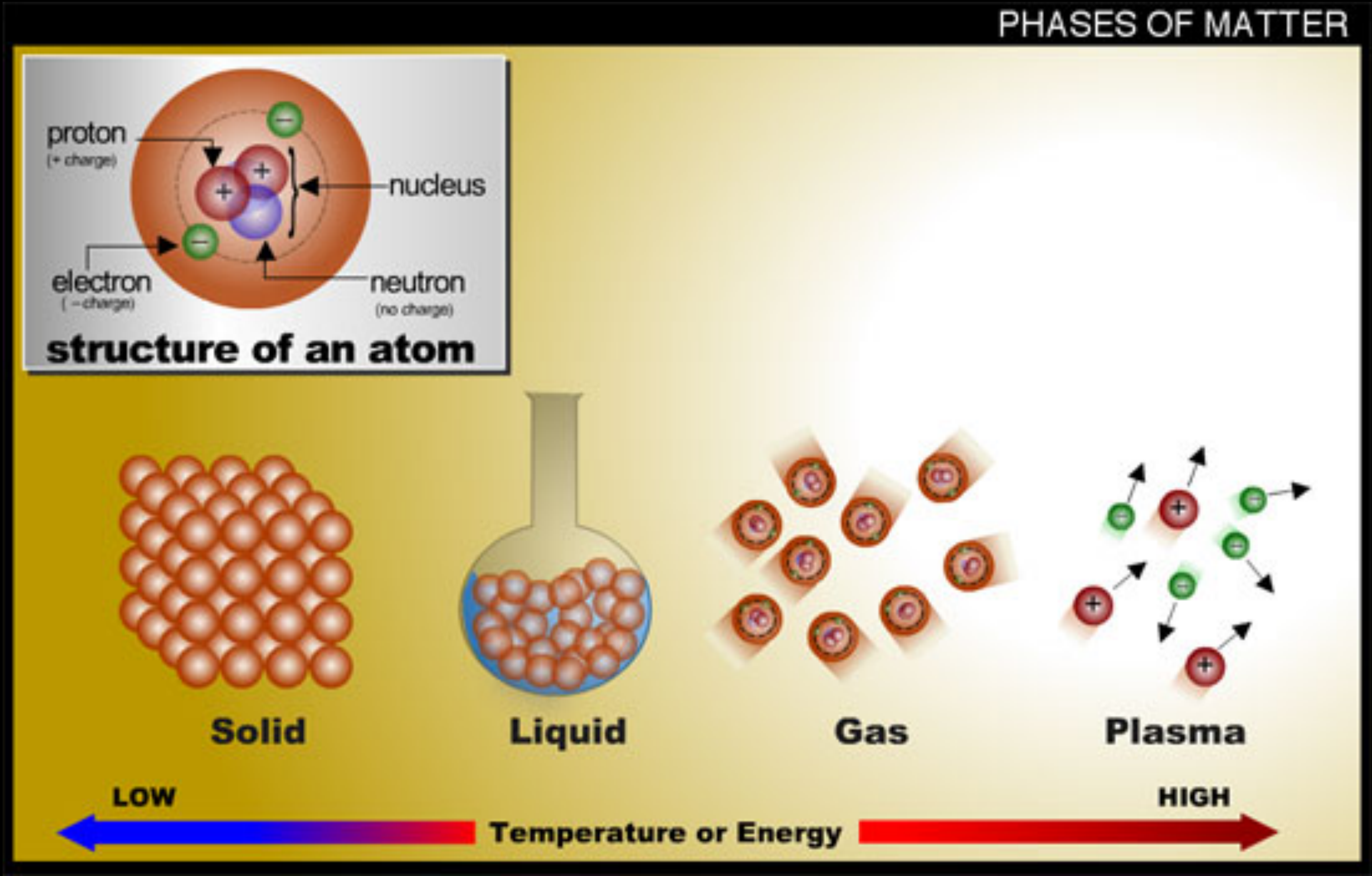
What is fusion energi?





Picture courtesy of the
SOHO/EIT collaboration

Plasma



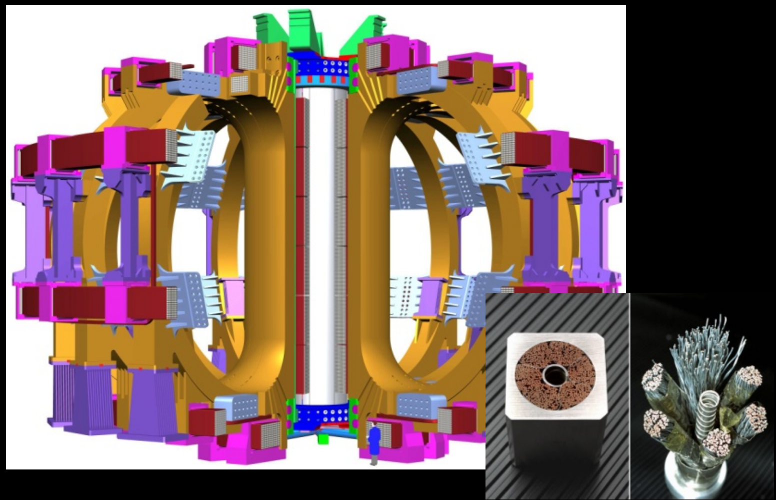
PHASES OF MATTER
proton
(+ charge)
nucleus
electron
(− charge)
neutron
(no charge)
structure of an atom
Solid
Liquid
Gas
Plasma
LOW
HIGH
Temperature or Energy

Plasma – needed for today's technology!

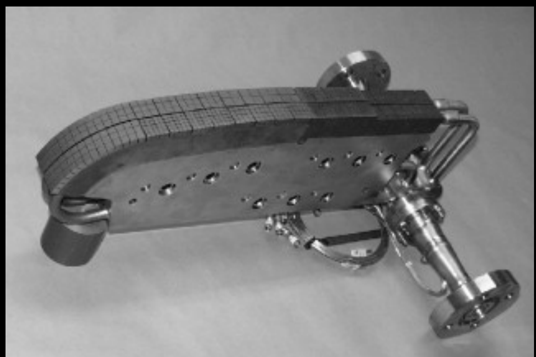
01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
15—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

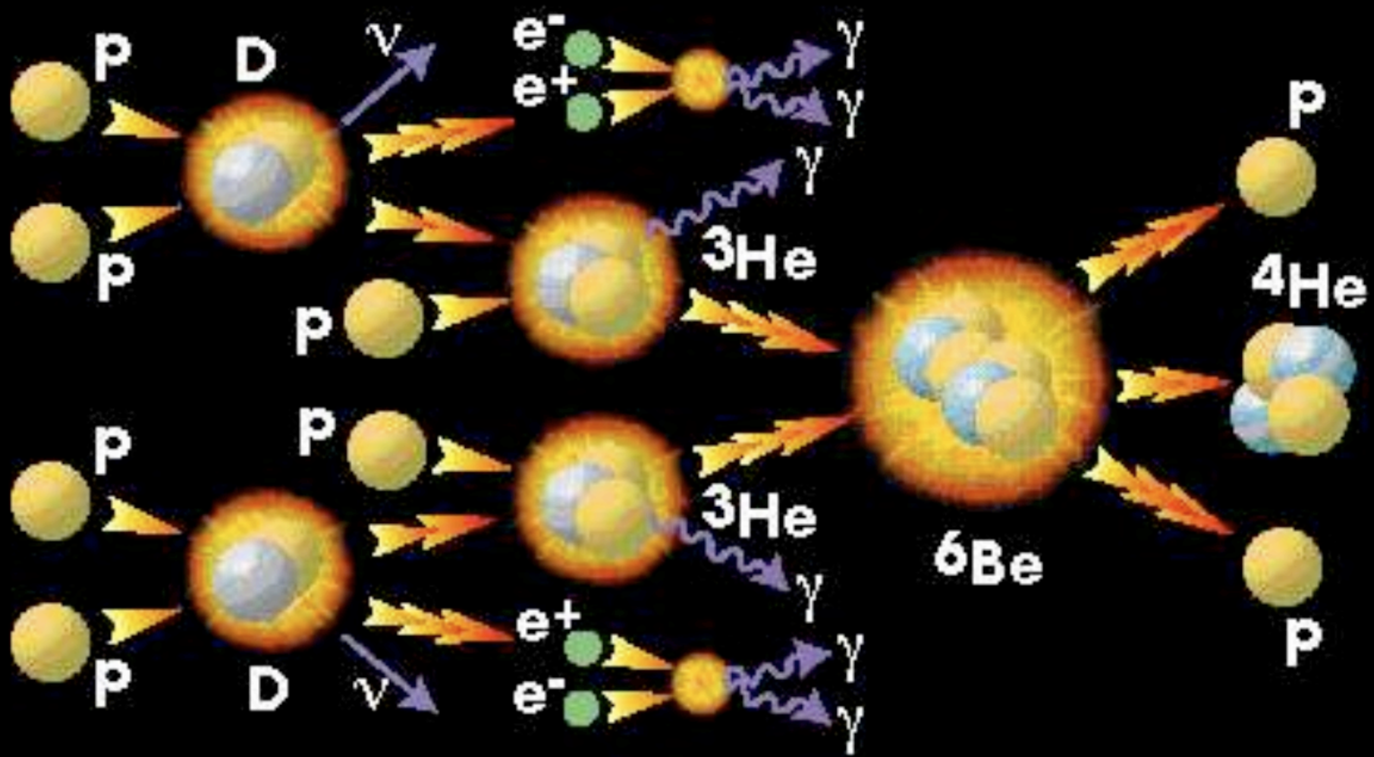
Fusion Technology - Spin Off Examples

Superconducting Magnets for medical use



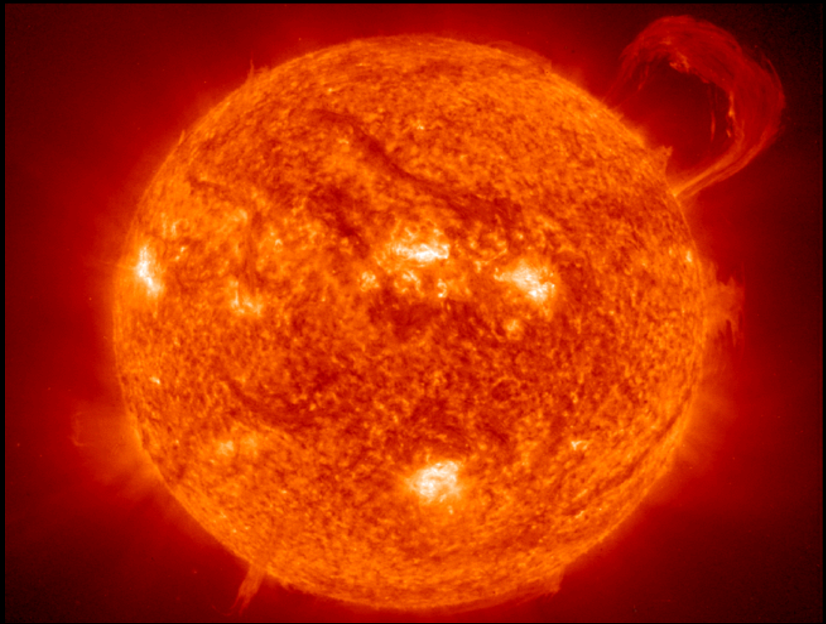
New materials: CarbonFibreComposites for Airplane breaks





Fusion reactions in the sun

The energy we use on earth started as fusion energy !



Renewables (direct energy):

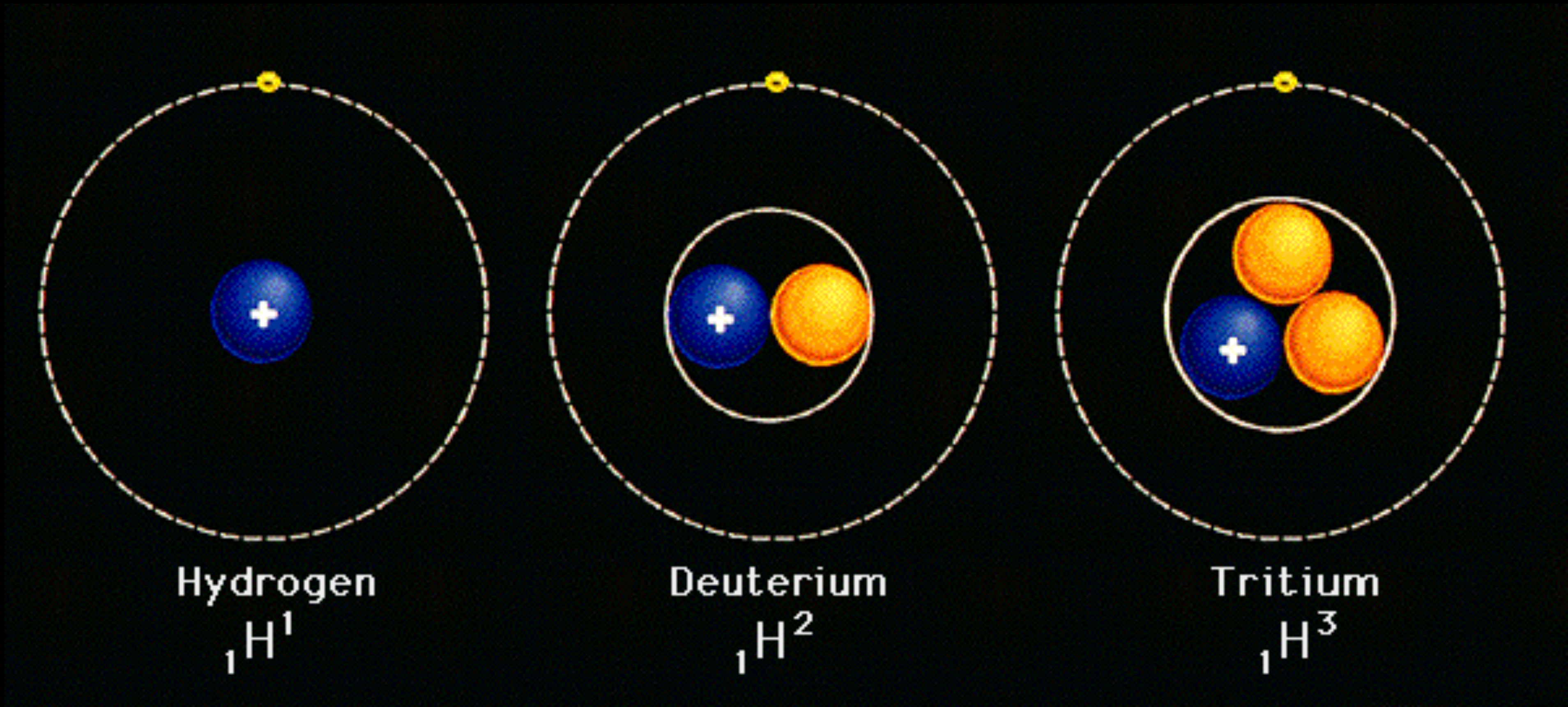
*** solar, wind, hydro**

Fossil (stored solar energy in organic material):

*** coal, oil, gas**

Fission (uranium is formed during supernova explosions)

HYDROGEN ISOTOPES



Radioactive
Half life
12.6 years

Fusion reactions

$$D + T \rightarrow {}^{4}He(3.5\,MeV) + n(14.1\,MeV)$$

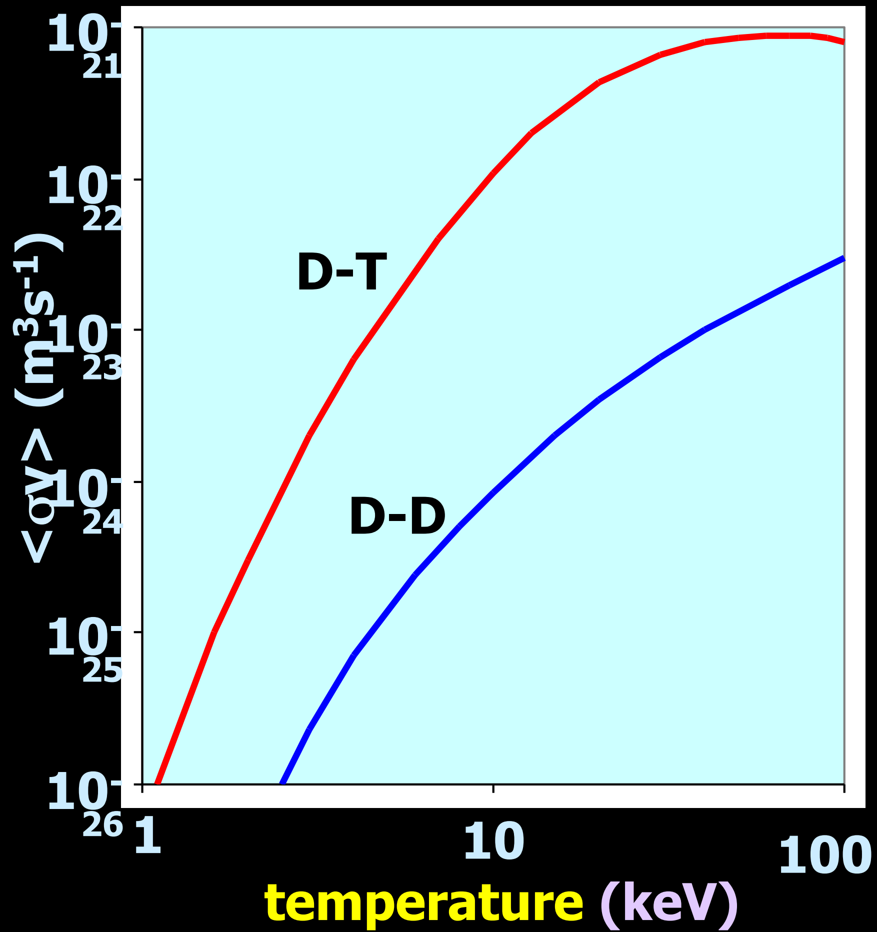
- **Fusion power per unit volume:** $p_{fusion} = n_D n_T \langle \sigma v \rangle E$

Where

n is the fuel ion density

E is the fusion energy per reaction

REACTIVITY <σv>



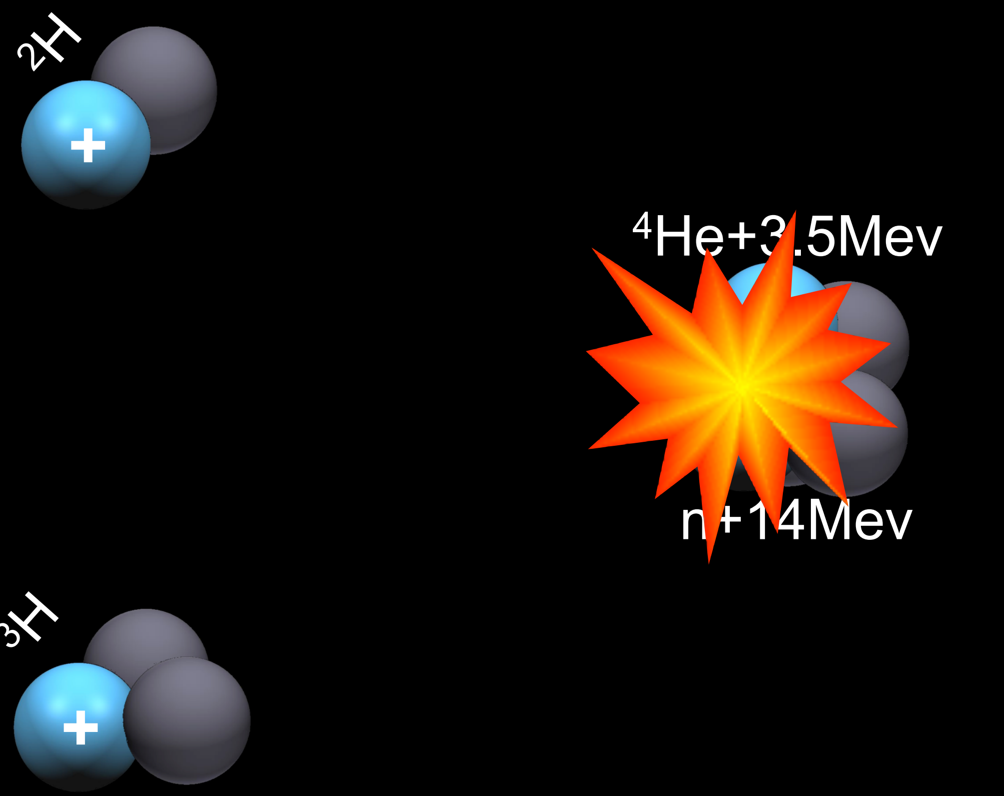
(1 keV = 10 million °C)

NUCLEAR FUSION REACTIONS RELEASE ENERGY

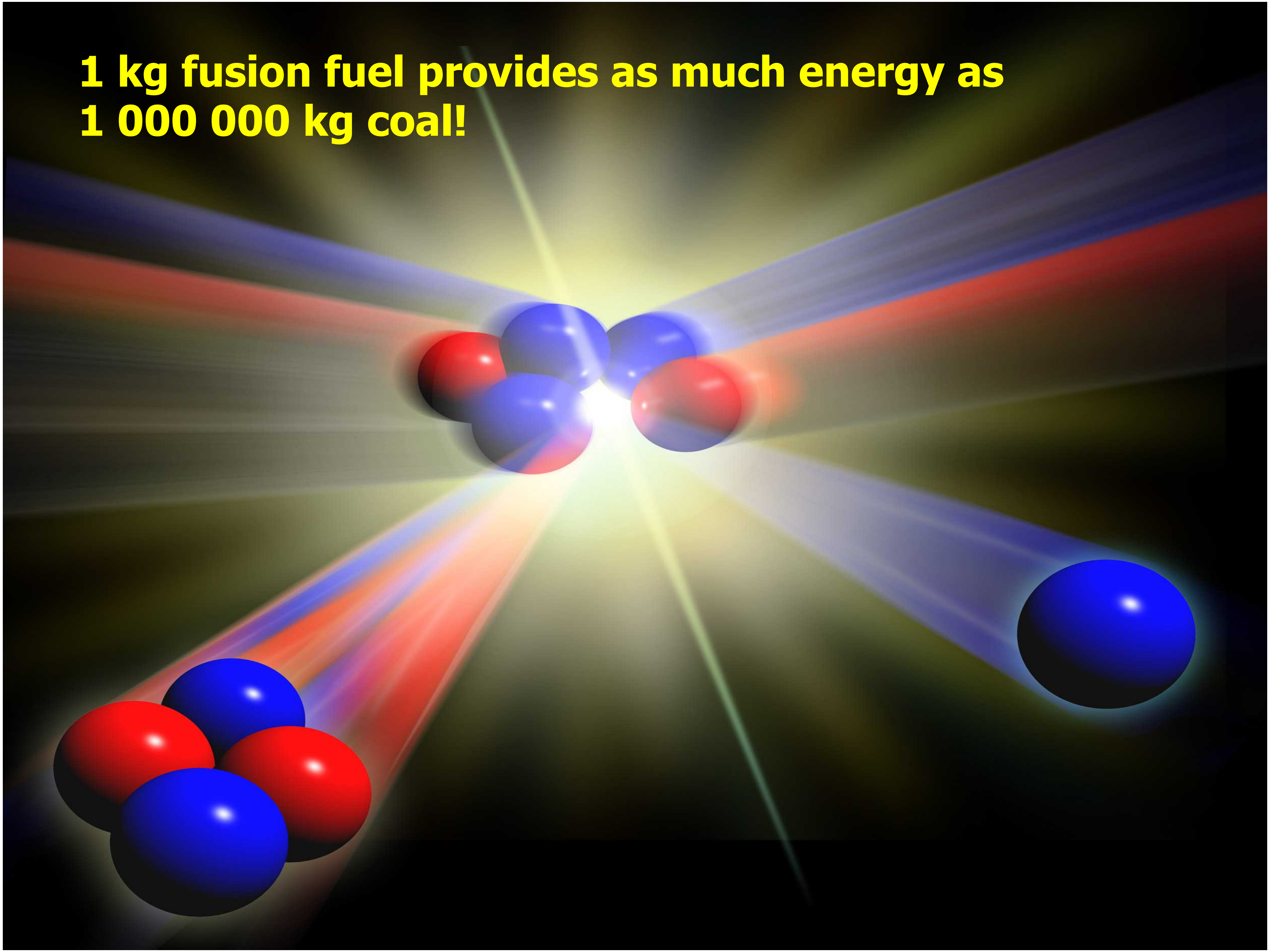
(deuterium) *(tritium)* *(helium)*

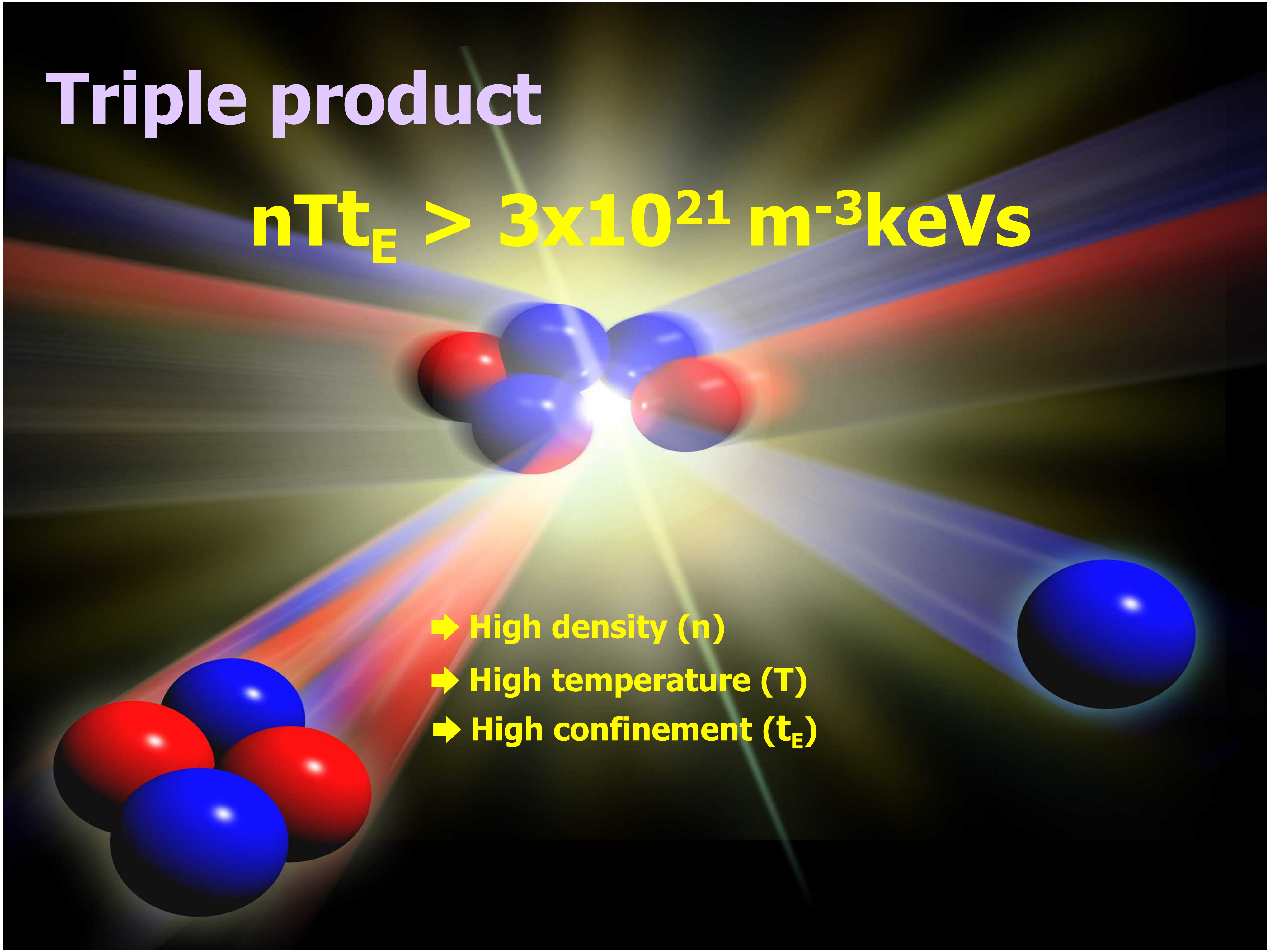
$$^{2}H + {}^{3}H \longrightarrow {}^{4}He + n + \text{Energy}$$

$$E = \Delta mc^2$$



$1 MeV \approx 1.6\ 10^{-13} J$


1 kg fusion fuel provides as much energy as
1 000 000 kg coal!


Triple product
$nTt_E > 3x10^{21}\ m^{-3}keVs$
➡ High density (n)
➡ High temperature (T)
➡ High confinement (t_E)

Energy confinement

How long is the energy in the system (home or plasma) ?

Energy confinement time $\tau_E = \dfrac{W}{P_{\text{loss}}}$ **W ~ energy density**

Home:
τ_E **~ 0.5-1 day**
Winter ~ 90-120 days

Plasma in tokamak:
τ_E **~ 0.2-1 seconds (JET)**
Plasma duration ~ 30 s

The heat must be kept!

BUT HOW PRODUCE FUSION IN THE LAB?

1- On Earth protons are usually not “free”, they are bound in atoms

We need to
ionize the atoms and

PRODUCE THE PLASMA

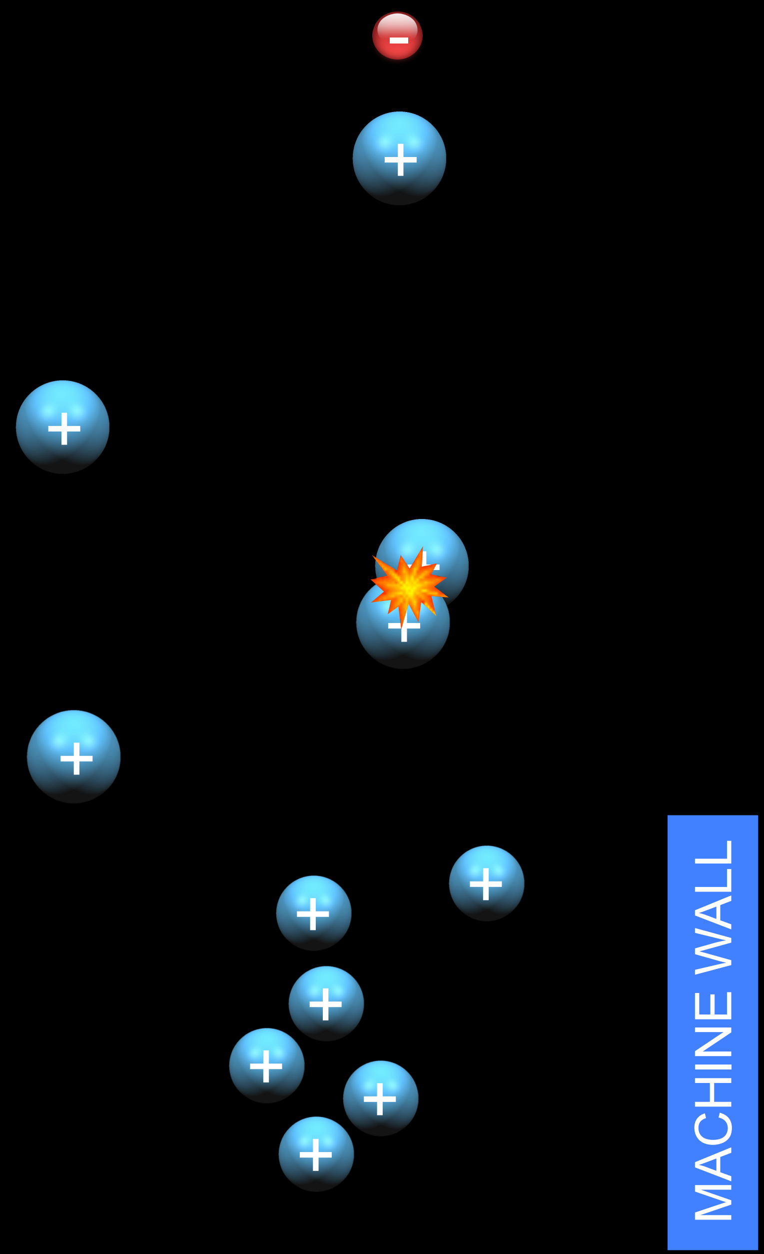
2- Once nuclei are “free” they will not easily fuse

We need to
HEAT THE PLASMA

(≈100 million °C)
until the kinetic energy is high enough to overcome the electrostatic force

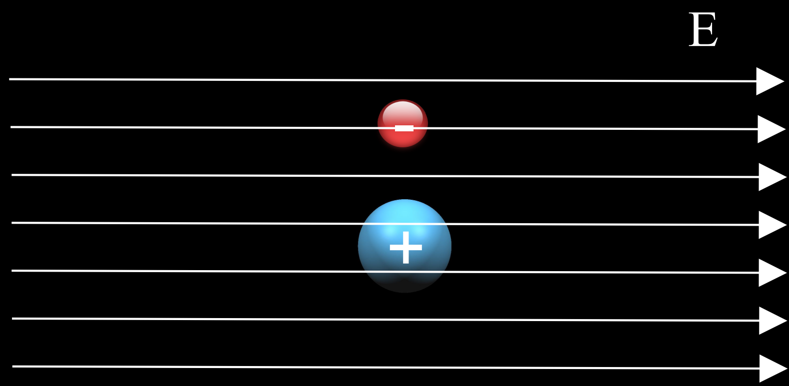
3- The plasma is very hot and it should not touch any material

We need to
CONFINE THE PLASMA



PLASMA GENERATION AND HEATING

To ionize the gas an **ELECTRIC FIELD** is used



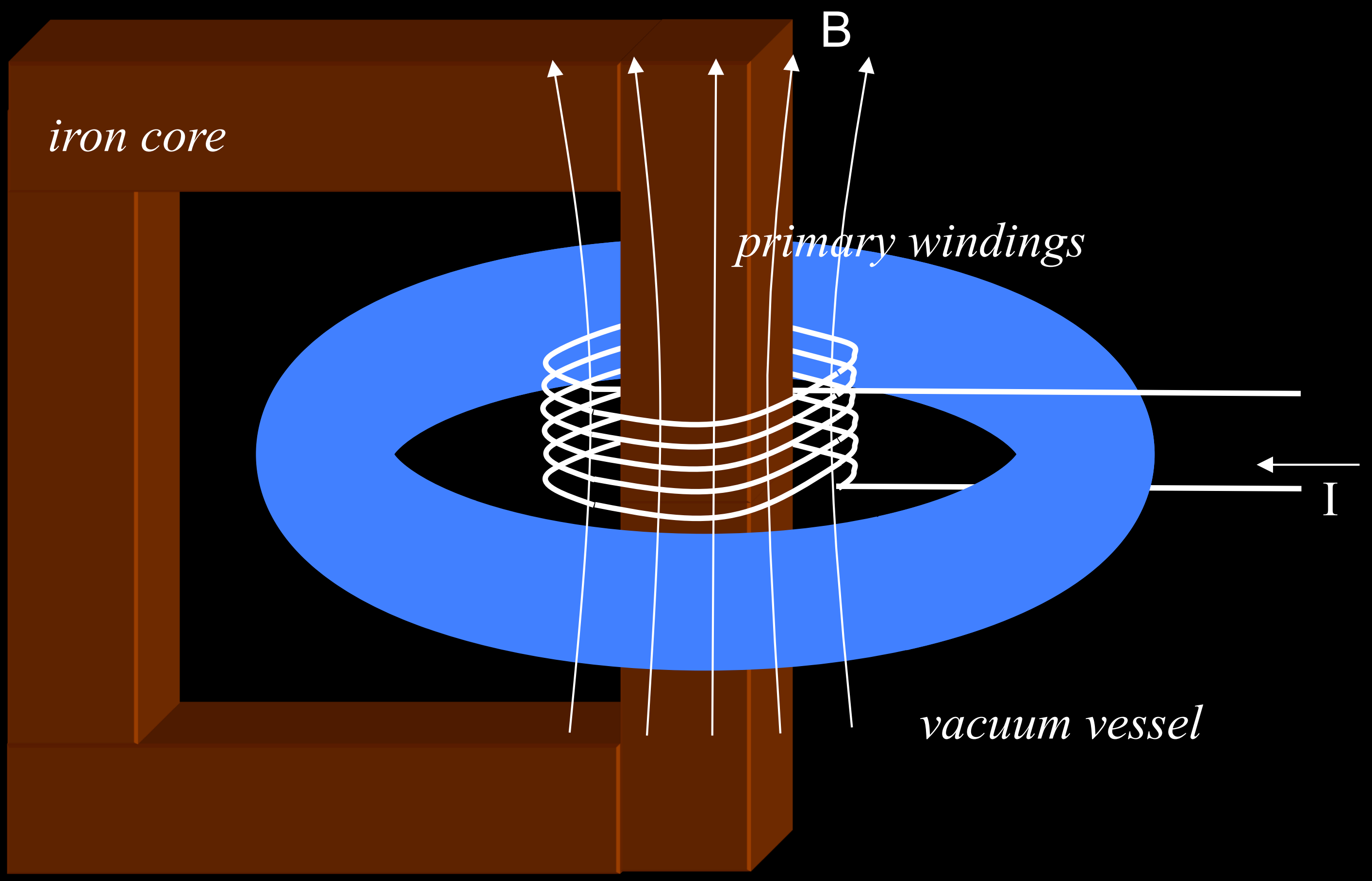
To heat the plasma several methods are used.
One is to use the **OHMIC HEATING** produced
by a **ELECTRIC CURRENT** that flows in the plasma:

$$P = R\,I^2$$

Like the heat produced in a light bulb

PLASMA GENERATION AND HEATING

How is the electric field and current produced?



Faraday's law:

$$V = -\frac{\Delta \Phi_B}{\Delta t}$$

EXTRAP T2R

voltage: $V \approx 25$ Volt
electric field: $E \approx 3 \text{V/m}$
plasma current: $I_{plasma} \approx 100$ kA

PLASMA CONFINEMENT

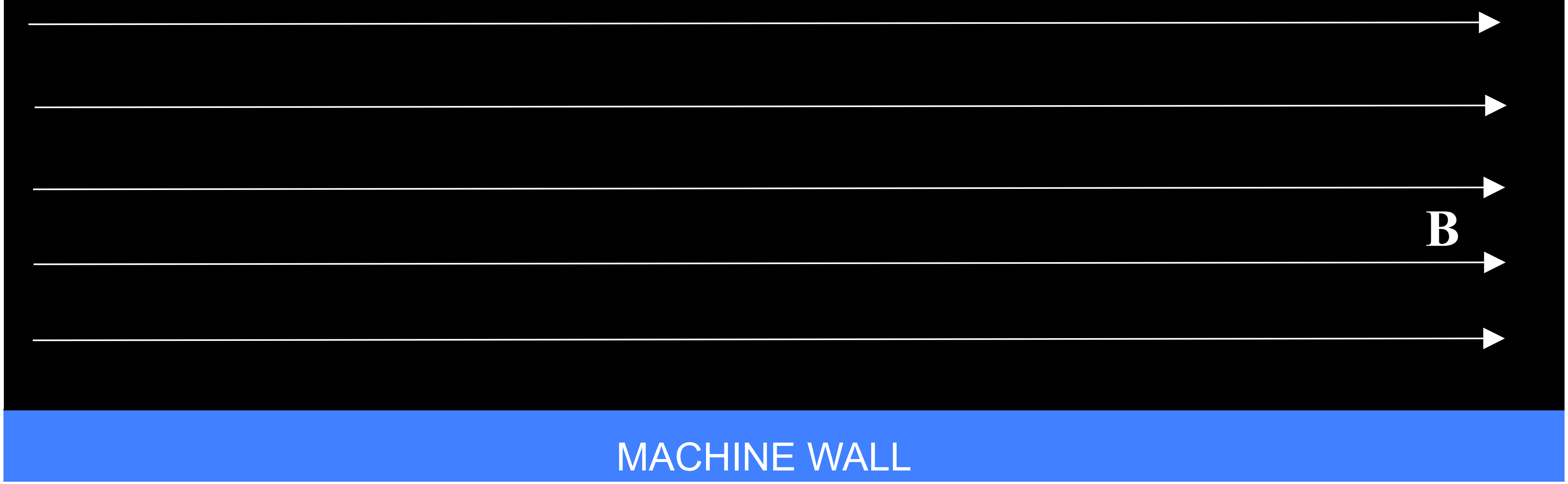
Charged particles - circular motion in the direction perpendicular to the magnetic field.

The particles can also move along B

$$r = \frac{mv_{\perp}}{qB}$$

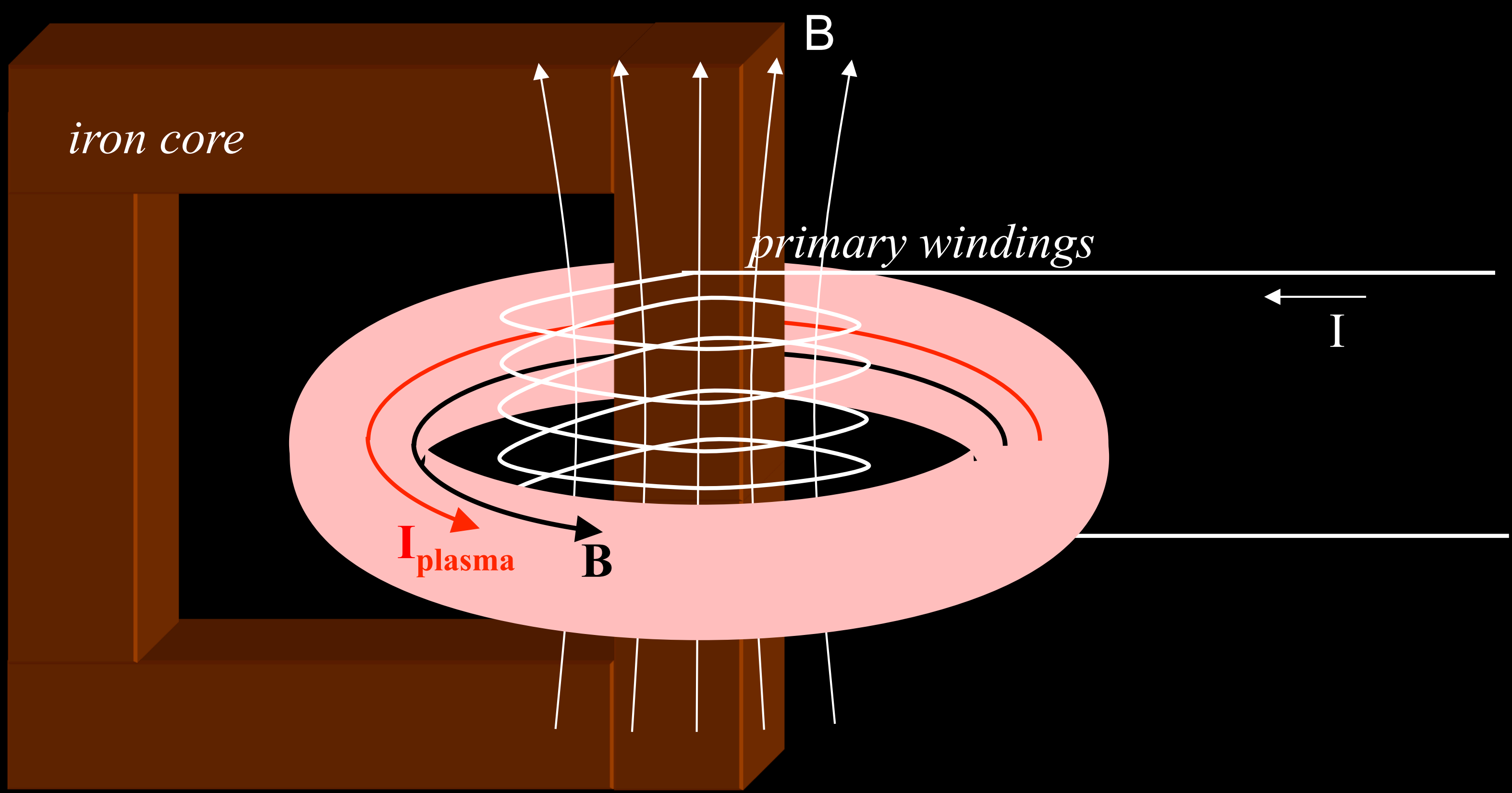
EXTRAP T2R Larmor radius:

electrons:	$r \approx 0.1$ mm
protons:	$r \approx 4$ mm



PLASMA GENERATION AND HEATING

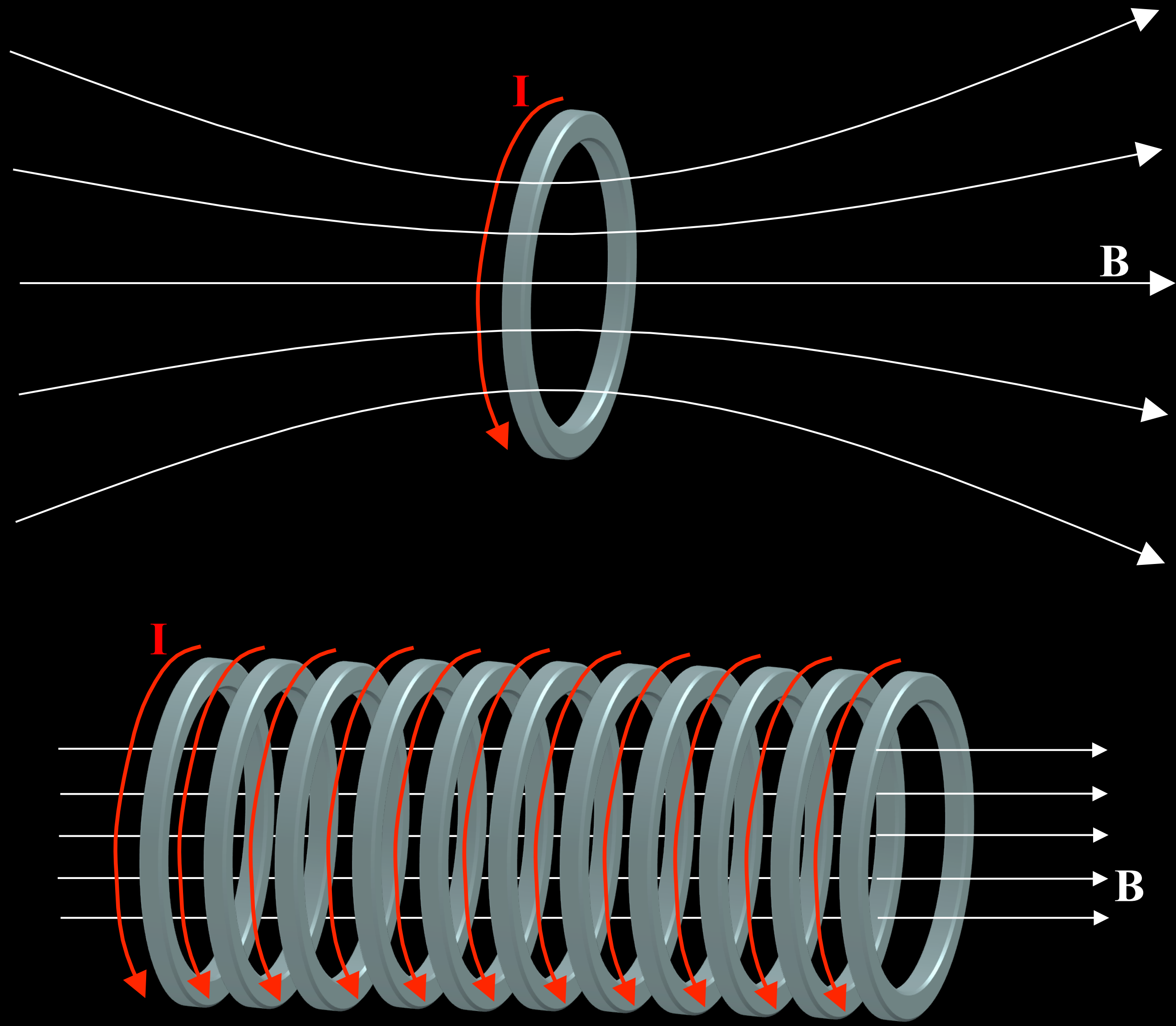
How is the electric field and current produced?



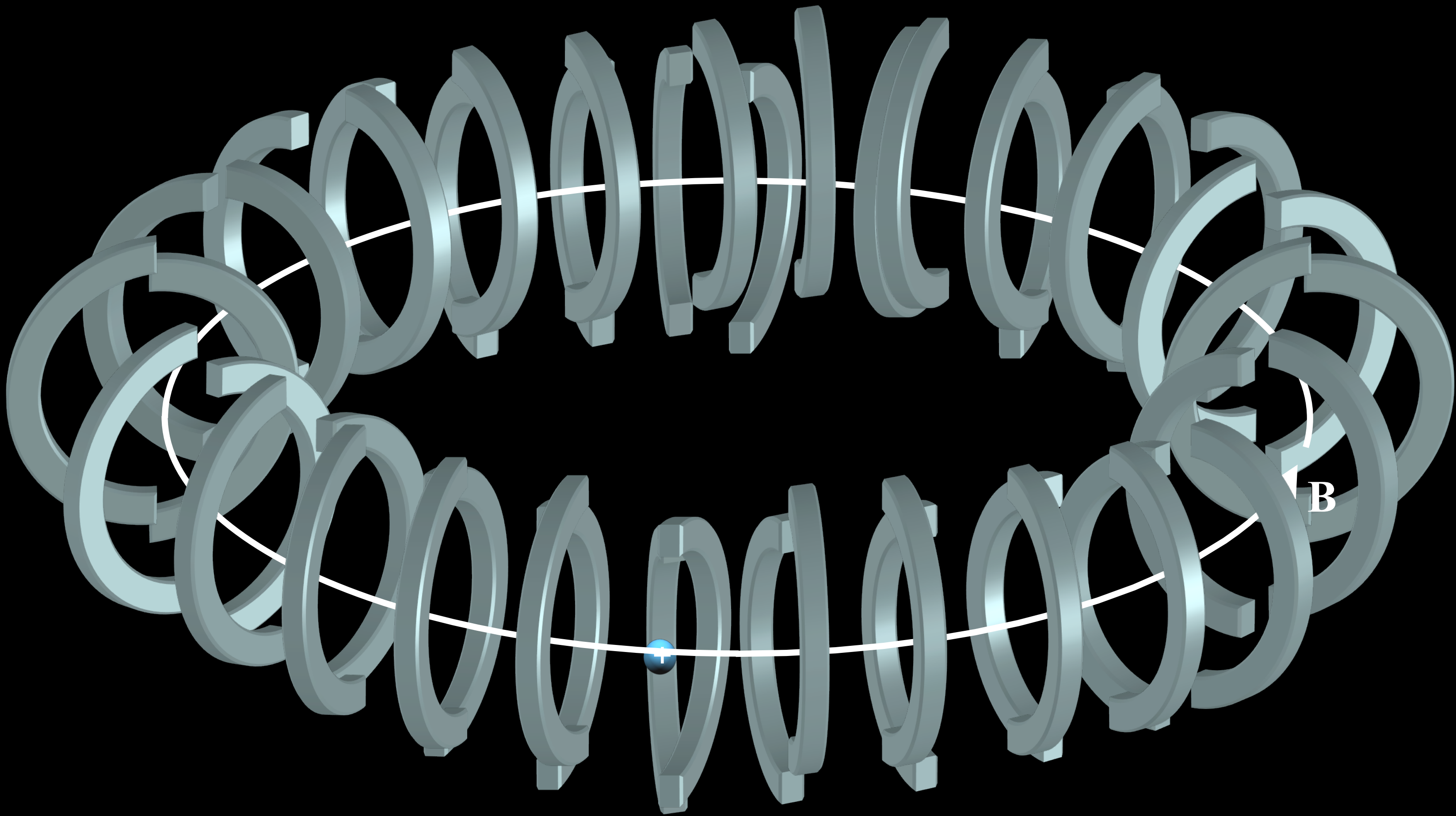
We need to generate a toroidal magnetic field

TOROIDAL FIELD COILS

The toroidal field is produced by current flowing in coils:

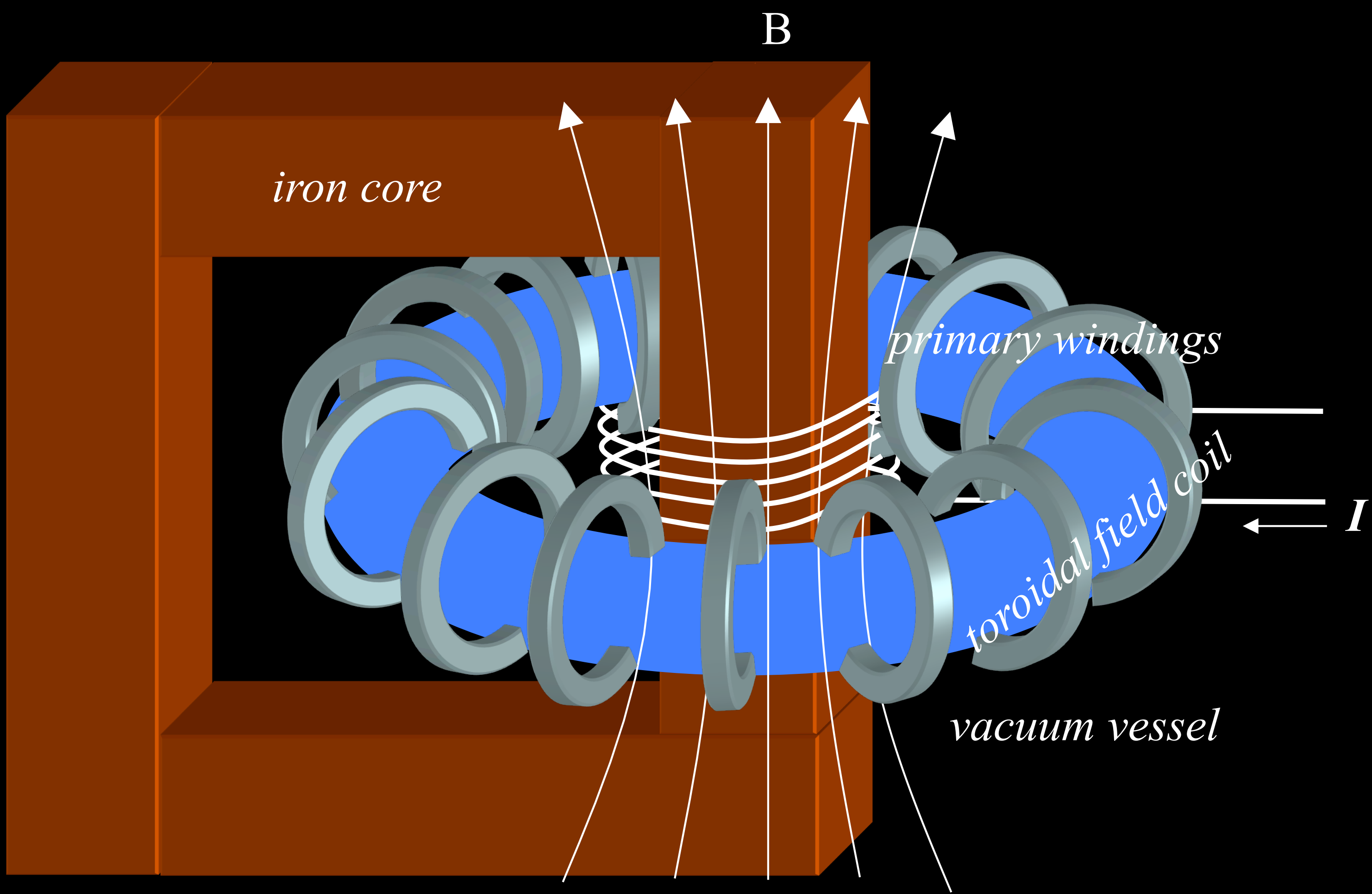


TOROIDAL FIELD COILS

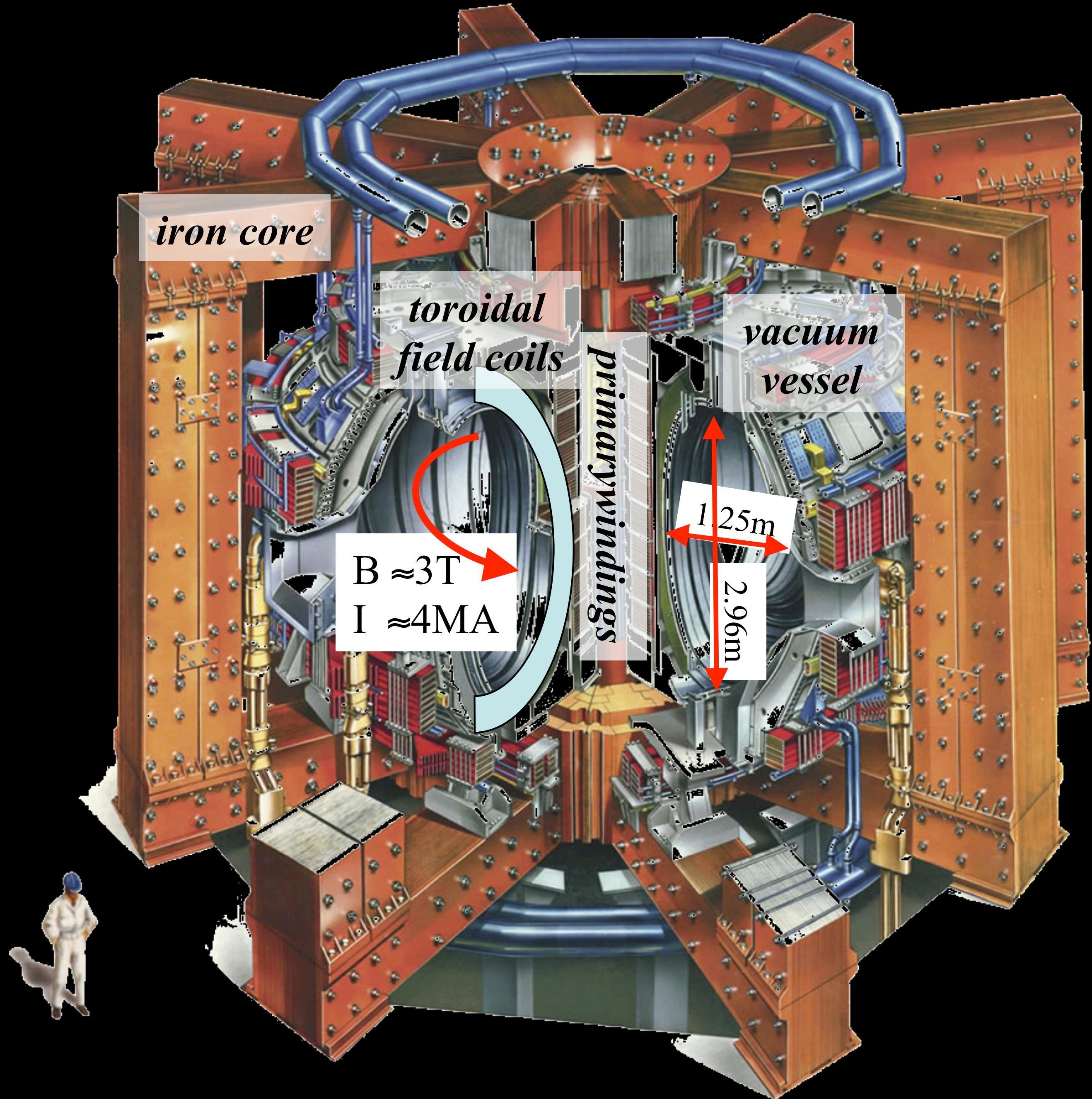


EXTRAP T2R toroidal magnetic field: $B \approx 0.1$ T

THE MACHINE: all pieces together

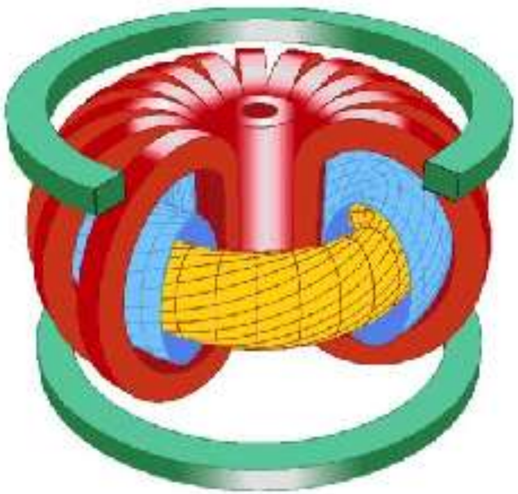


JET, the largest tokamak in the world



Different magnetic confinement schemes

Tokamak



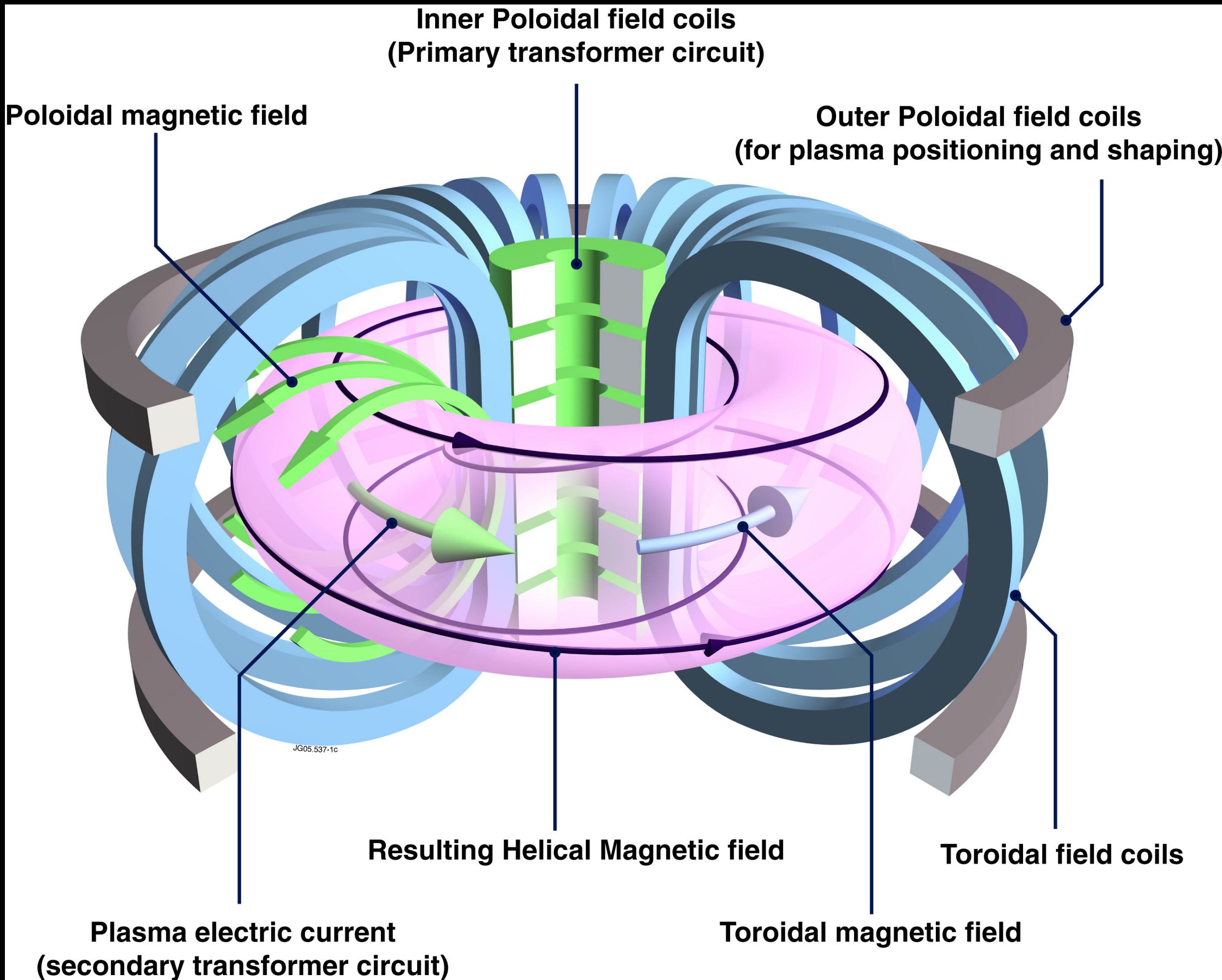
Stellarator

Reversed-field Pinch

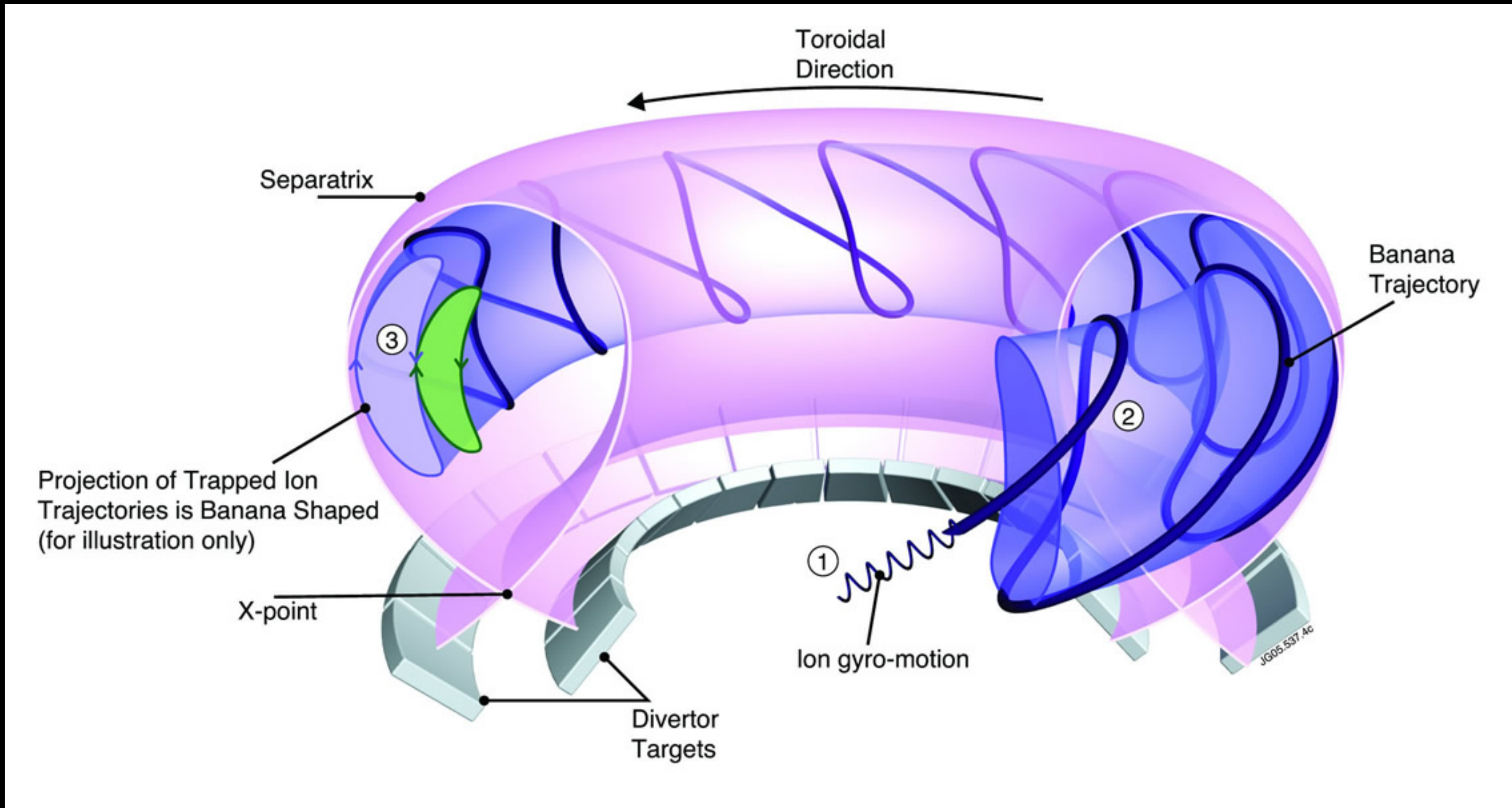
EU world leading

The tokamak is presently the main line

Magnetic confinement



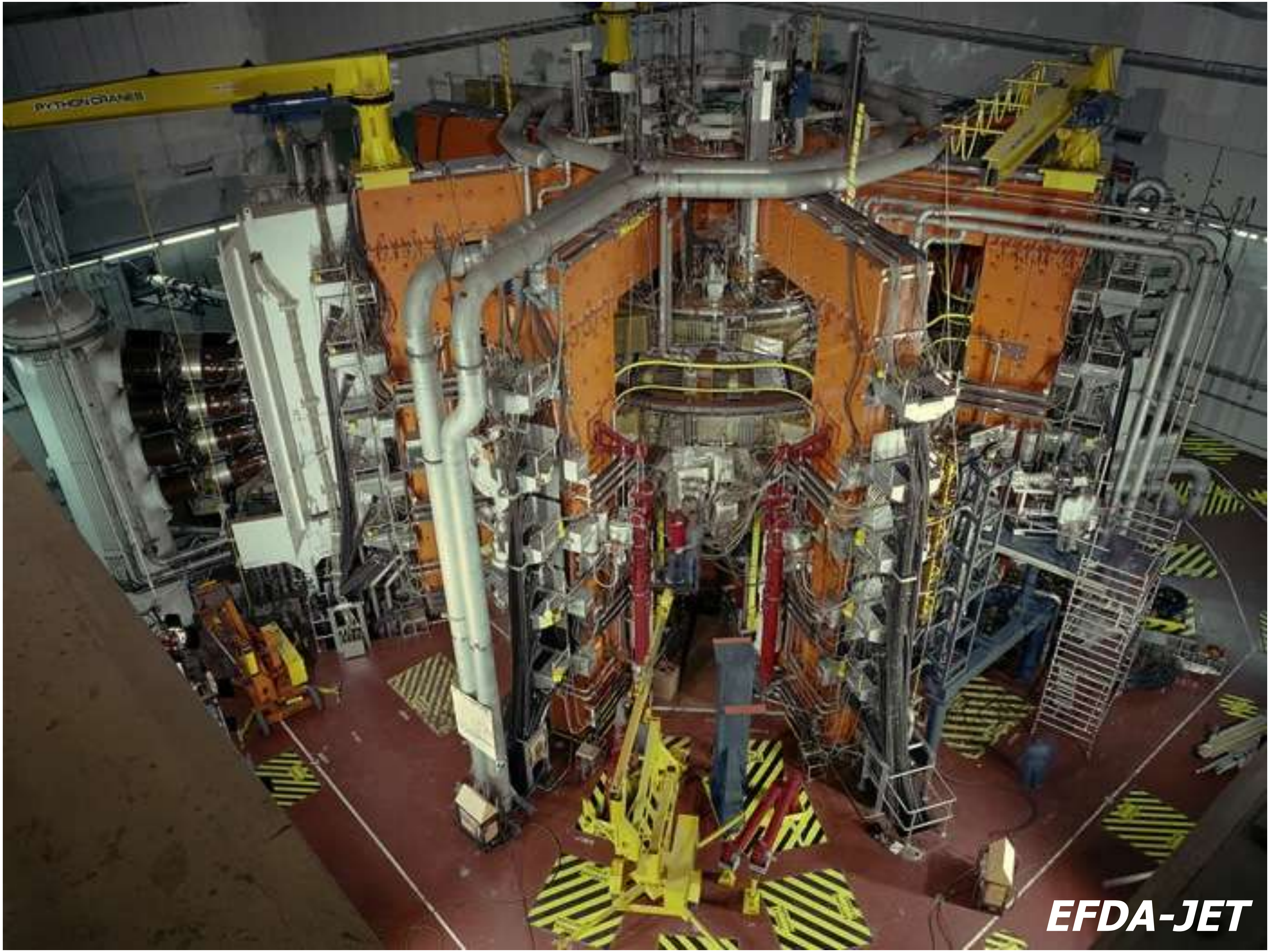
Magnetic confinement



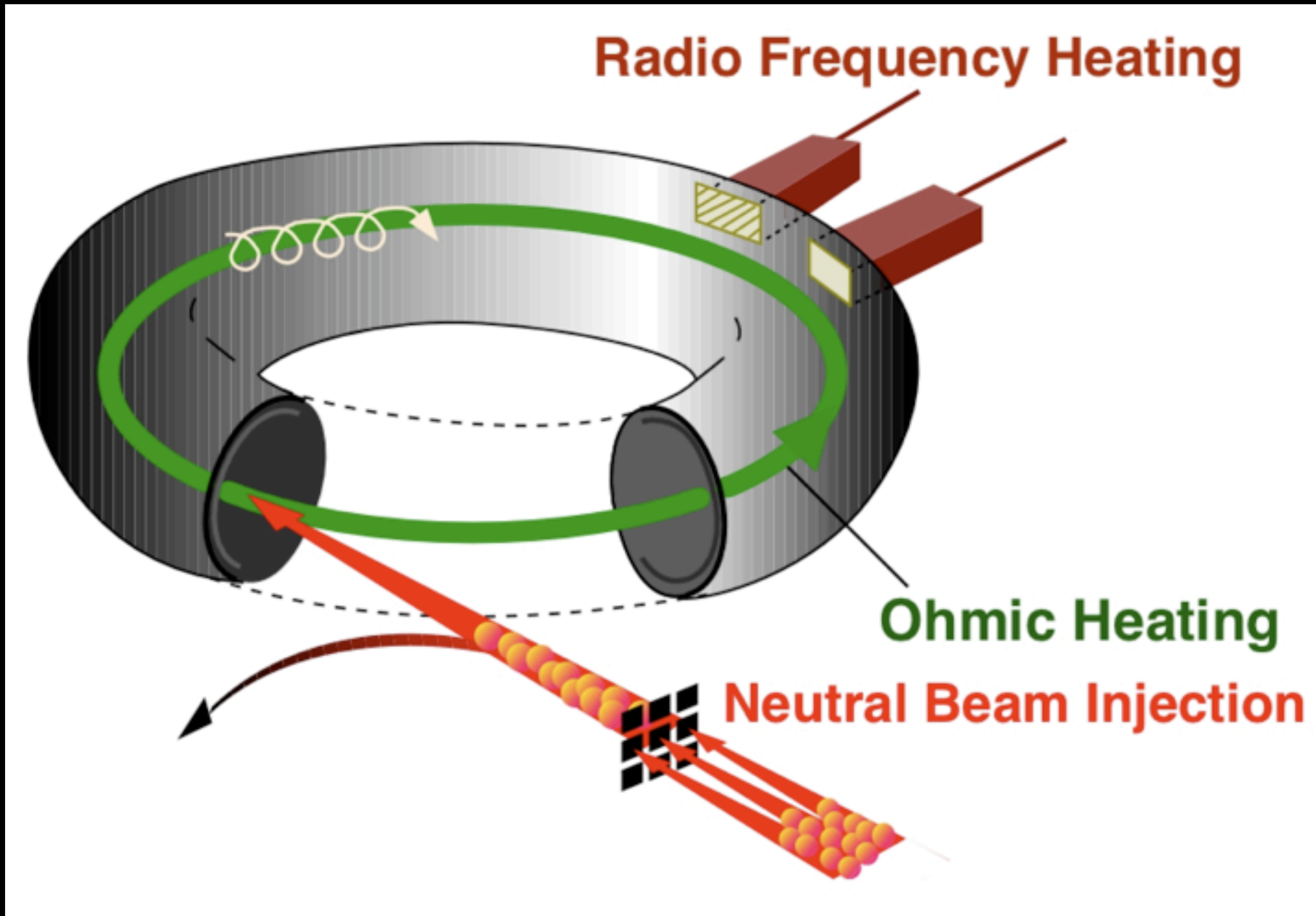
Magnetic field coils

An octant section of JET's torus, held in a C-frame, 1982

Final octant section being installed in 1982


PYTHON CRANES
EFDA-JET

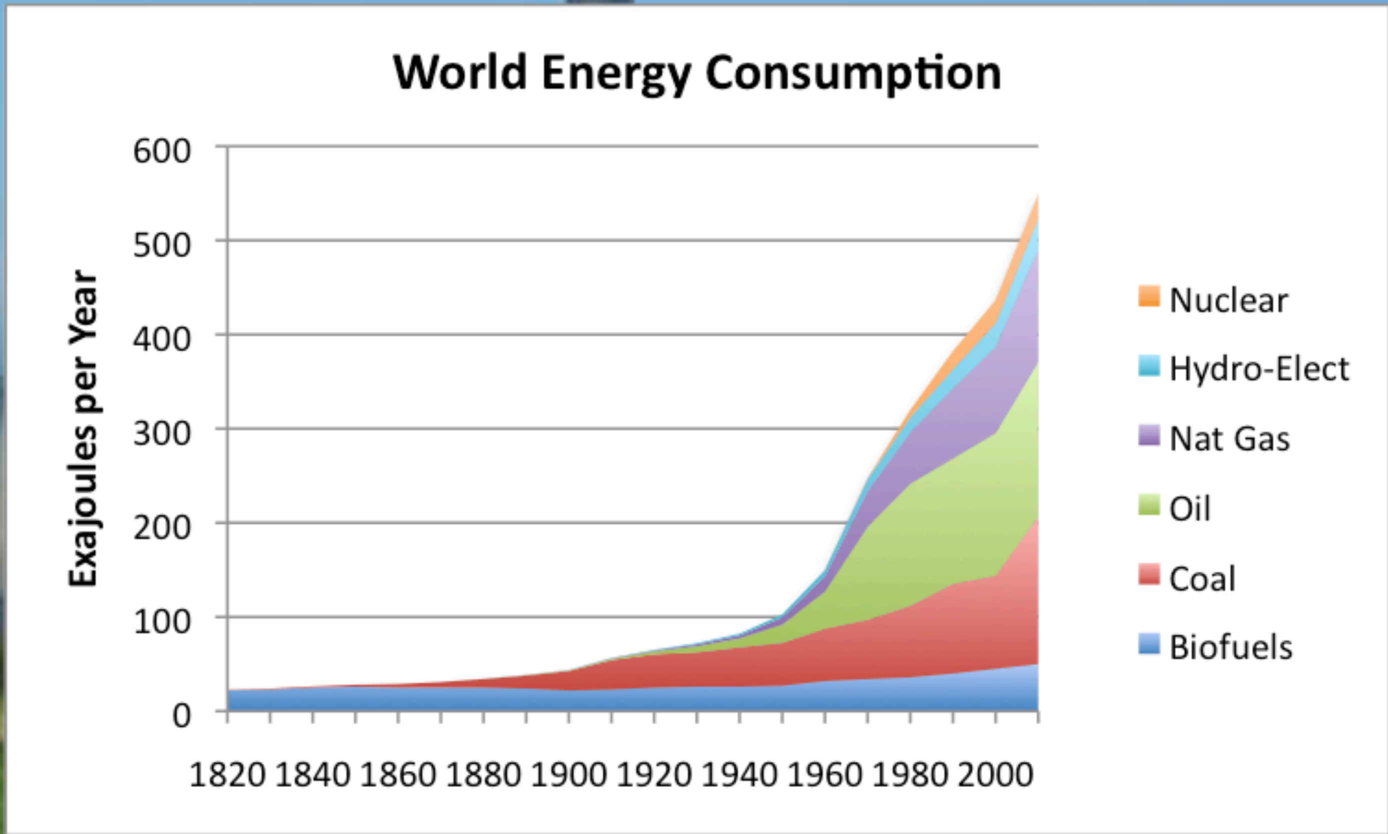
Plasma heating



Do we need fusion?

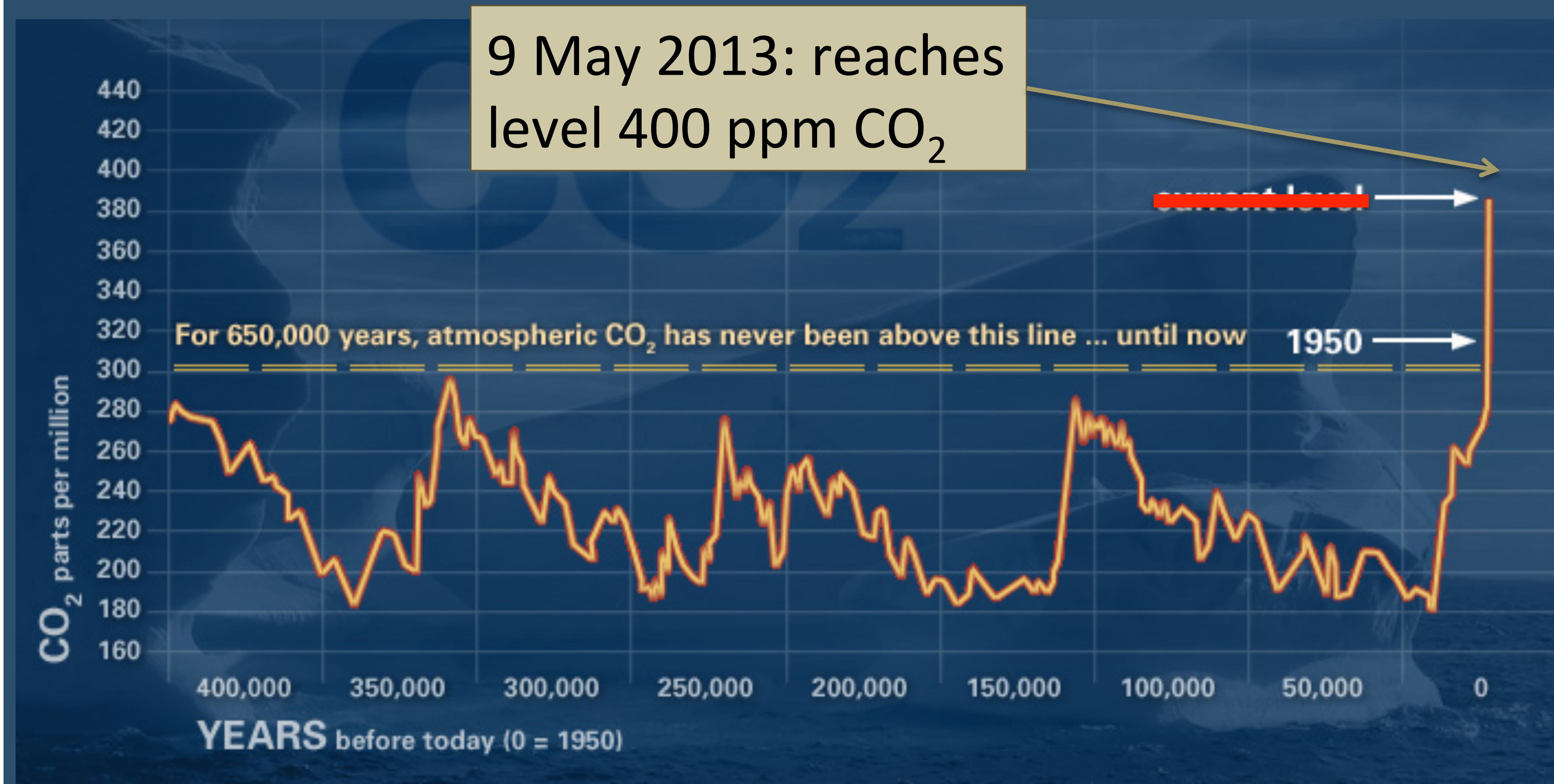
Fossil energy completely dominates..

GLOBAL HEATING



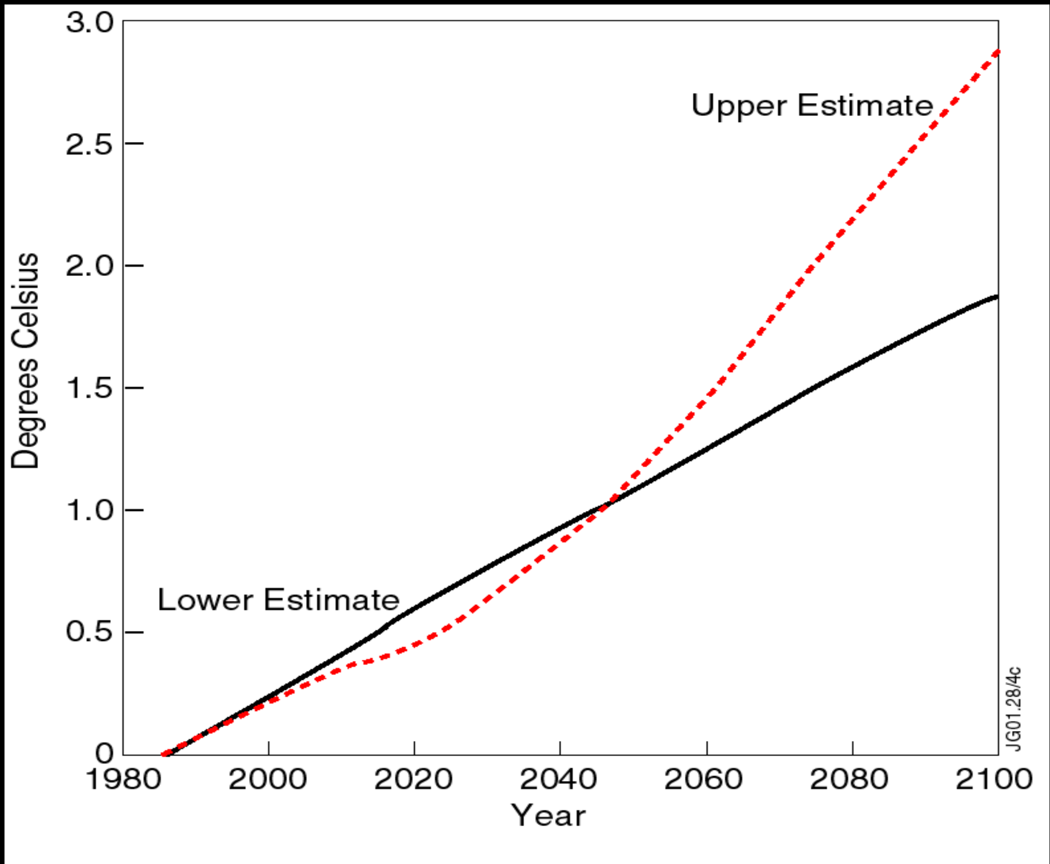
Human impact on CO_2 in atmosphere

Since the industrial revolution (19th century) man has burnt enormous amounts of fossil fuel, which has changed our atmosphere



Fossil fuels are problematic

Fossil fuels are currently being burned and lost forever

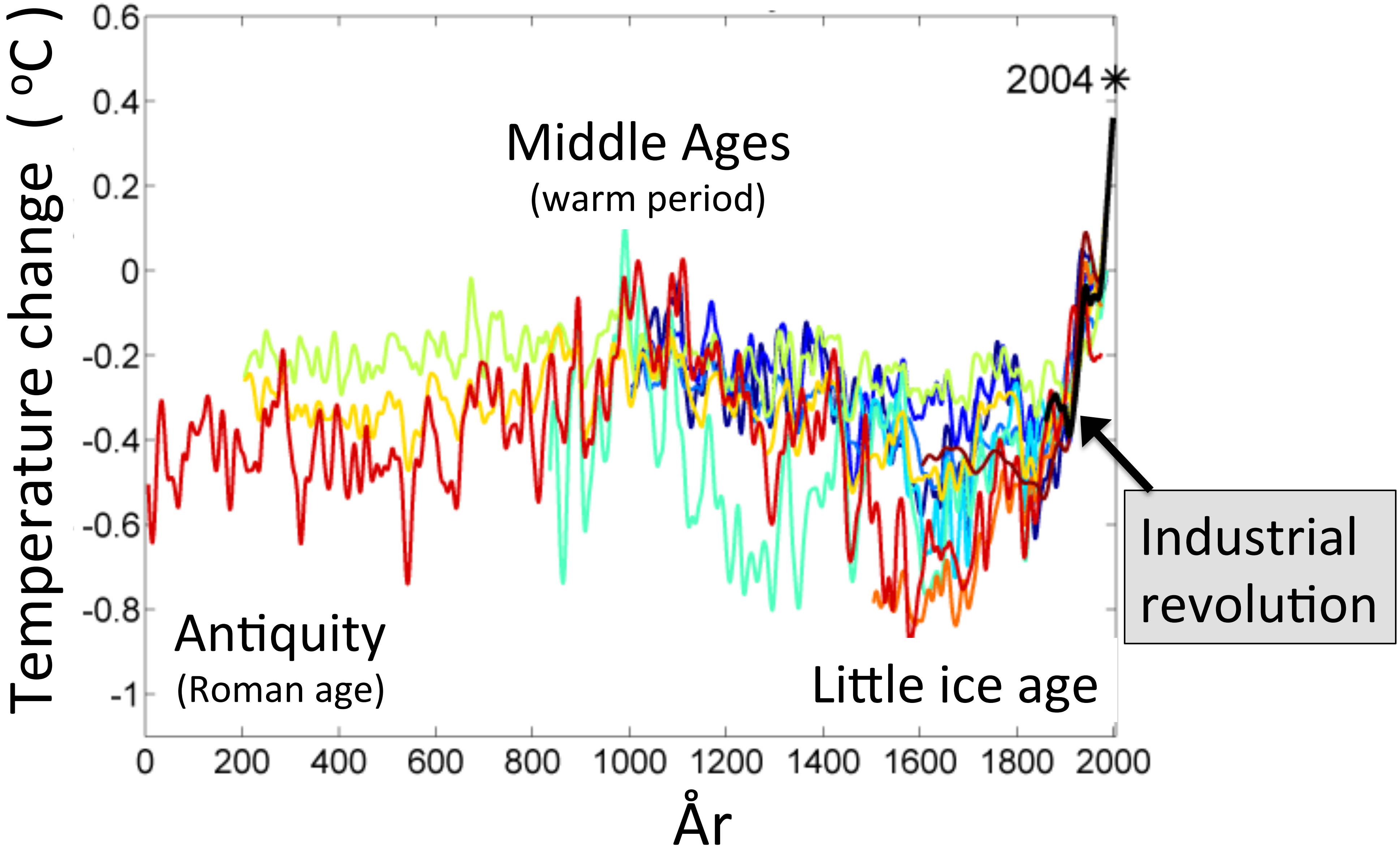


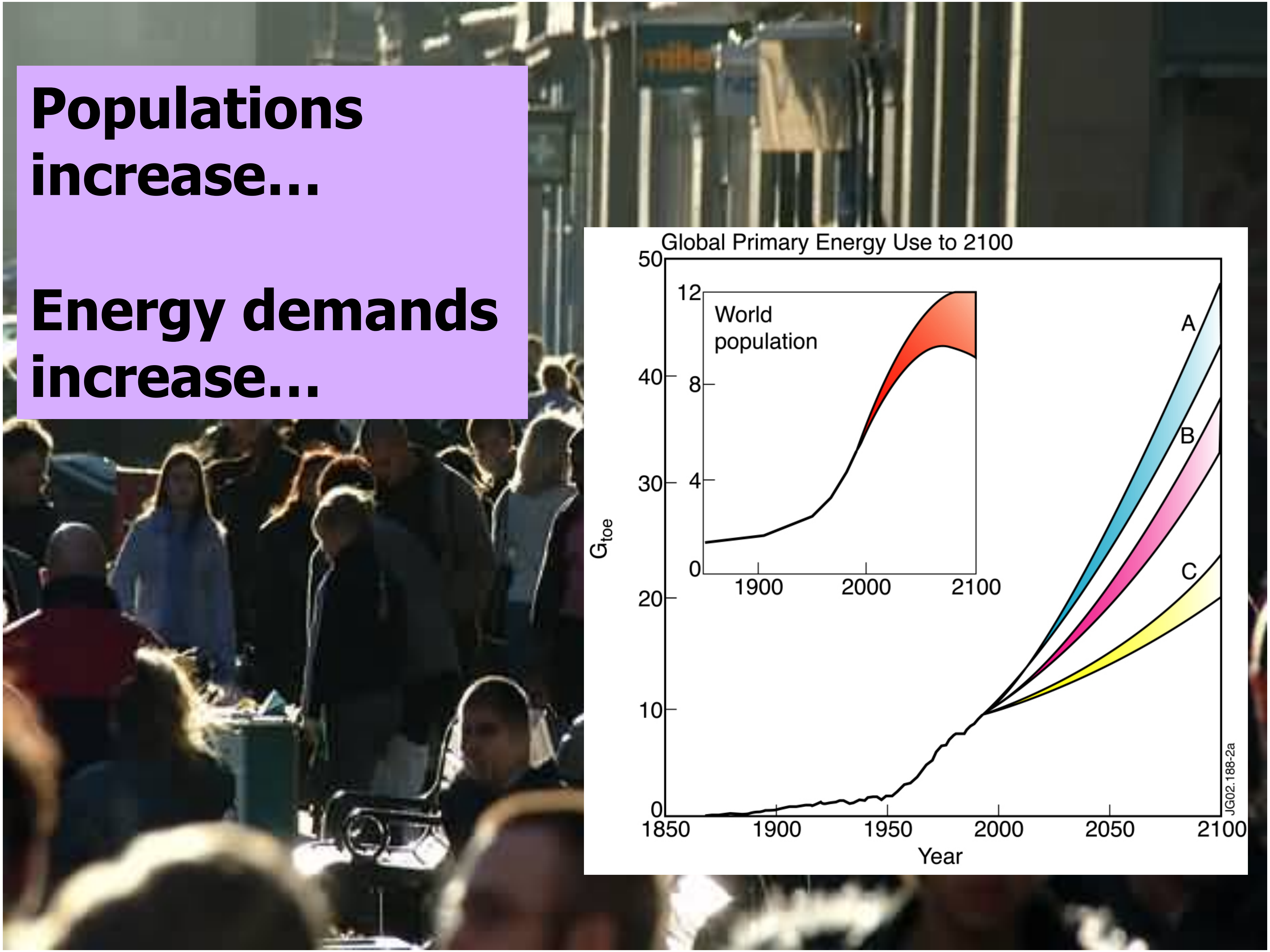
GLOBAL WARMING due to excessive production of greenhouse gases from power stations

Fossil fuels are essential in the petrochemical and pharmaceutical industries

Significant economic and political impact

We have also changed the global temperature



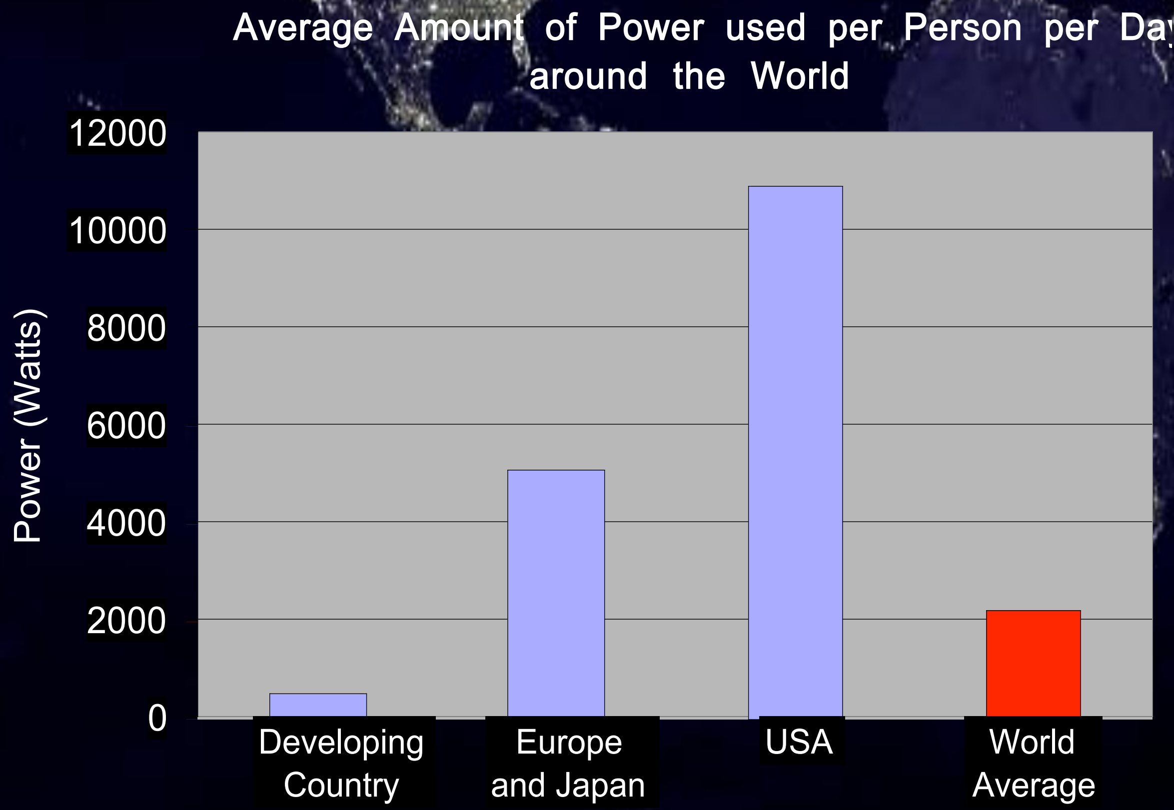


Populations increase…

Energy demands increase…

Global energy consumption

Energy use in developing countries is low, but increasing

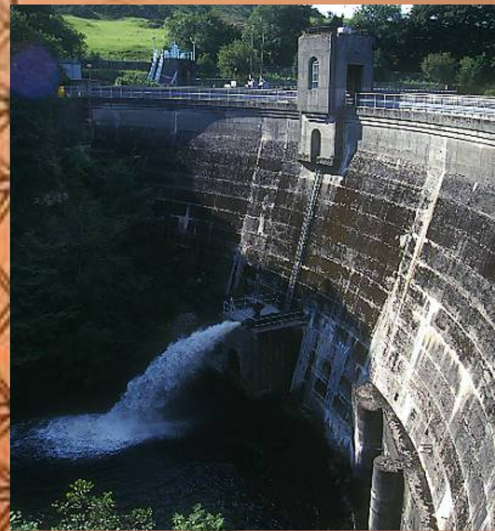


In 50 years the global population may have doubled

Energy use may have increased with factor 2-3

Picture courtesy of NASA/GSFC

Sustainable energy sources



Renewables (bio, wind, wave, solar, geothermal, hydro)

BUT:

- **Low energy density**
- **Intermittent; need storage systems**

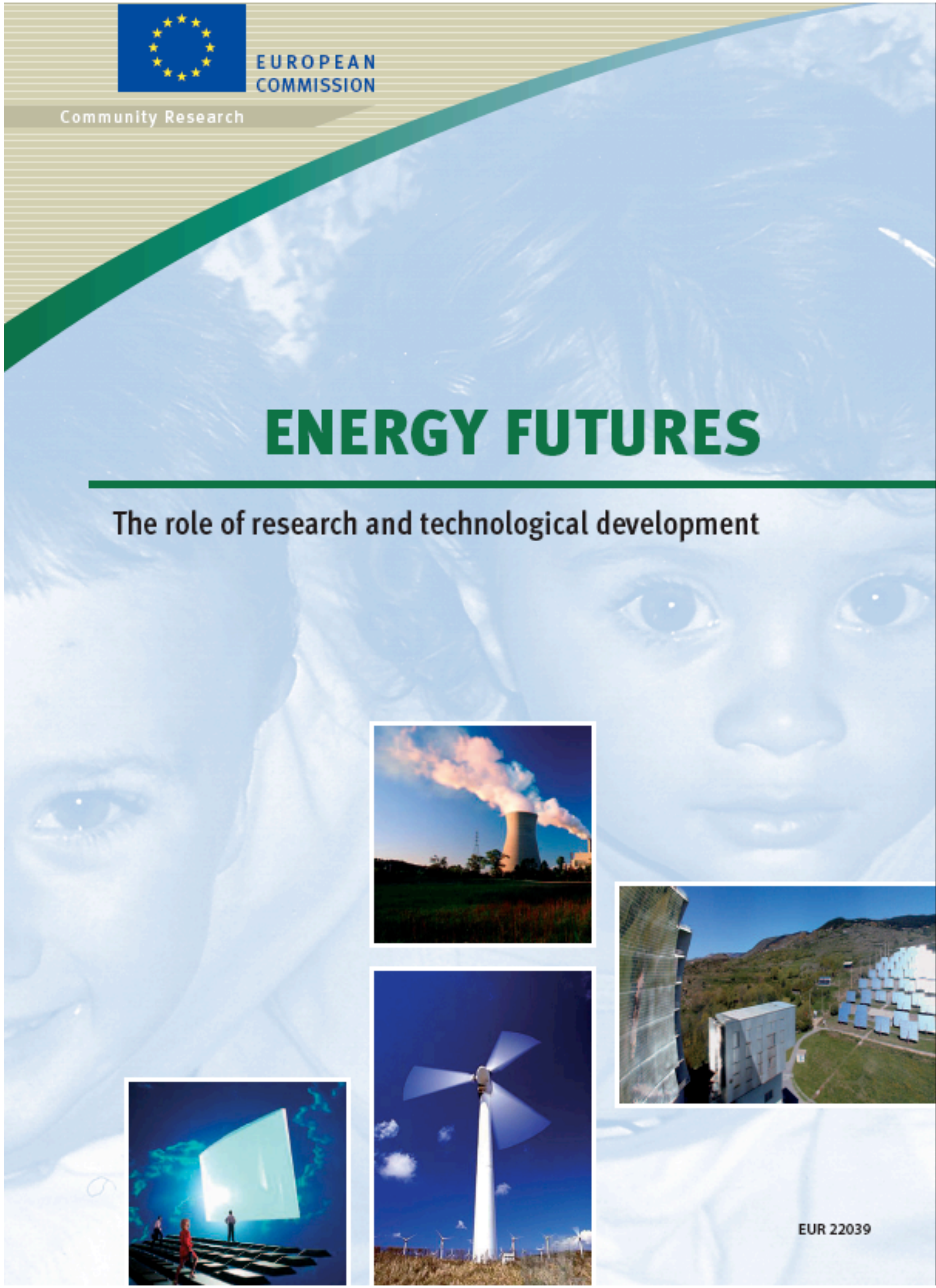
Renewables are not enough...

EU Commission study from 2006:
"Energy Futures -
The role of research and technological development"

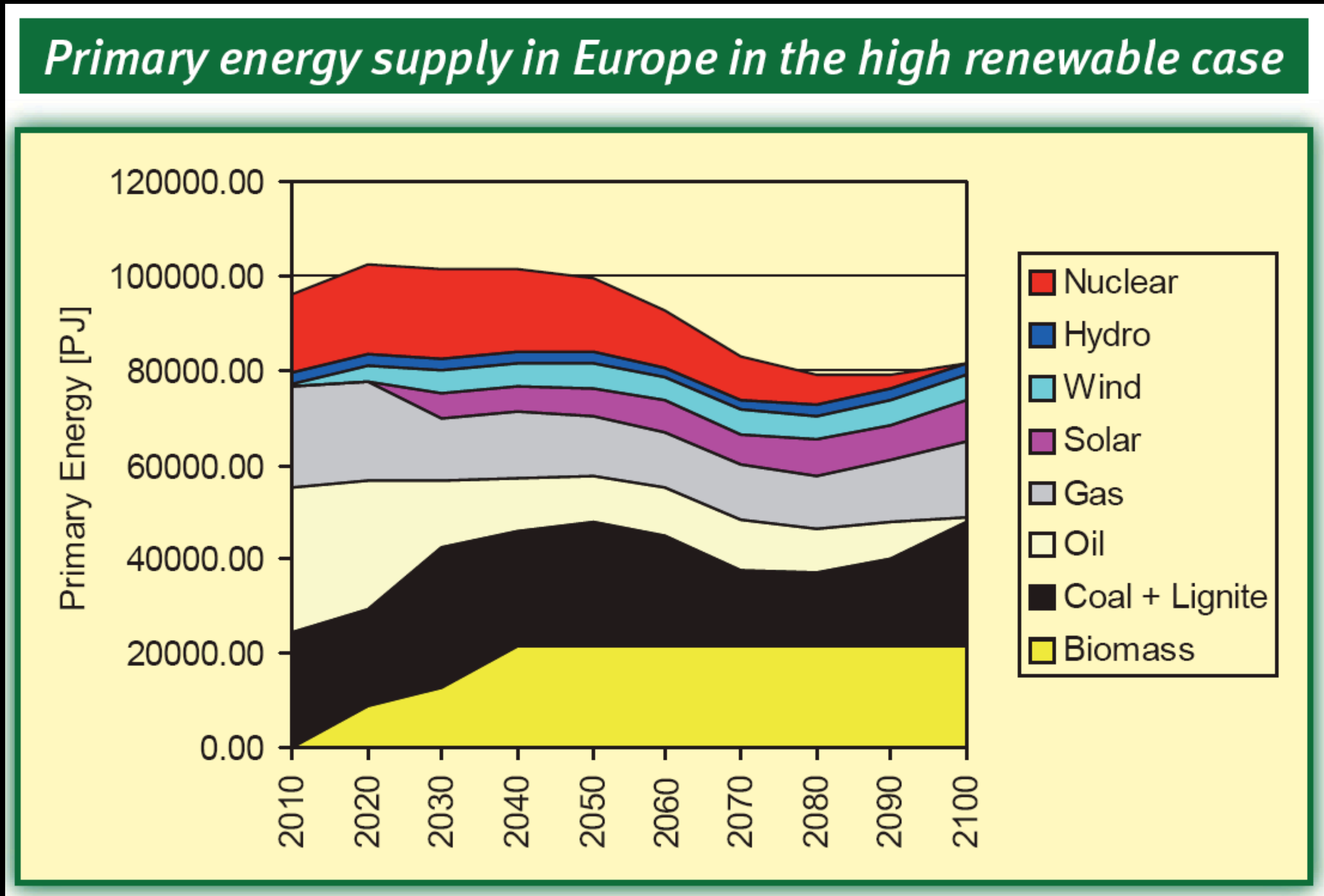
Four long time scenaries for Europa were studied.

Alternative with <u>strong contribution of renewables</u>:
At most 50% of the produced energy is renewable year 2100.
biomass 25%
solar 11 %
wind 7%.

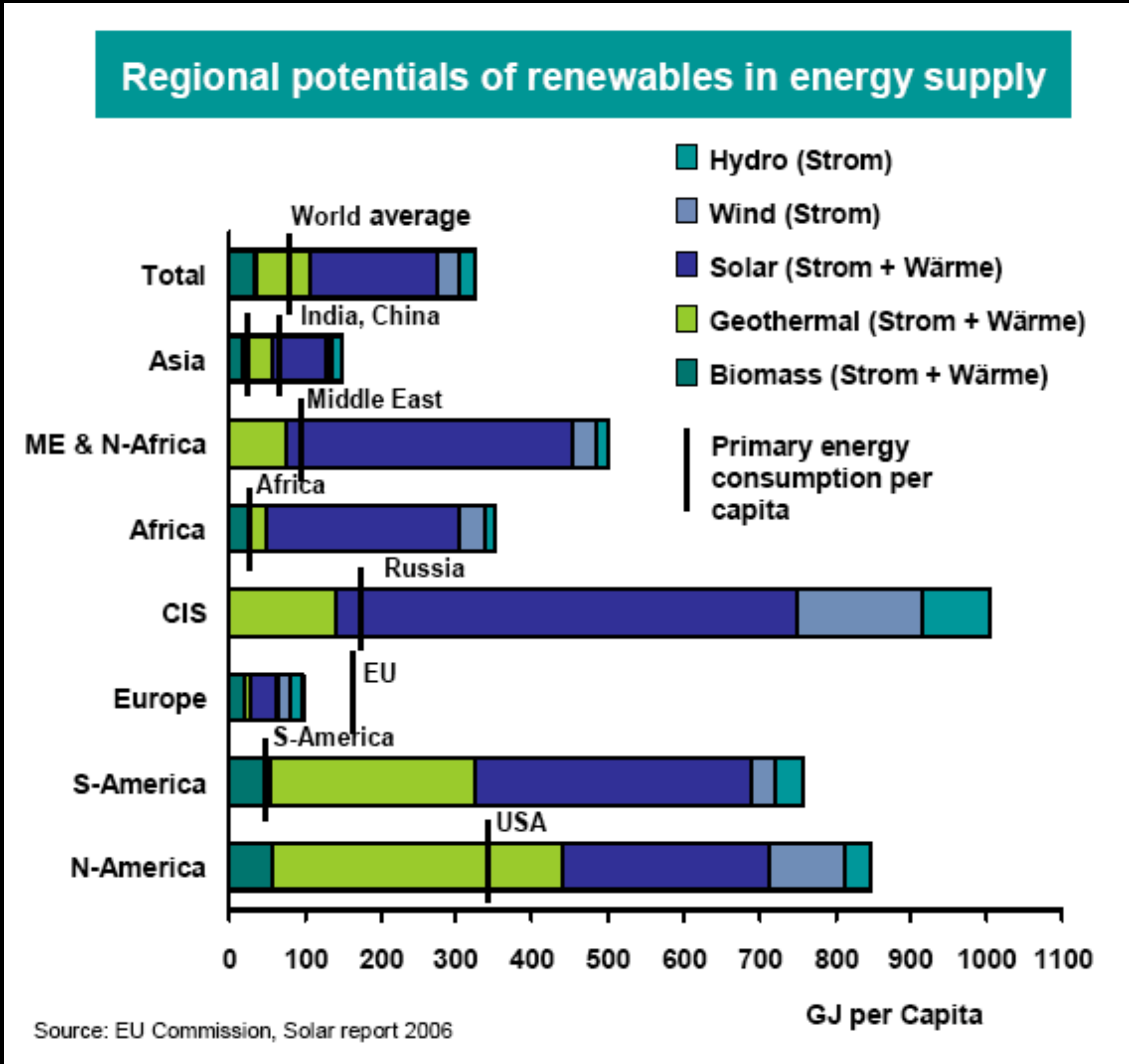
50% sustainable energy is missing!



Europe's energy future; scenarios



Europe's energy future, scenario with maximized renewable contribution



Europe

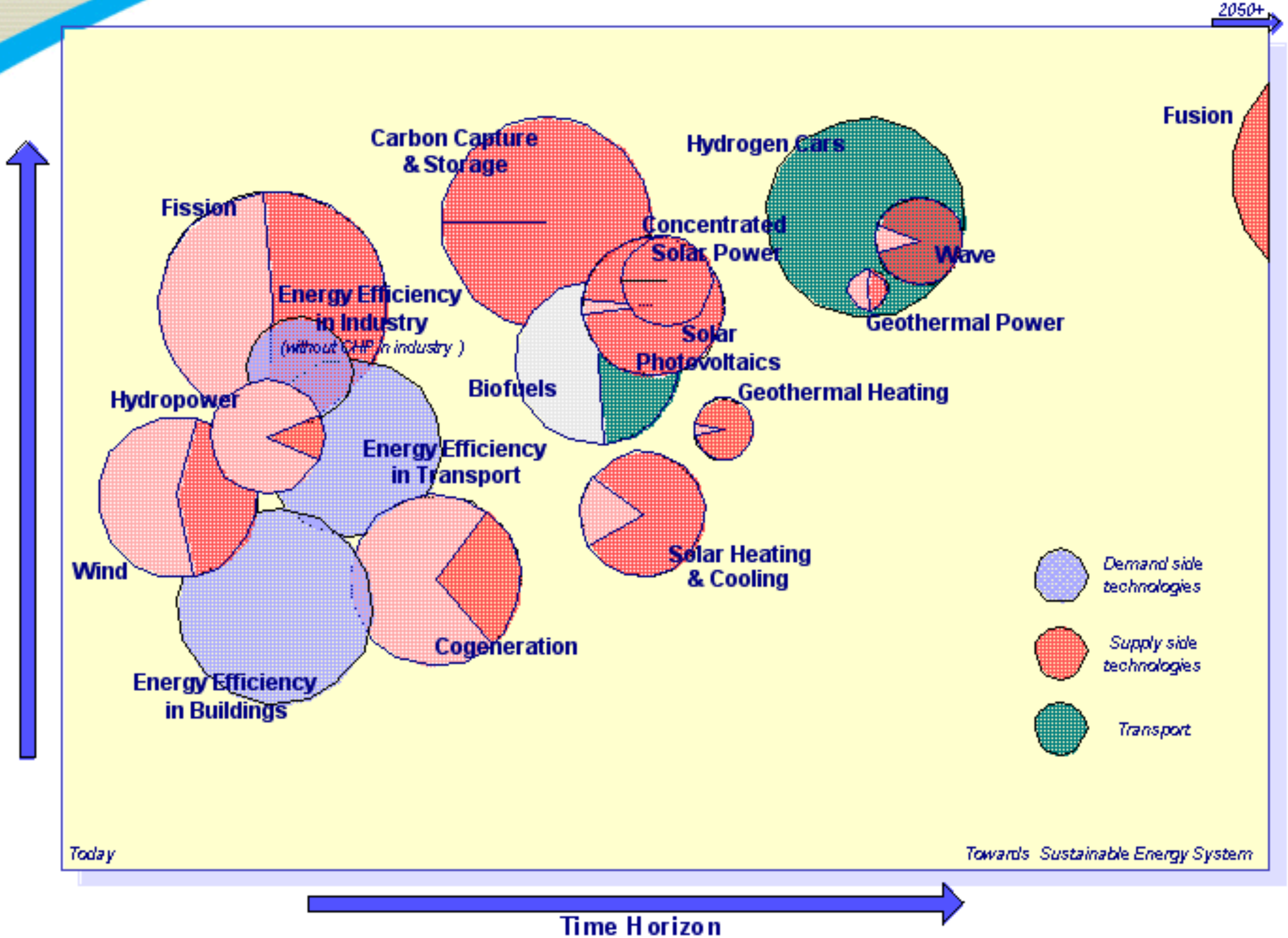
has weak potential for renewable energy

European Strategic Energy Technology Plan (SET-Plan)

European Commission

December 2007

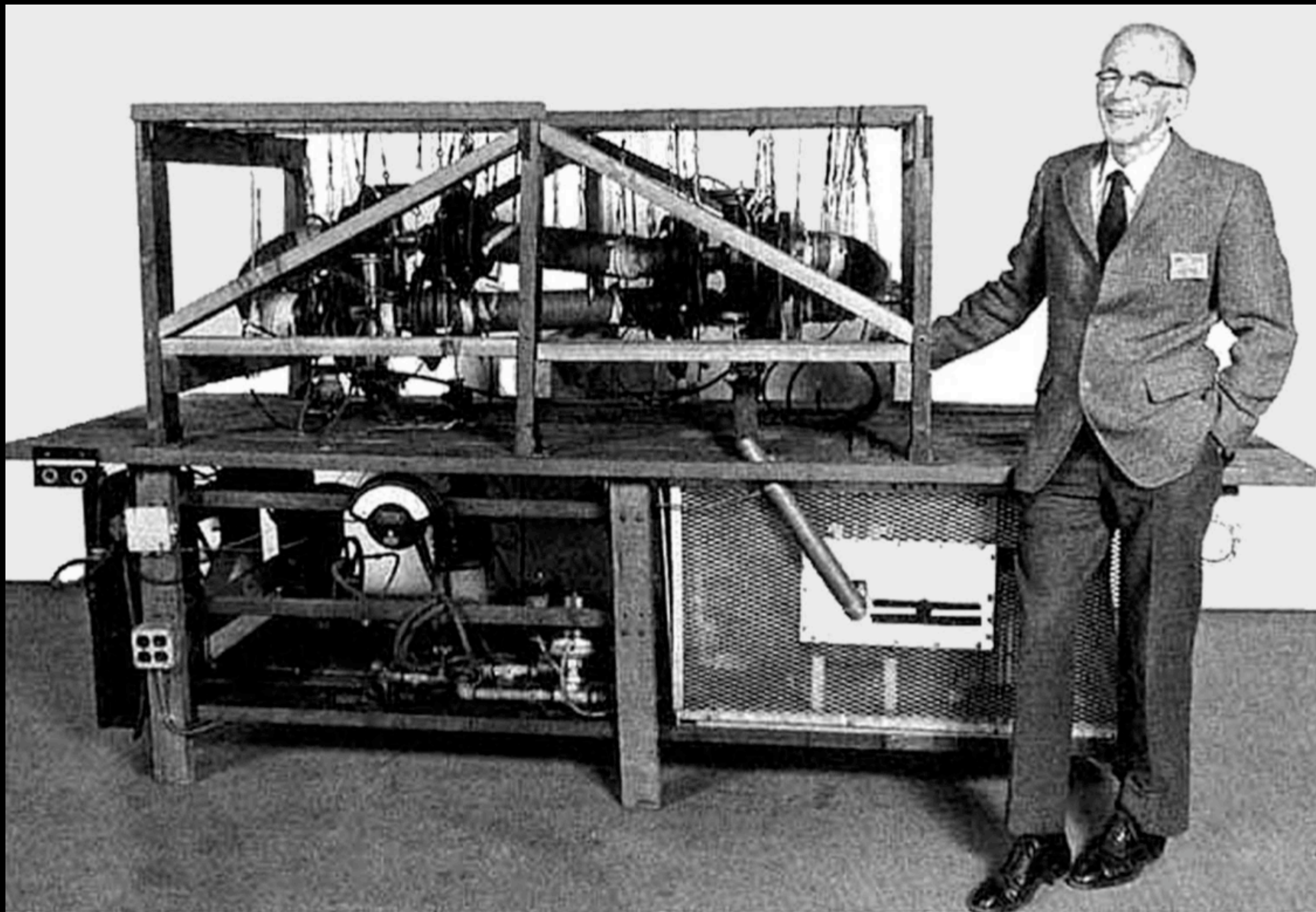
Potential of technologies



Fusion power advantages

- Negligible climate effect – no emission of greenhouse gas
- No long lived radioactive waste, no transports of waste
- No risk for nuclear meltdown
- Fusion energy is SUSTAINABLE ENERGY:
- Fuel for millions of years easily accessible in....

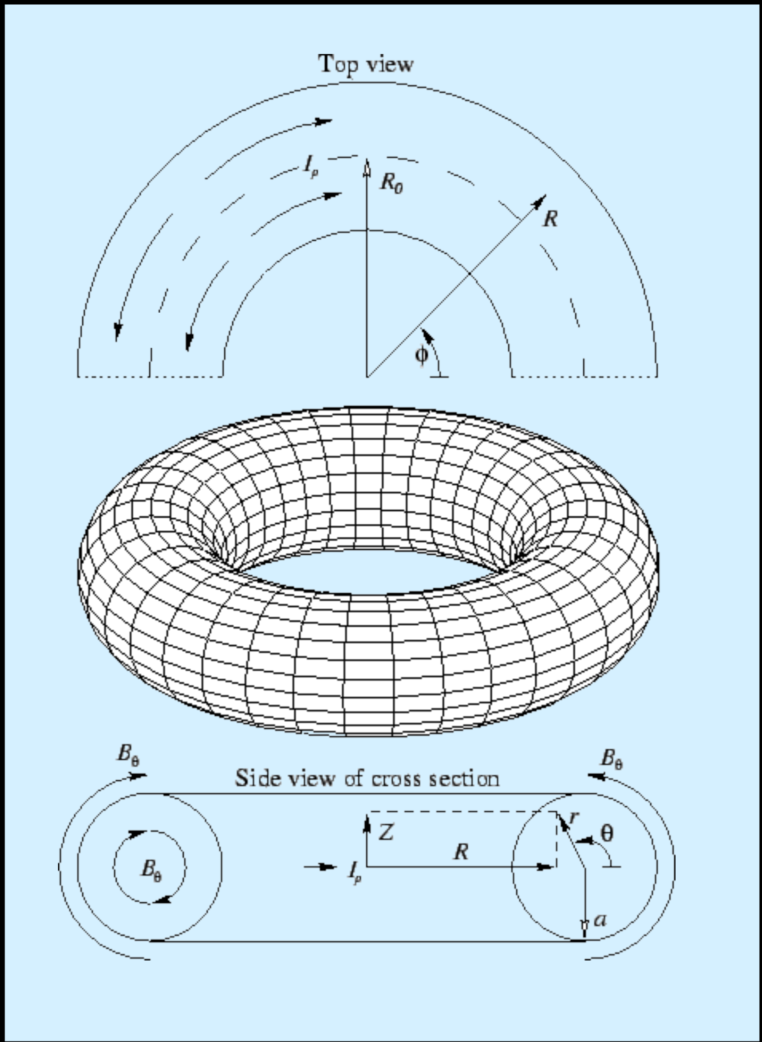
How shall we develop fusion power?



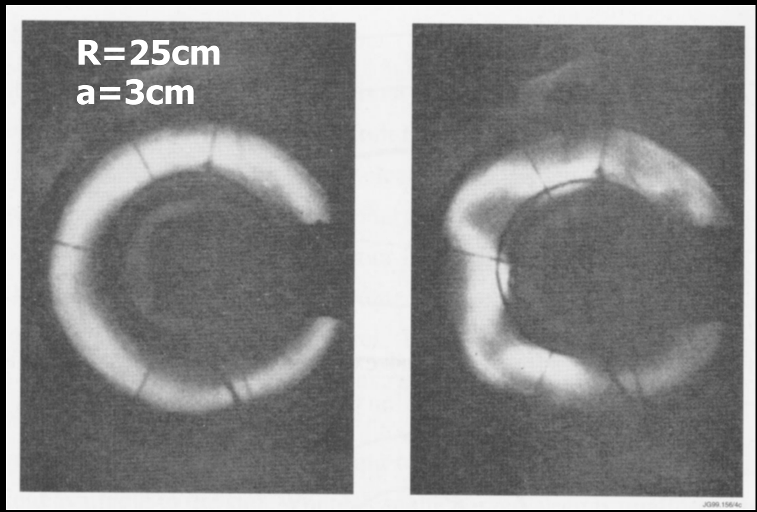
Stellarator – early 1950's

The Pinch Effect - 1940's

Peter Thonemann and Sir George Thomson's idea

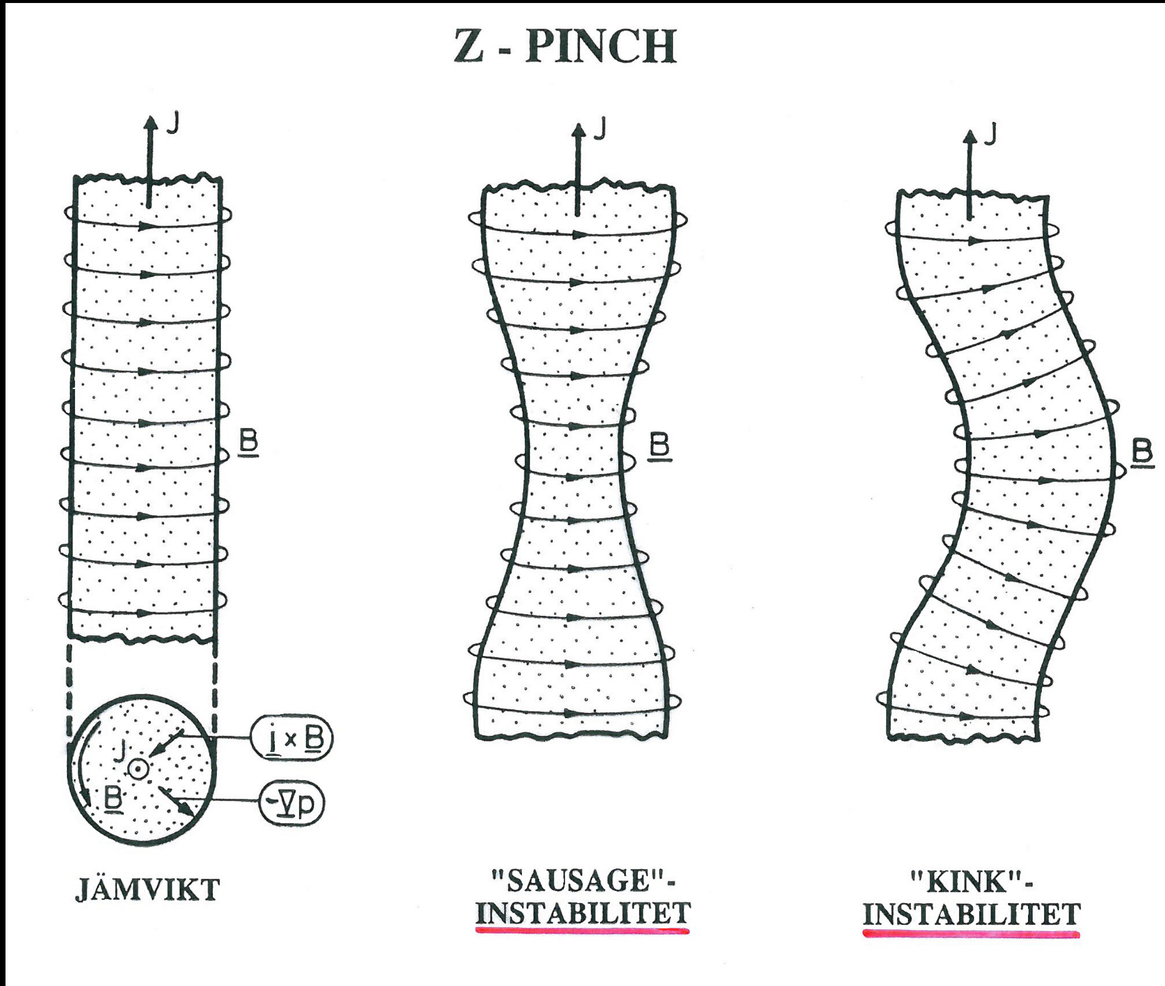


Alan Ware, Thomson
Imperial College.



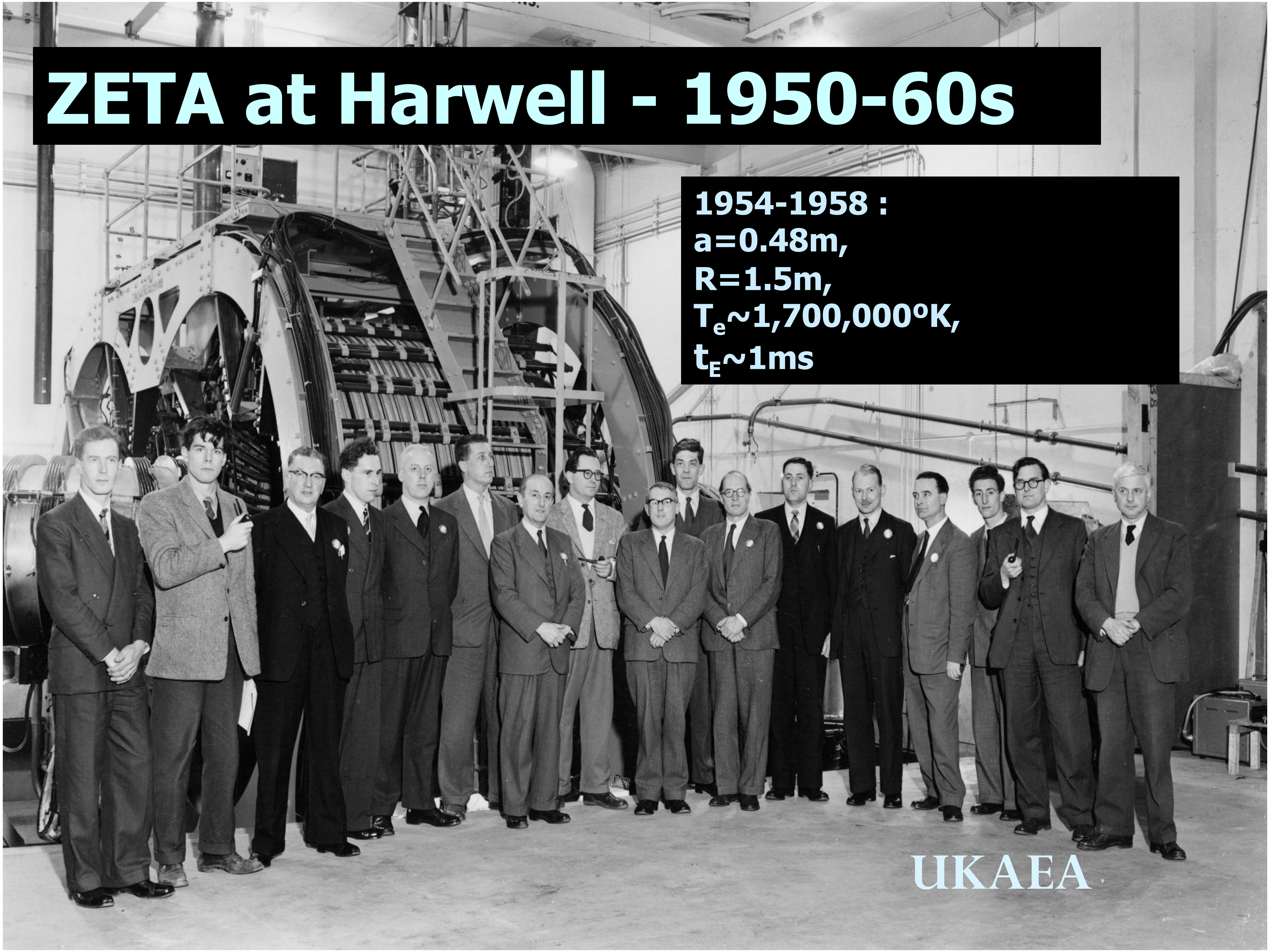
UKAEA

z-pinch instabilities

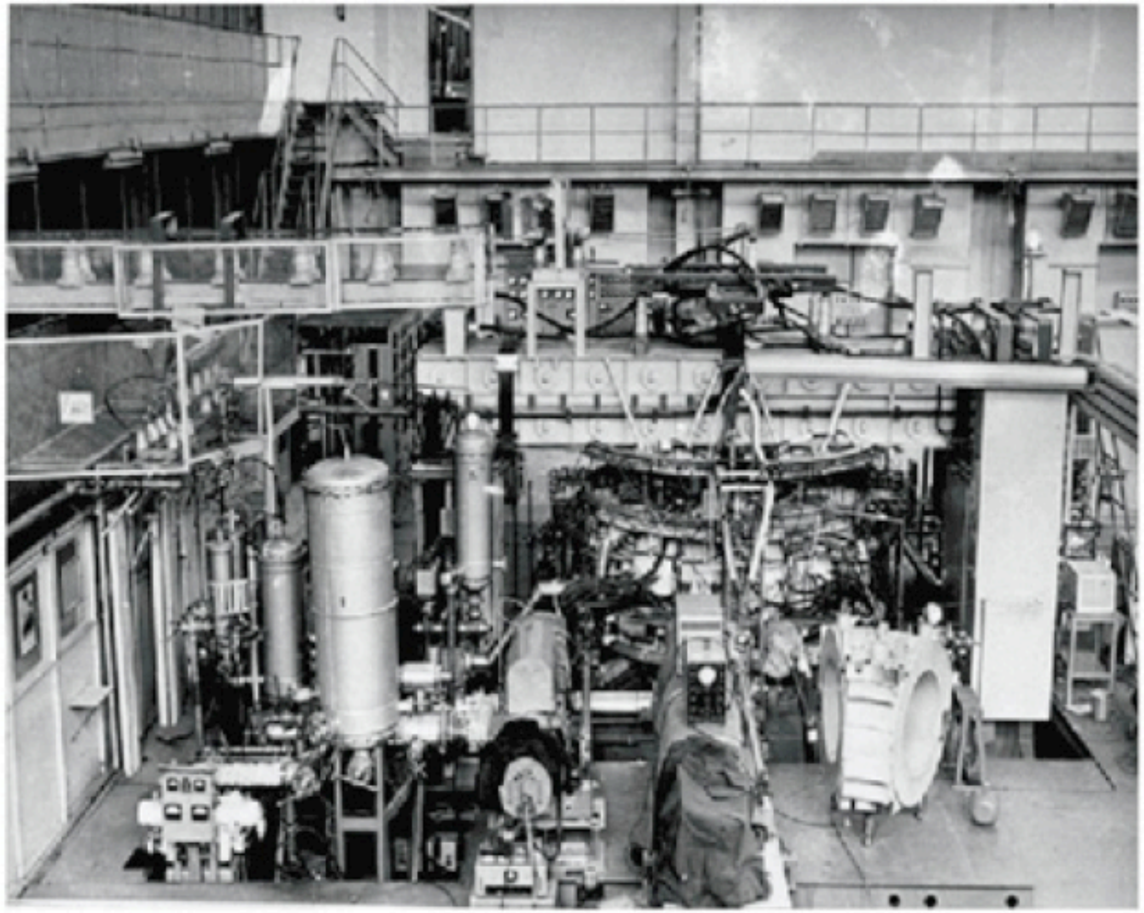


ZETA at Harwell - 1950-60s

1954-1958 :
a=0.48m,
R=1.5m,
T_e~1,700,000ºK,
t_E~1ms



The Tokamak- a Soviet invention



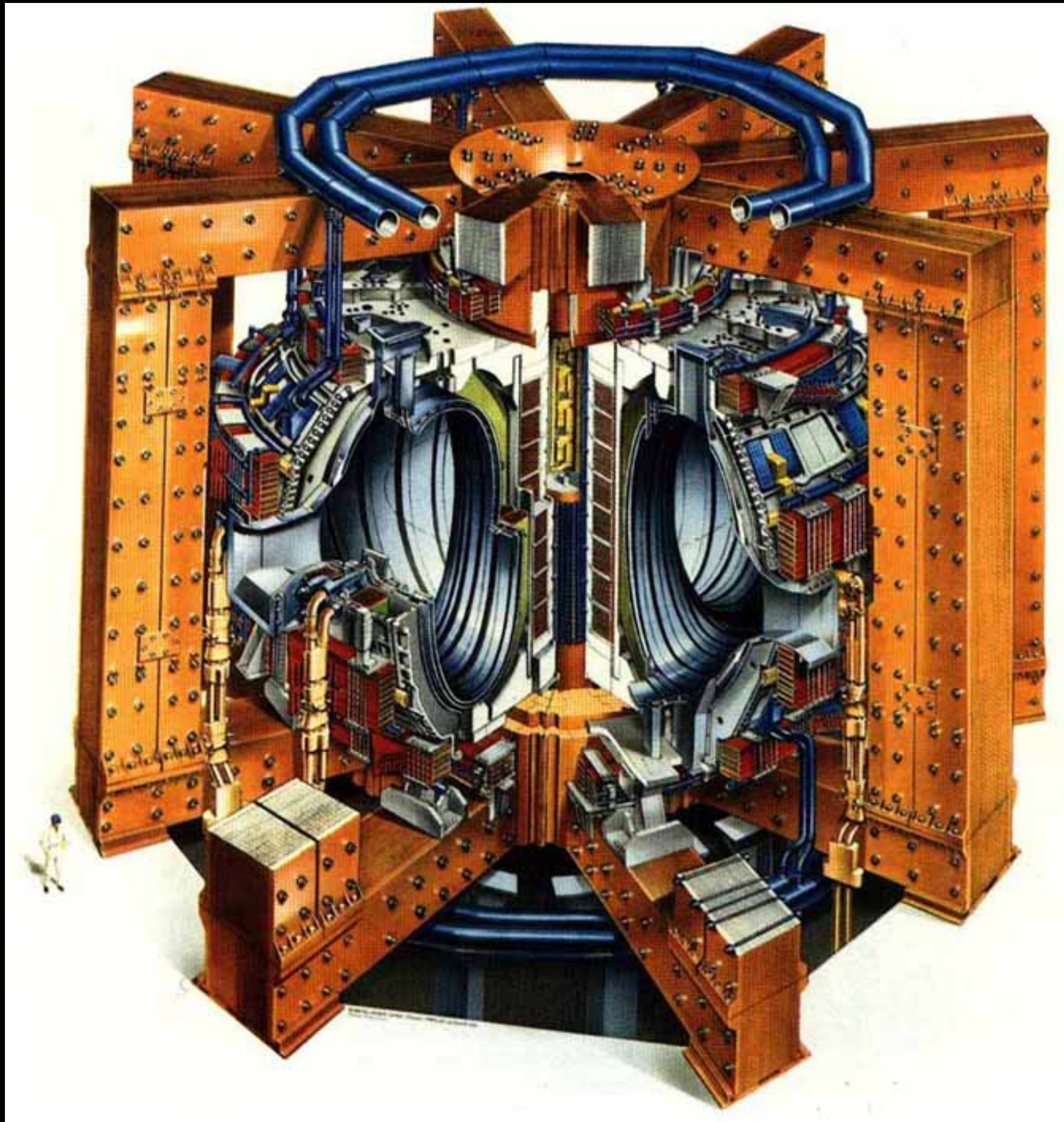
Tokamak T-3 (1962)
R = 1 m, a = 0,15 m, B = 3,8 T, I = 150 kA

Time:
1950-60

Place:
Moscow

Characteristic:
Strong magnetic field

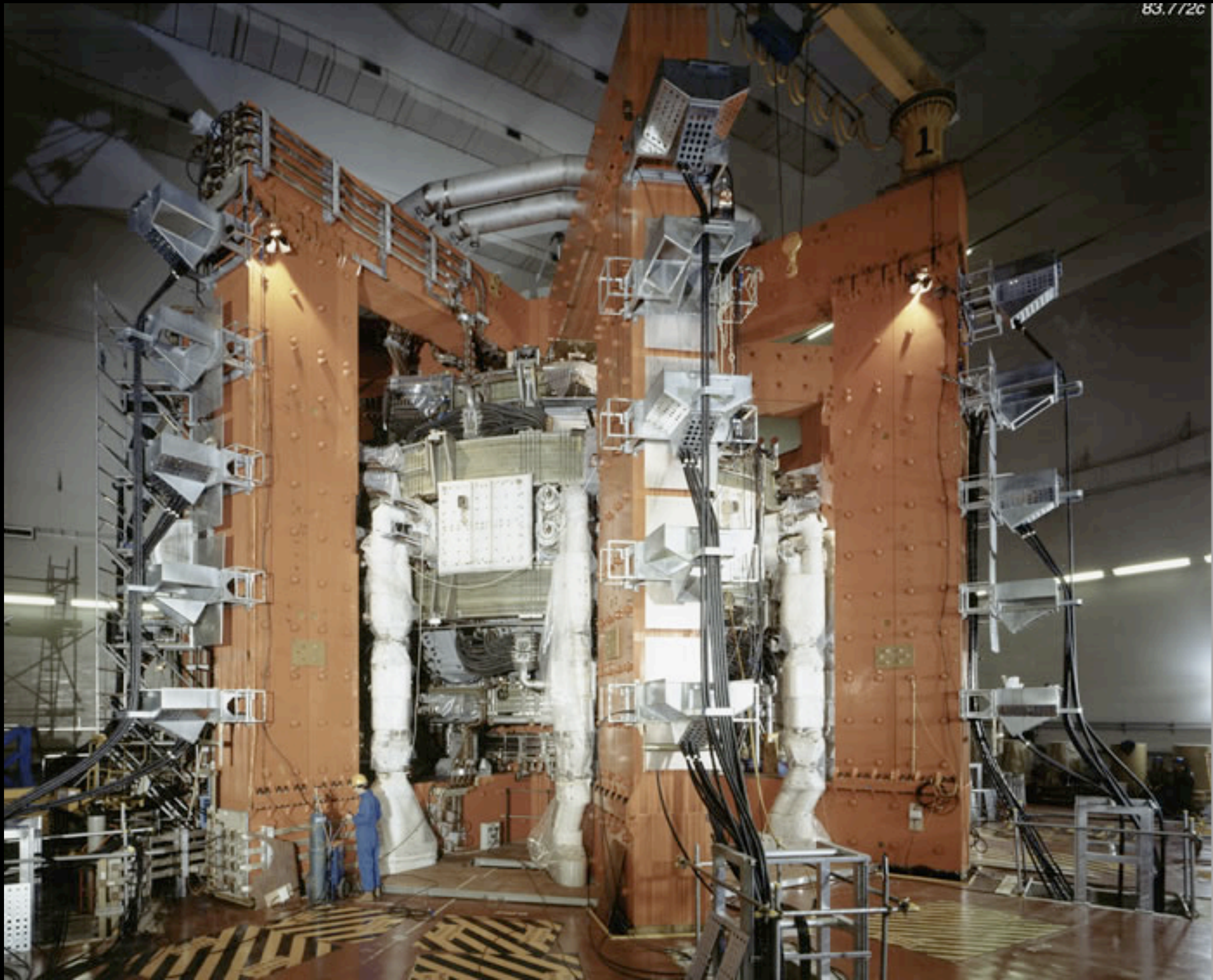
JET – the world's largest fusion experiment



Location:
Culham, England

European project

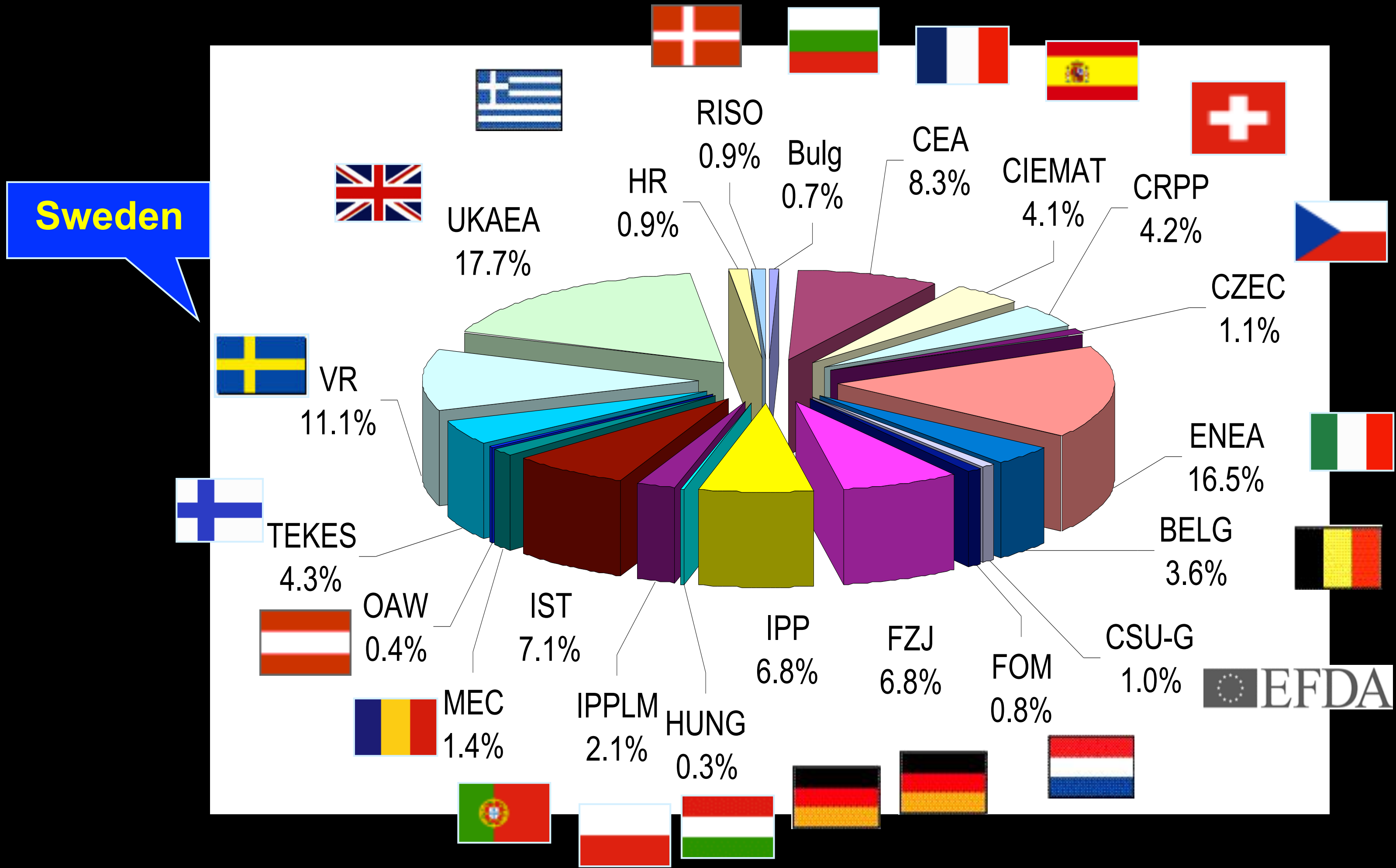
JET – the world's largest fusion experiment



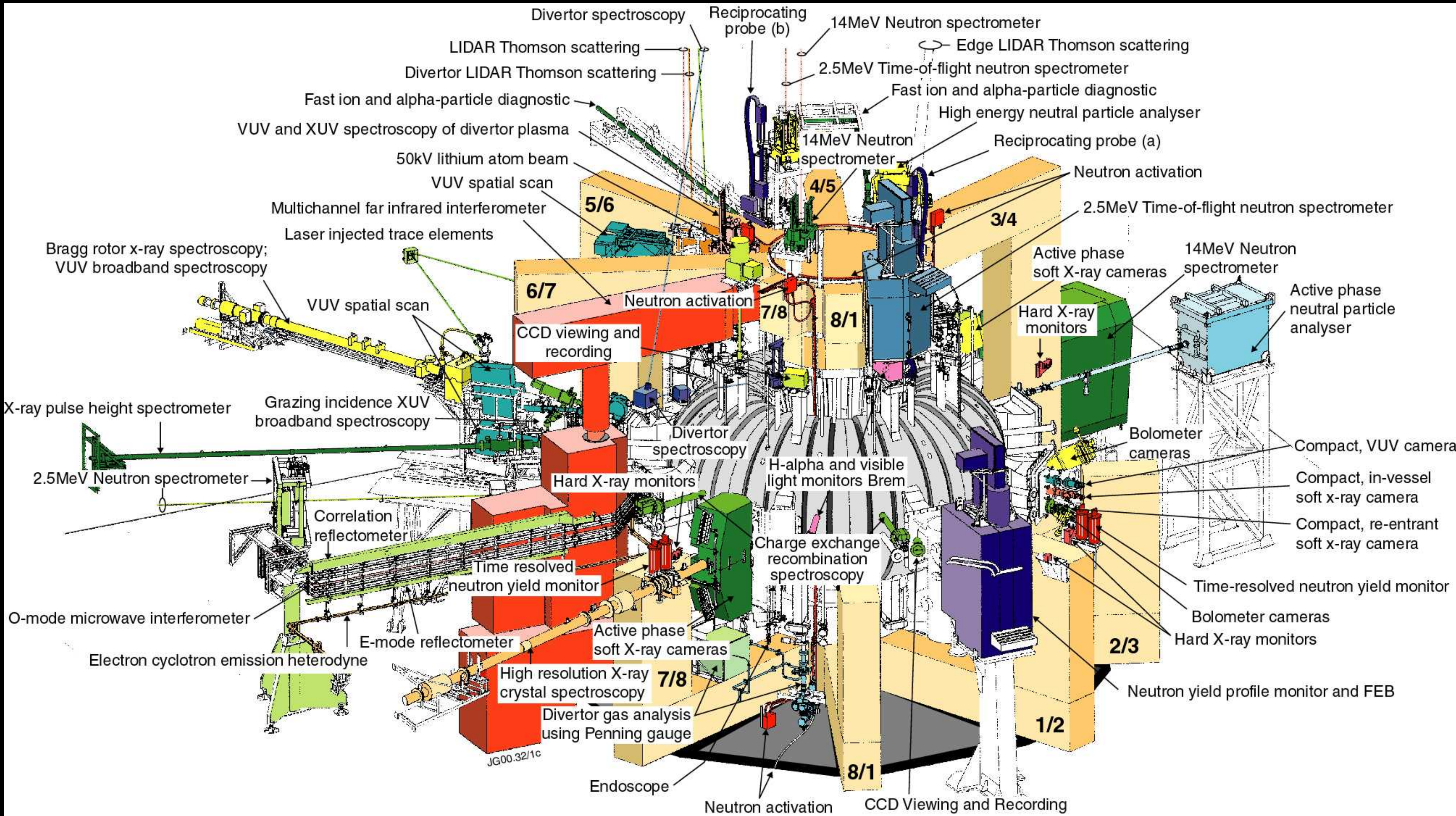
JET Tokamak

JET, Culham, England

Participation in the JET campaigns of late 2005 - 2006



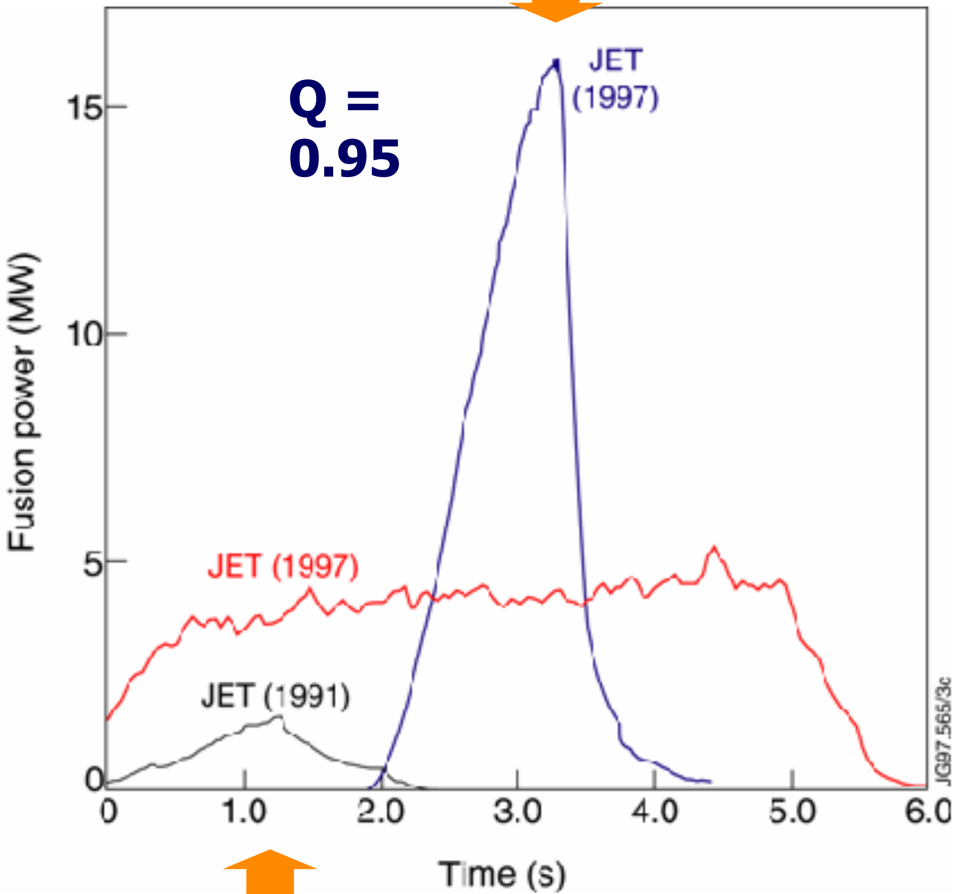
Diagnostics at JET



Demonstration in JET: production of fusion energy

16.2 MW
(World Record)

Q = 0.95



1.7 MW
(World First)

Heating

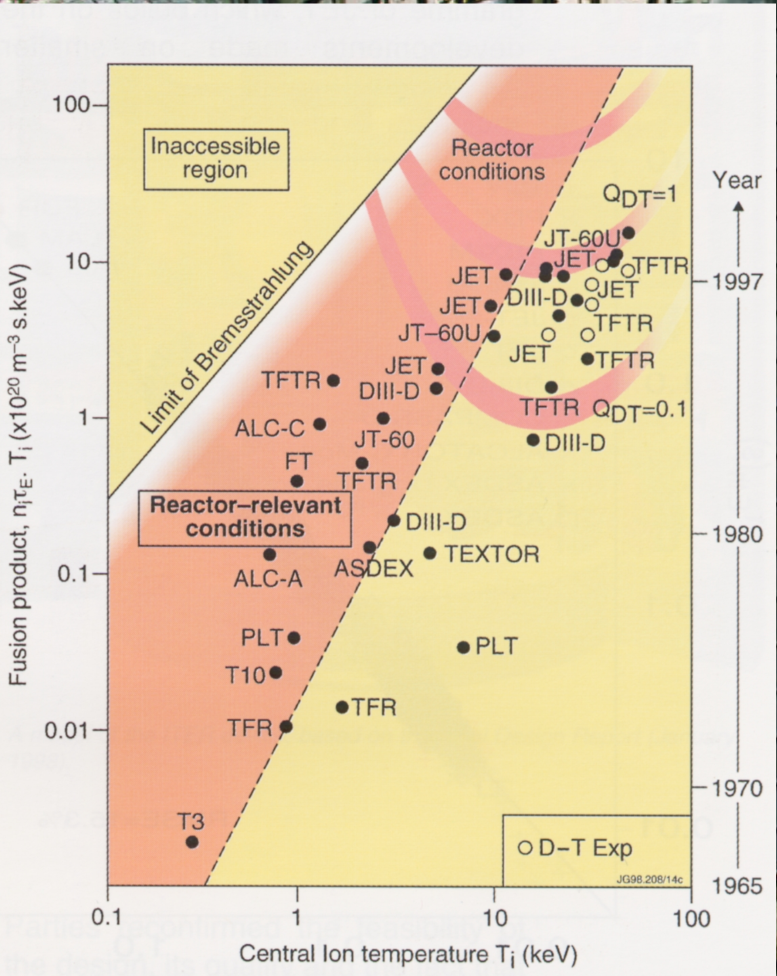
25 MW

2 s, Q=0.6

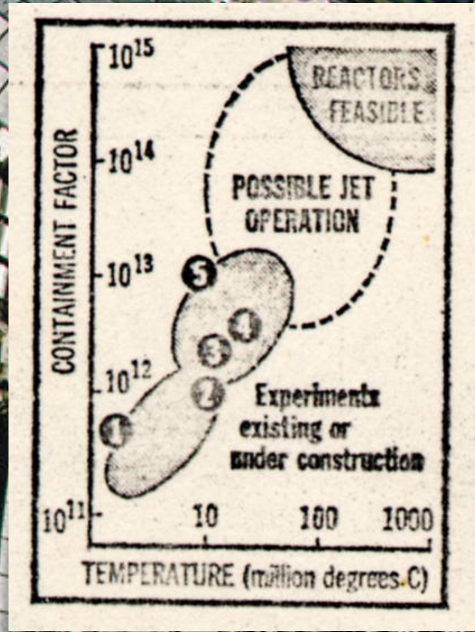
16 MW

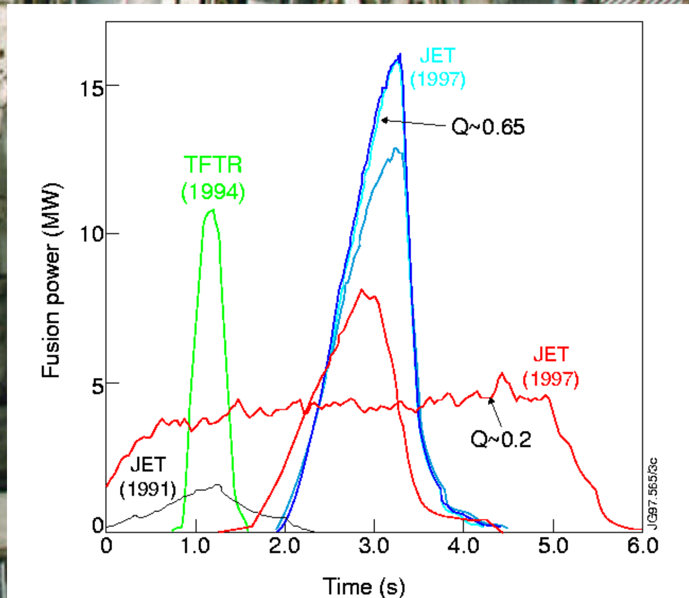
Fusion Energy

Success at JET



This plot shows how, over several decades of research, the key performance parameters of fusion devices (the plasma ion temperature and the fusion triple product) have moved towards the conditions required for a reactor.



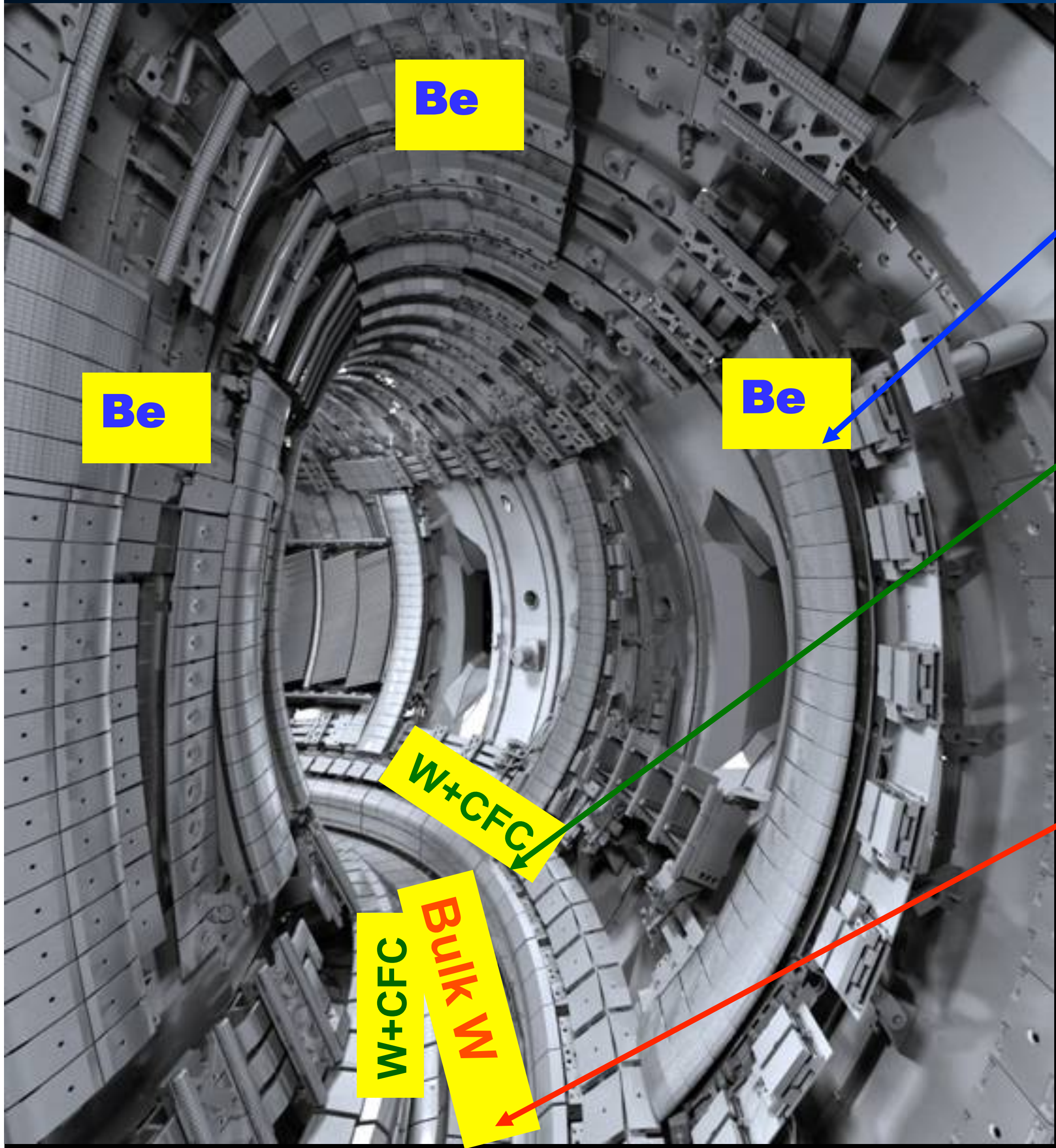


UKAEA

Fusion

Working with Europe

The ITER-Like Wall: Operation limits



-

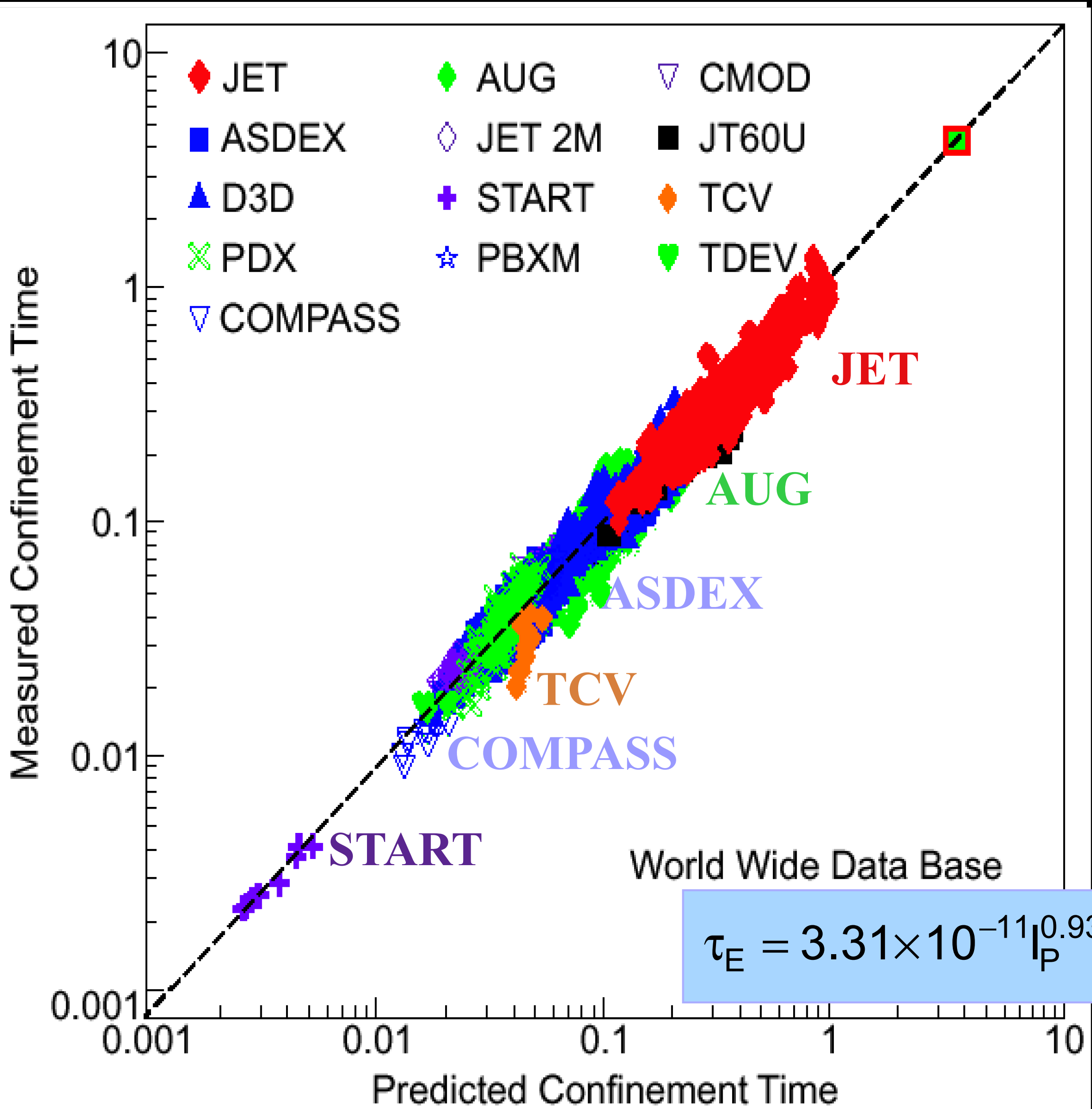
Solid Be
Surface temperature < 900°C

W-coated CFC
Temperature <1200°C

W stacks
Surface temperature limit
<1200°C-2200°C

G. Matthews and ILW Team

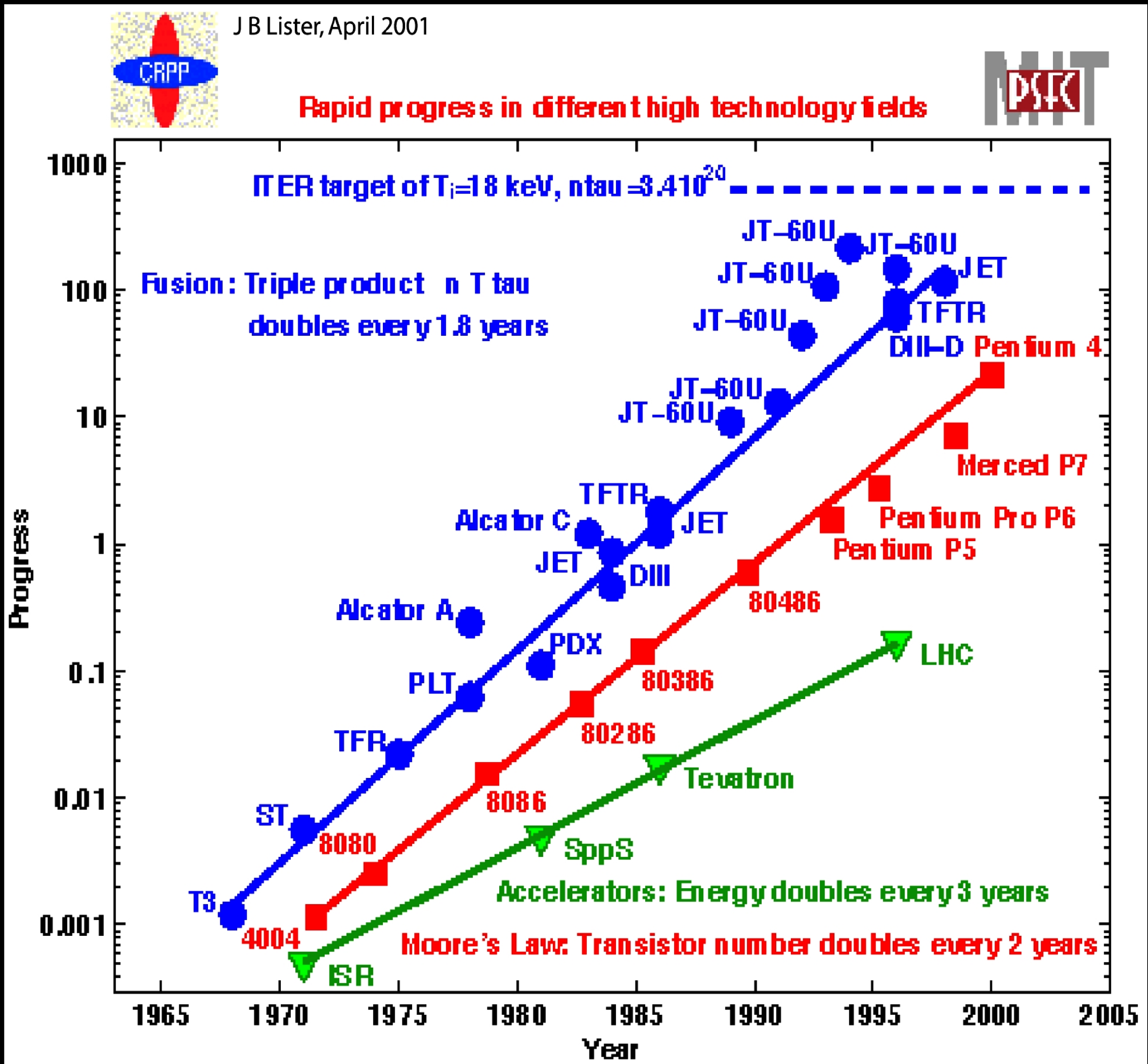
Progress in ITER like Scenario



$$\tau_E = 3.31\times10^{-11} I_P^{0.93} B^{0.15} P^{-0.69} R^{1.97} n^{0.41} M^{0.19} \varepsilon^{0.58} \kappa^{0.78}$$

Fusion devices in the EU make a major contribution to the databases for ITER

Fusion progress is comparable with other fields

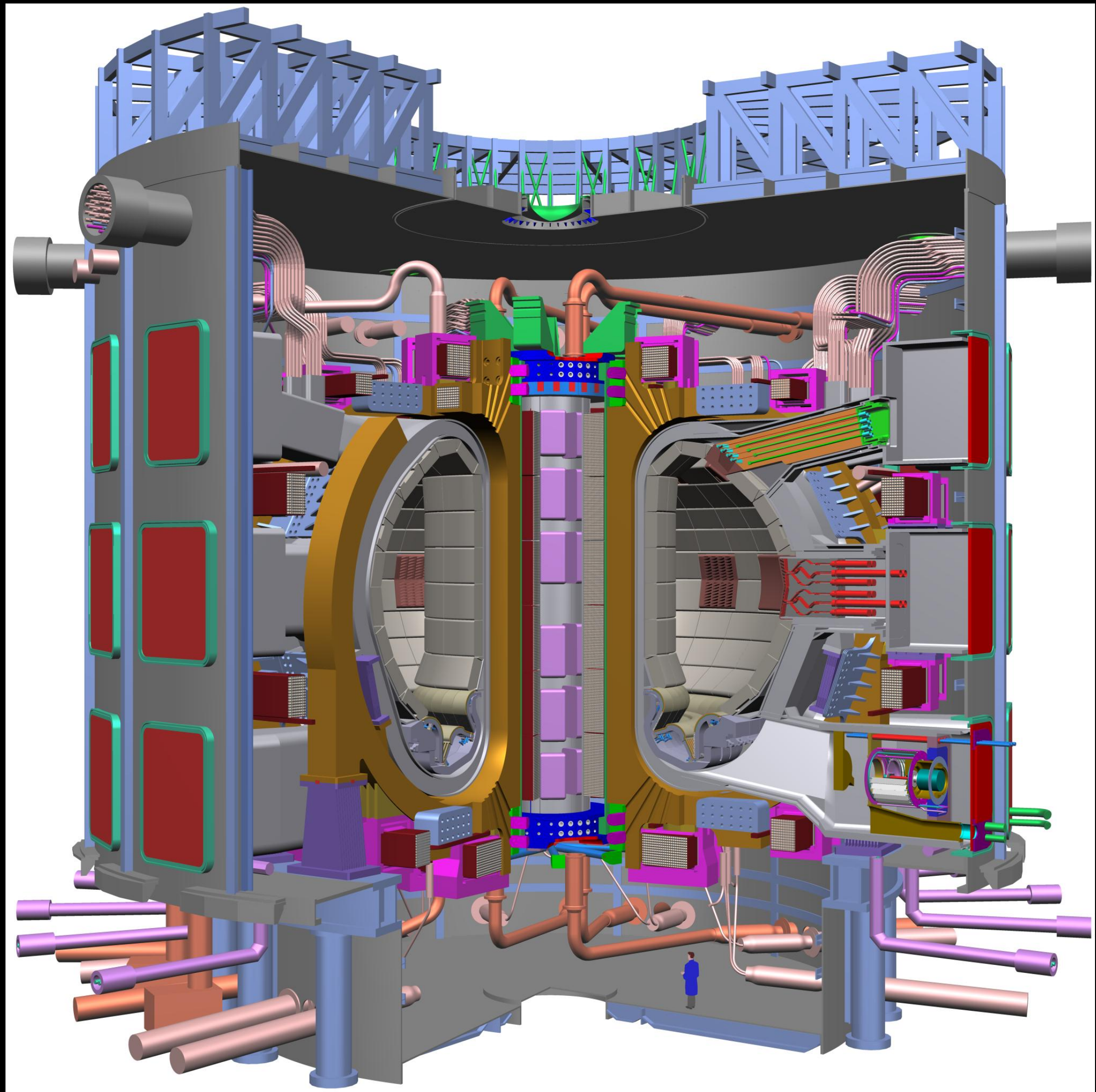


n = Density
a measure of the number of reactions we can have

T = Temperature
a measure of the energy given to the fuel particles

τ = Confinement time
a measure of the thermal insulation of the fuel

ITER – nest step towards fusion



Location:
Cadarache, France

Collaboration:
EU
China
Japan
Russia
South Korea
India
USA

History of ITER

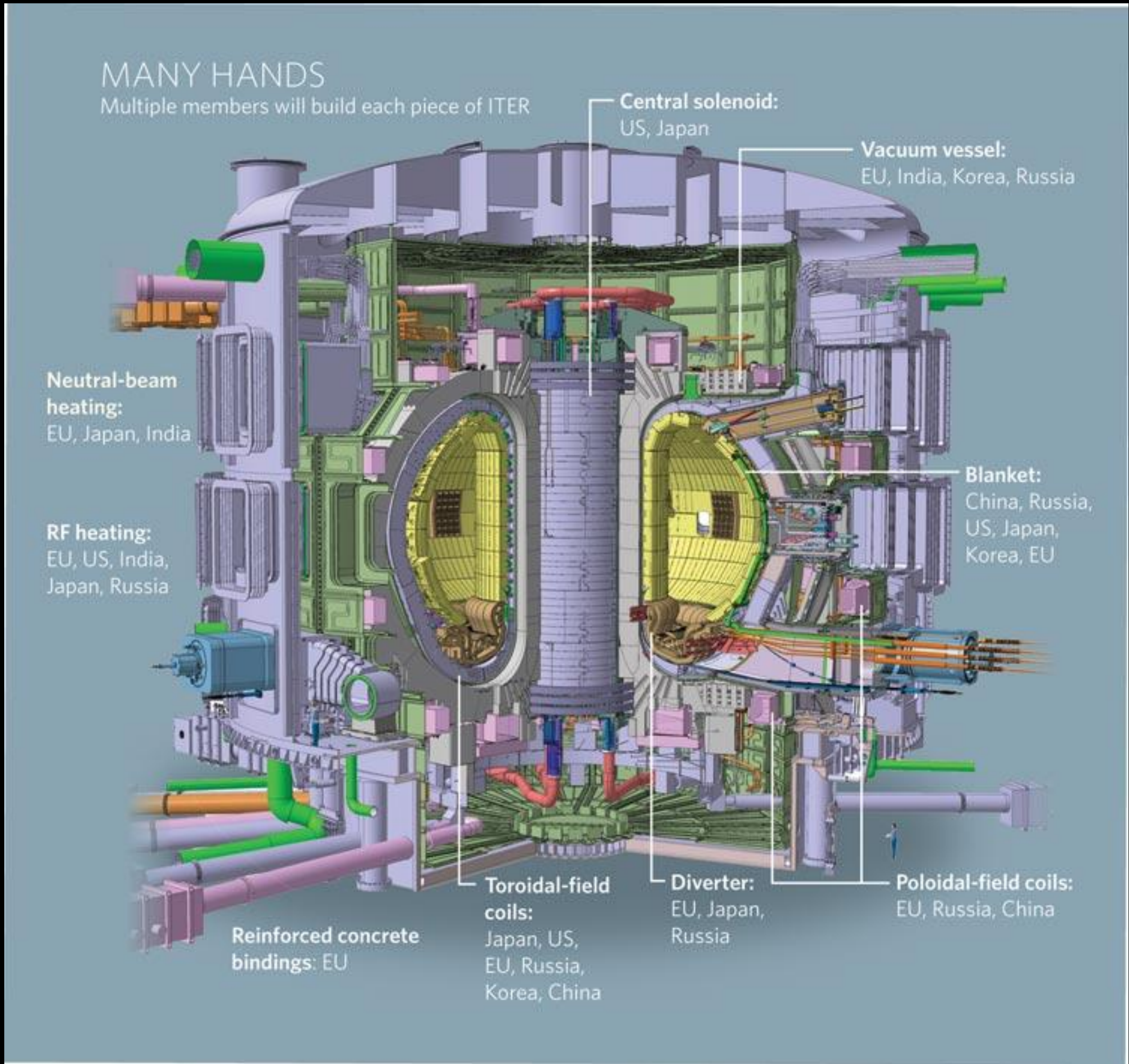
"For the benefit of mankind"

The idea for ITER originated from the Geneva Superpower Summit in 1985 where Gorbachev and Reagan proposed international effort
to develop fusion energy...

..."as an inexhaustible source of energy for the benefit of mankind".

November 21, 2006: China, Europe, India, Japan, Korea, the Russian Federation and the United States of America sign the ITER Agreement

ITER – the next step towards fusion



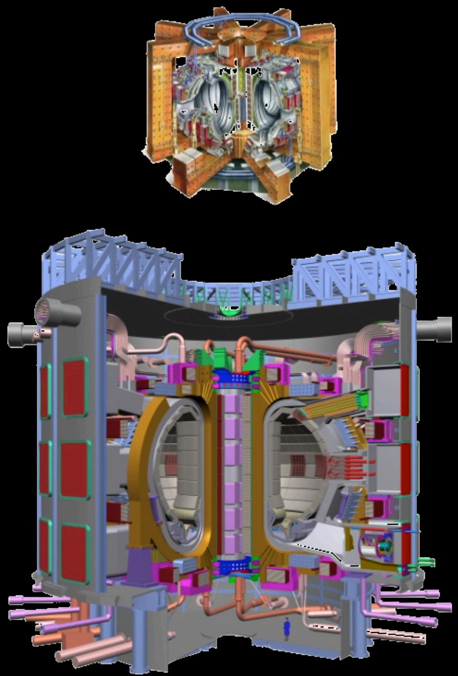
Place:
Cadarache, Frankrike

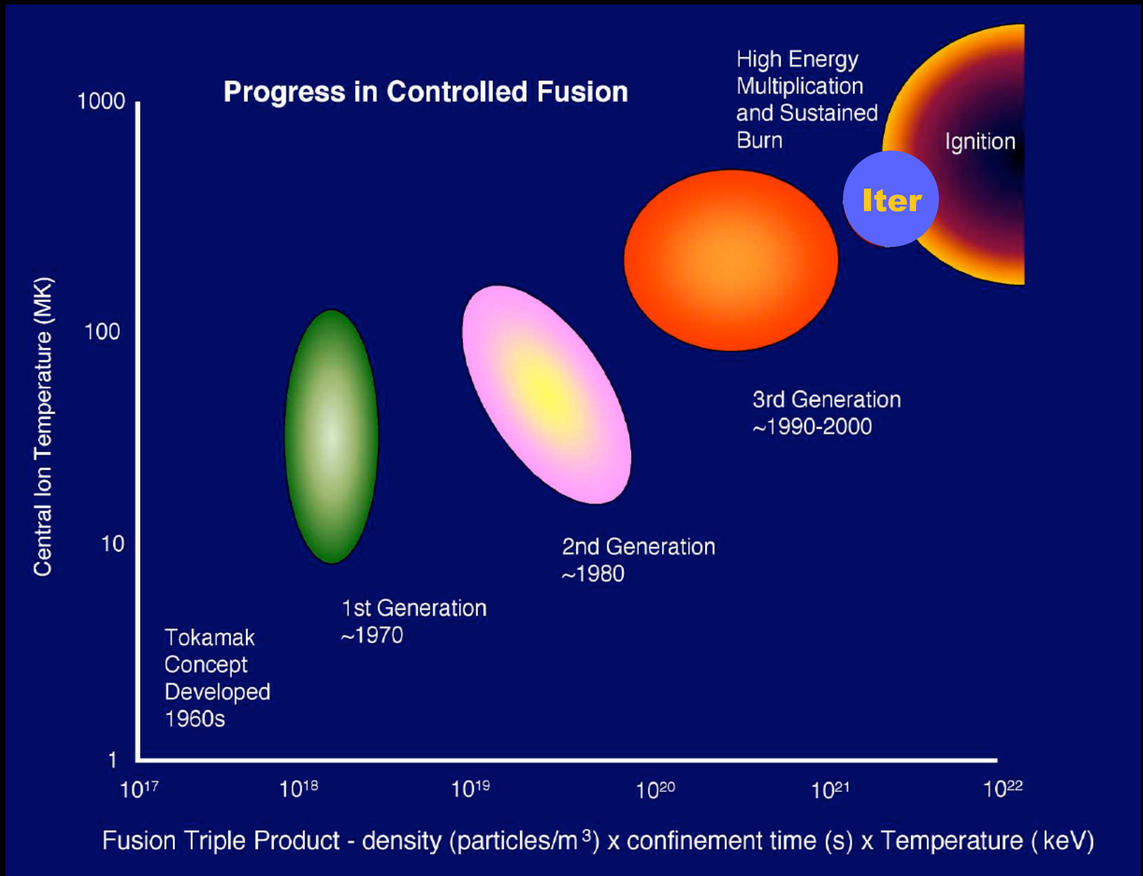
Cooperation:
EU
China
Japan
Russia
South Korea
India
USA

ITER progress

ITER represents a big step in fusion research but is in line with the continuous progress over the years

More than double the size of JET

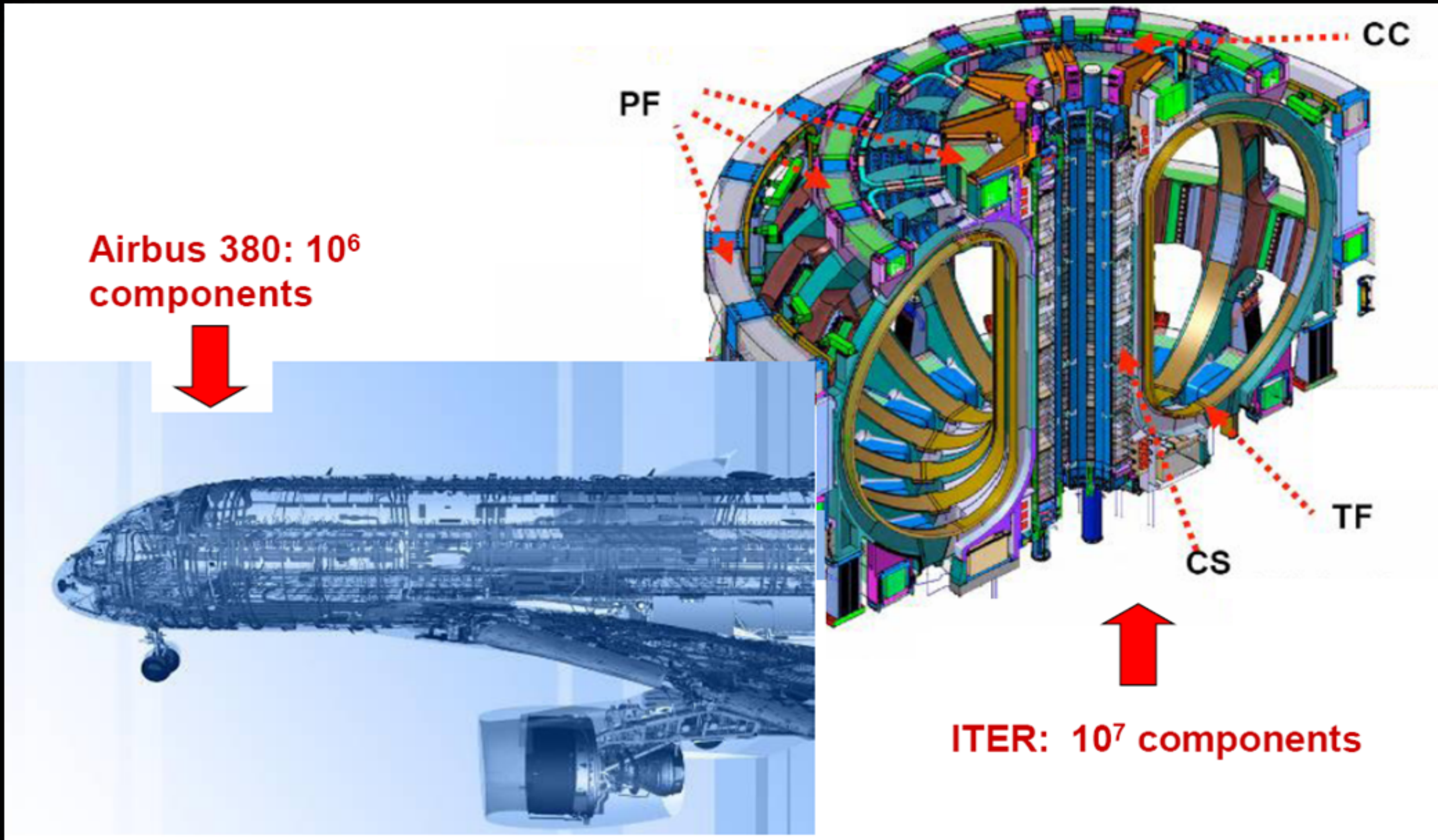




ITER - Goals

- Produce 500 MW fusion power.
  (10 times more power than what is needed to run the experiment).
- Smaller than a power station but big enough to prove principle.
- Optimize plasma physics.
- Test technology that is needed for a power station (*exception: materials*).
- In operation: for 20 years.

Integration - Engineering



Courtesy CIEMAT

Who participate in the ITER project?

The ITER partners represent more than half the earth's population.
ITER is the world's largest energy research project.

ITER
Wall sector

ITER site, Cadarache

Europe provides through
Fusion For Energy (http://fusionforenergy.europa.eu)

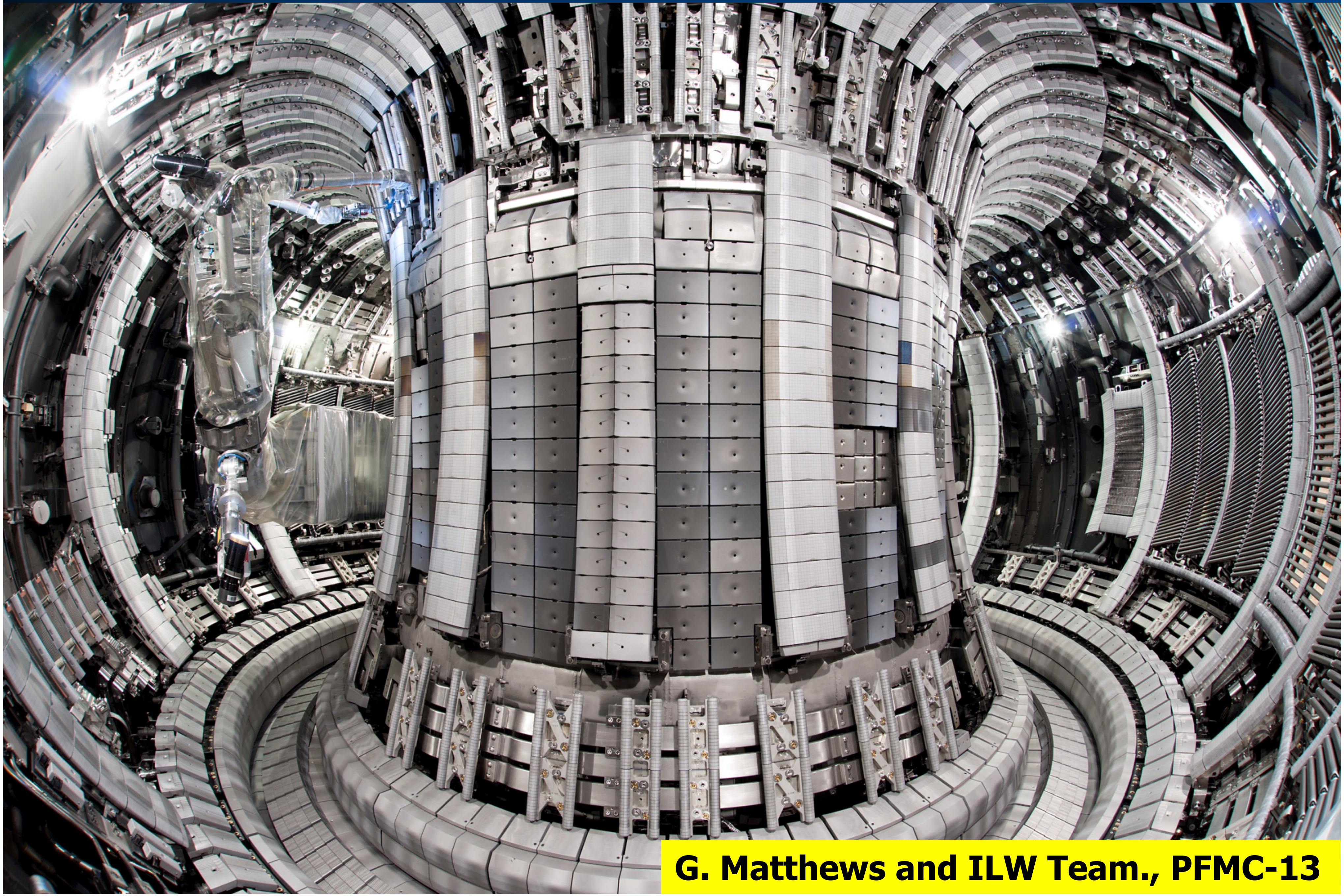
45 % of ITER construction costs
34 % of operation, deactivation, decommissioning

www.iter.org/newsline/-/2318

Experiments at JET prepare for ITER

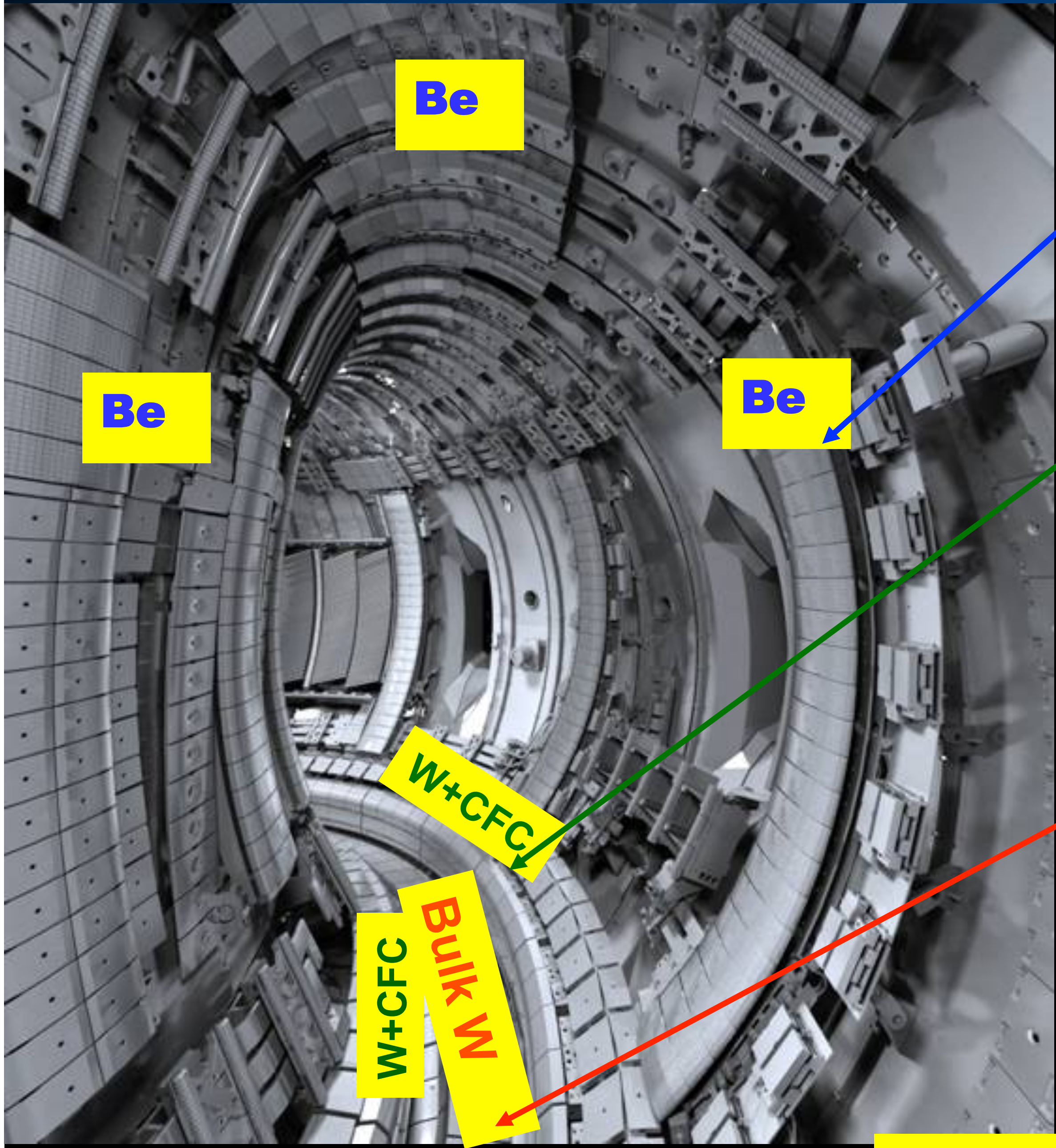
ITER–like wall
has been installed

The ITER-Like Wall: May 8, 2011



G. Matthews and ILW Team., PFMC-13

The ITER-Like Wall: Operation limits



Solid Be
Surface temperature < 900°C

W-coated CFC
Temperature <1200°C

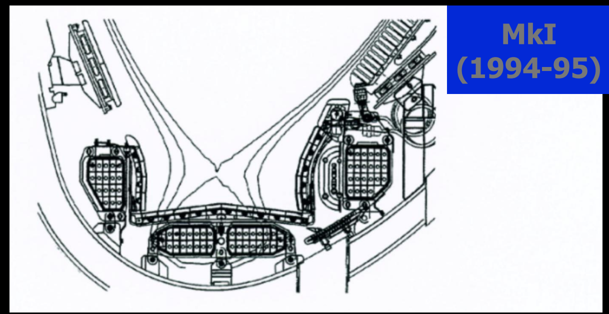
W stacks
Surface temperature limit
<1200°C-2200°C

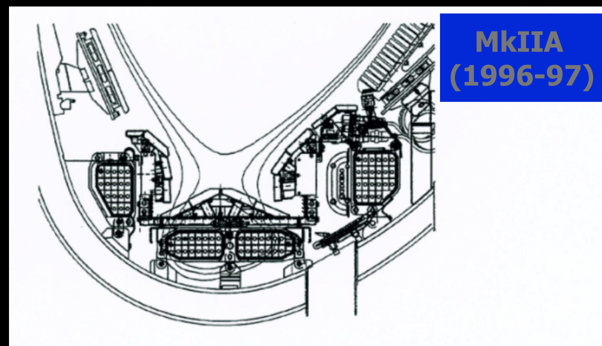
G. Matthews and ILW Team., PFMC-13

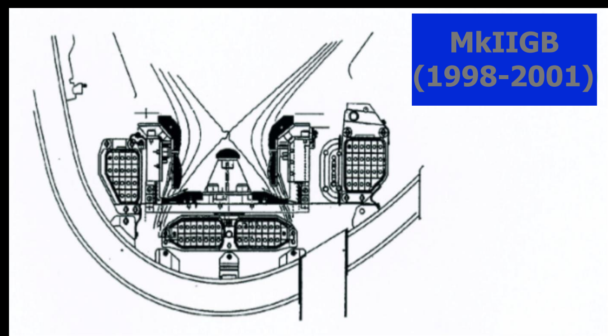
Keeping the plasma pure

- Fusion plasmas can become polluted by impurities from the vessel wall as it is heated up.
- Helium 'ash' is also produced by the fusion reaction.

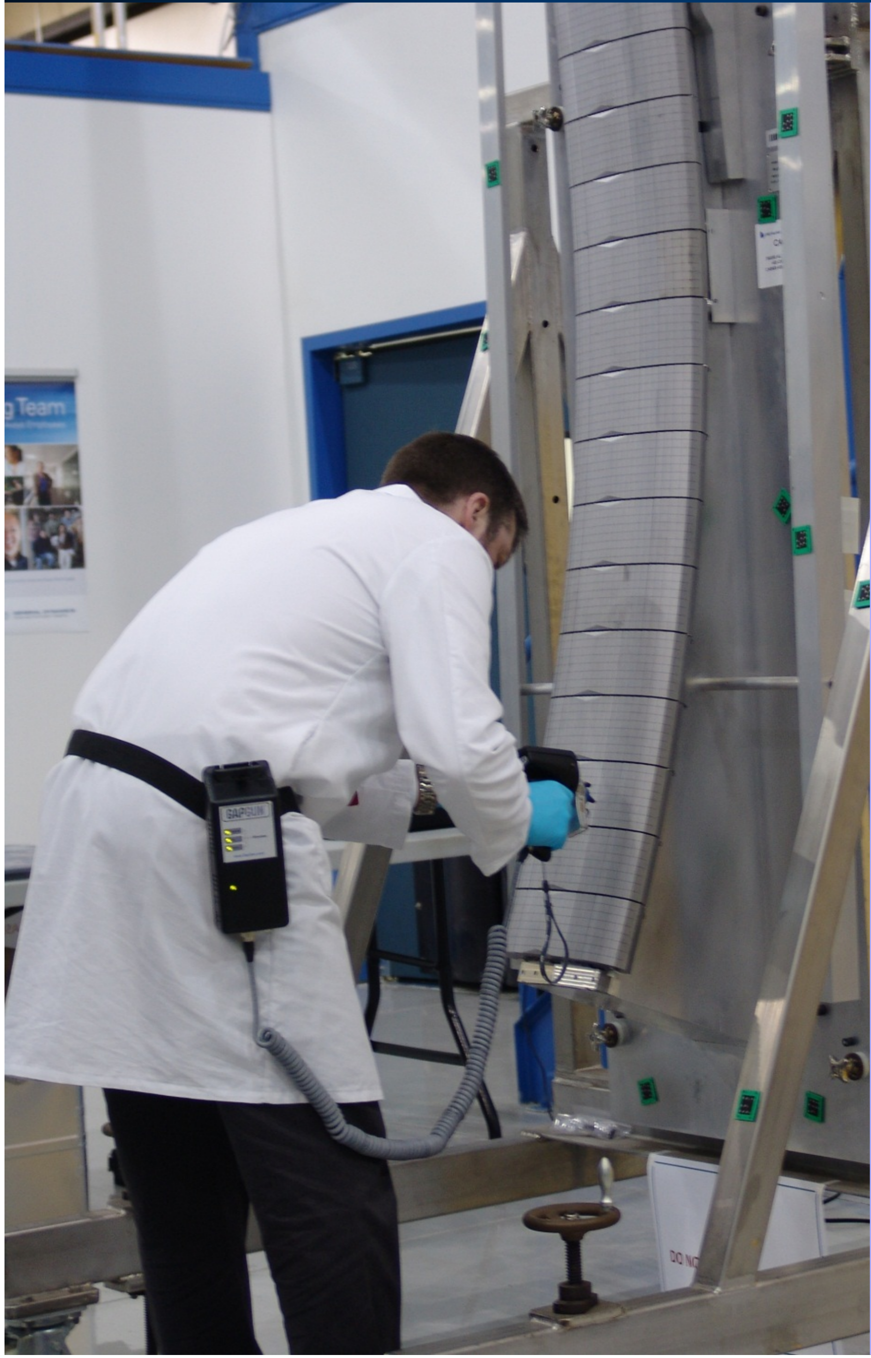
- In a 'divertor' the main plasma is separated from the target tiles by a 'private' plasma.
- Flows in the 'private' region can resist impurity influx.

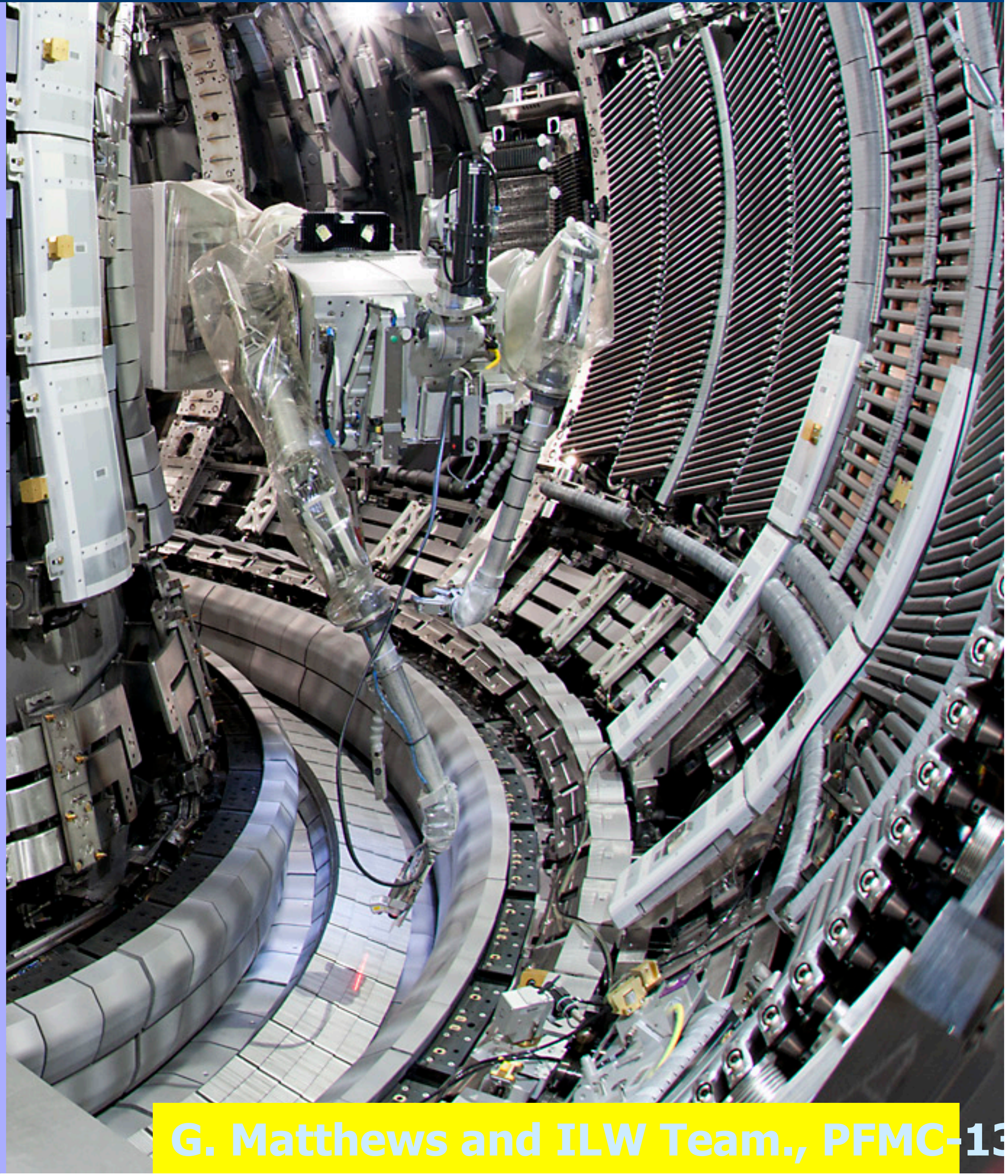






The ITER-Like Wall: Remote Handling

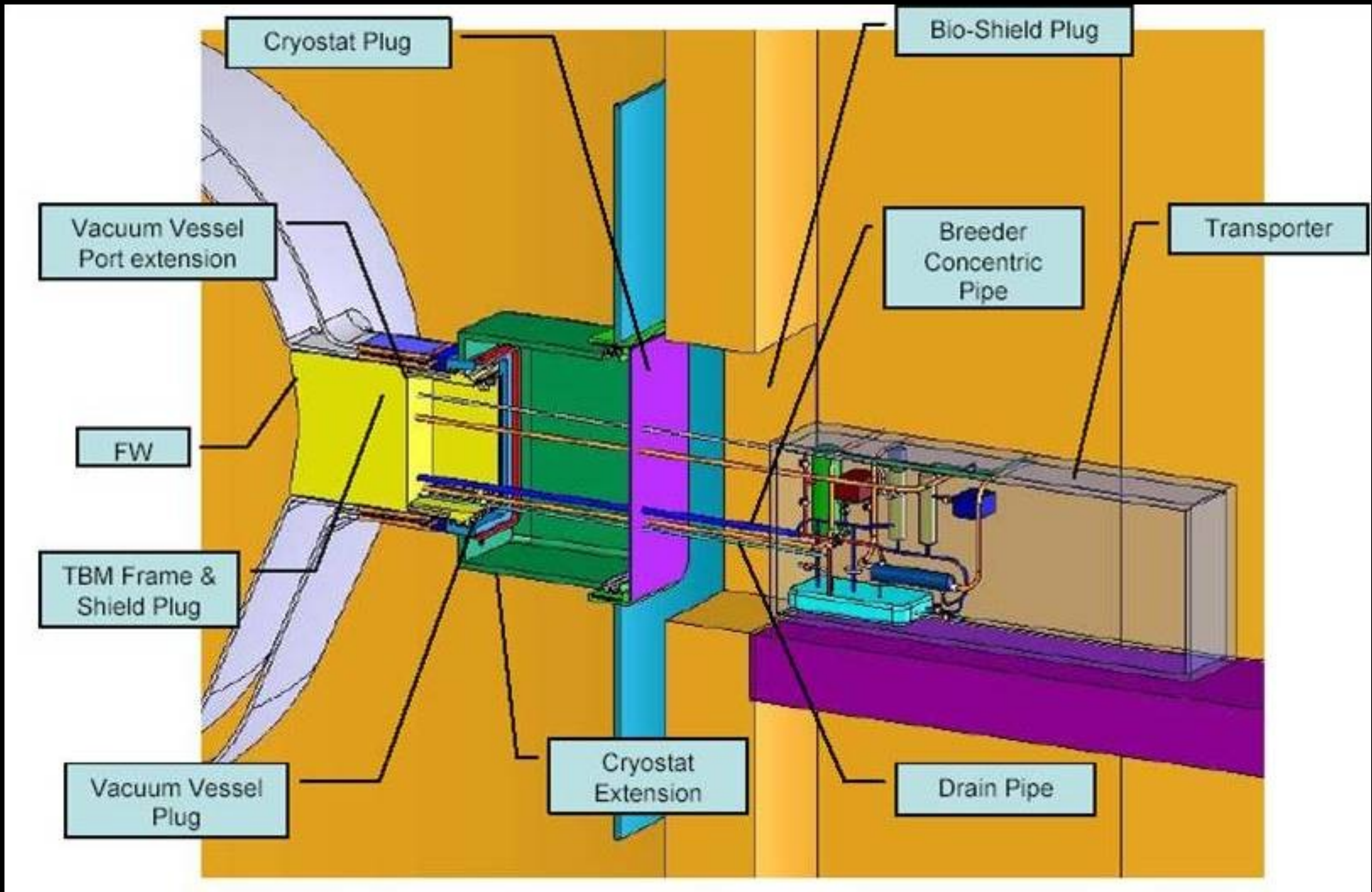




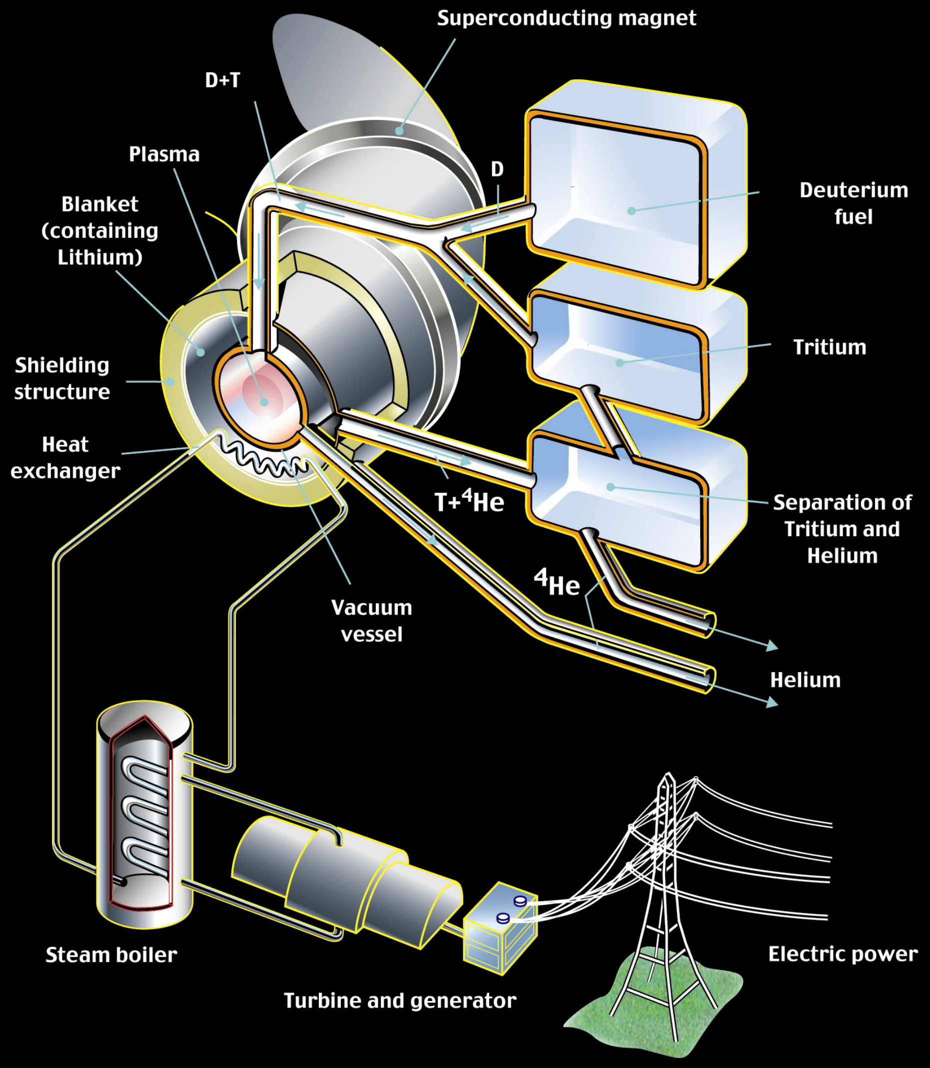
G. Matthews and ILW Team., PFMC-13

Tritium breeding in ITER

- three test blanket modules (TBM)

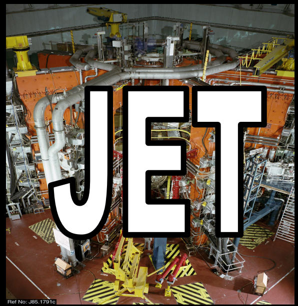
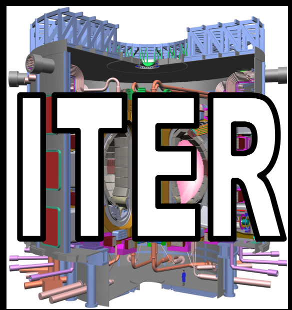


Fusion power station

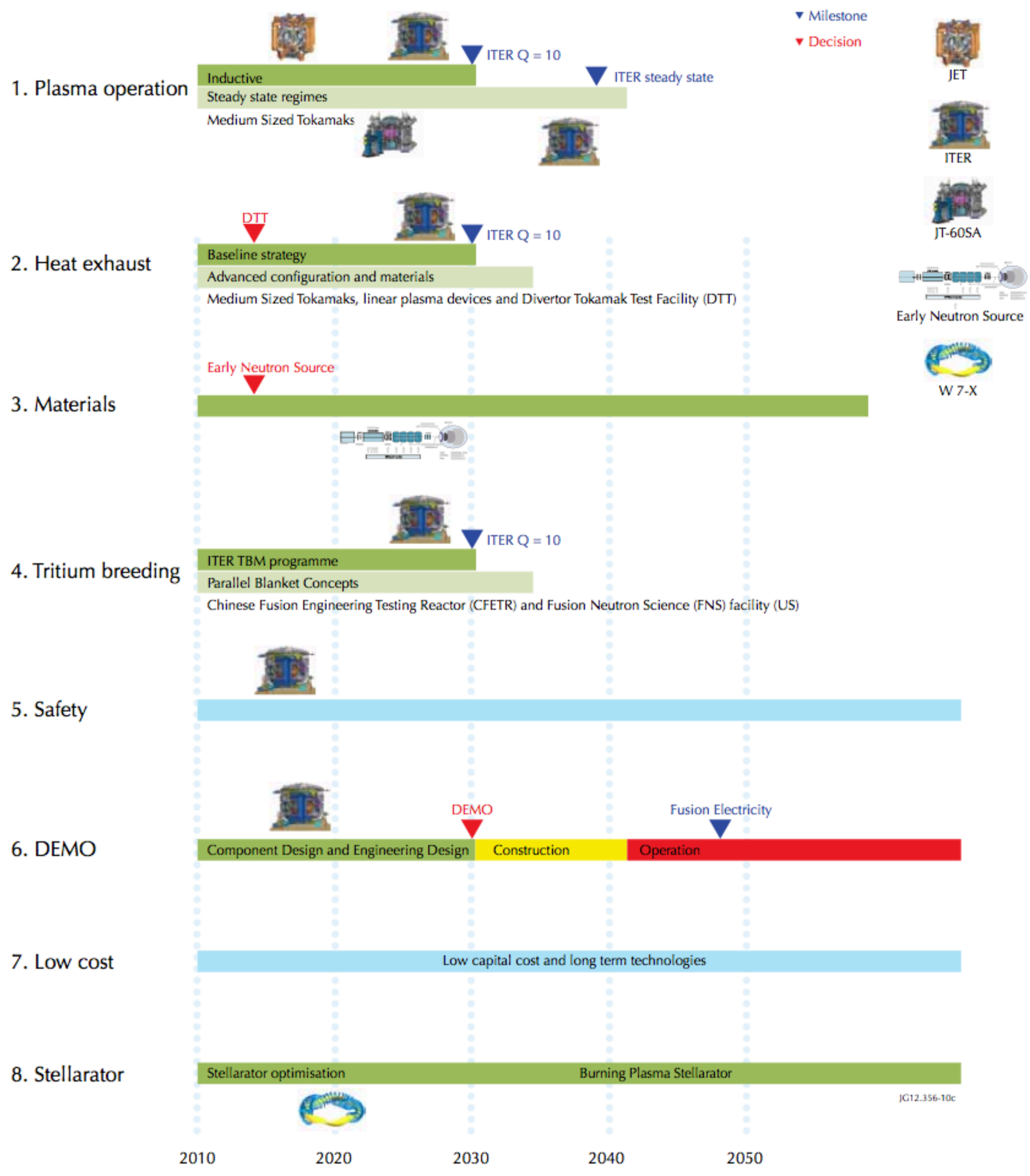


Blanket captures energetic neutrons from fusion reactions

Development of fusion energy

	When?	Fusion power	Pulse length	Q
 JET	1997	16MW	10 seconds	0.65
 ITER	2020-2030	500-700MW	30 minutes	10
 Kraft-verk	2030/40	1.5-2GW	days/stationary	30

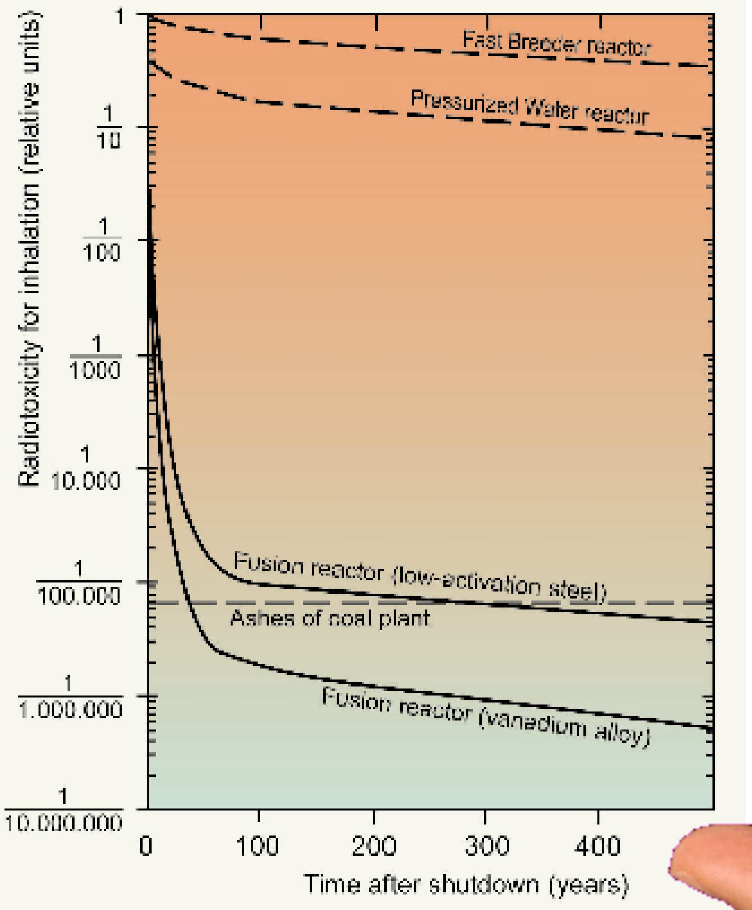
Fusion Roadmap



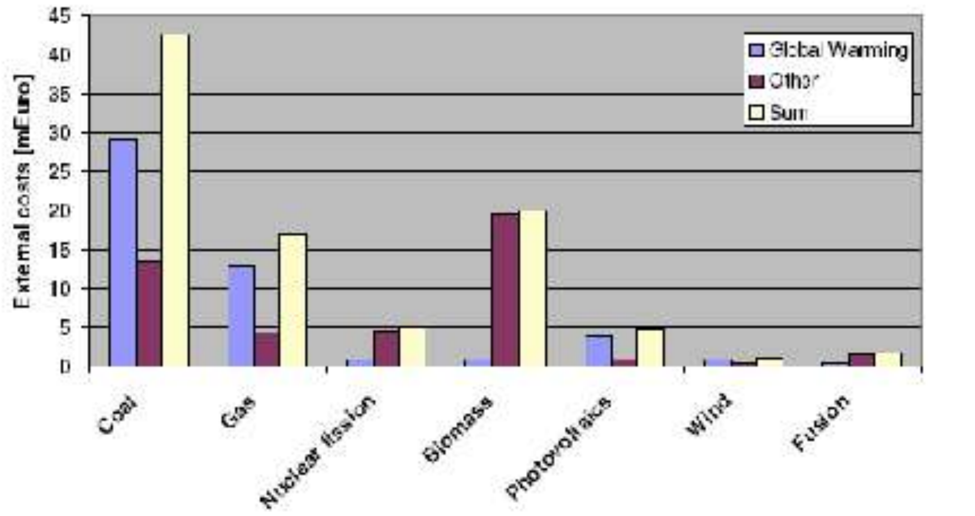
The missions to the realisation of fusion electricity

Fusion advantages

Low radioactivity



Low external costs



Fusion: safety and environmental issues - general considerations

- Negligible climate effects
- No emission of greenhouse gas
- No long lived radioactive waste
- No transports of waste
- No risk for nuclear meltdown
- Only small amount of tritium fuel active

Fusion energy is sustainable energy

See http://ec.europa.eu/research/energy/euratom

Fusion: safety and environmental issues - general considerations

Studies of
- potential impact of fusion power on the environment
- possible risks with operating large-scale fusion power plants

Results: fusion is a very **safe** and **sustainable** energy source.

European Safety and Environmental Assessment of Fusion Power (SEAFP):
- conceptual designs of fusion power stations and their safety
- environmental assessments, including
- identification and modelling of conceivable accident scenarios

Fusion: safety and environmental issues - general considerations

SEAFP; good inherent safety qualities:
• absence of 'chain reaction'
• no production of long-lived, highly radiotoxic products.

Worst possible accident would not breach confinement barriers.

Even *if* confinement barriers would be breached,
accidental radioactive release from a fusion power station cannot reach levels that would require evacuation of the local community.

The inherent safety characteristics of a fusion reactor are due to
• very low fuel inventory in the reactor during operation
• rapid cooling, extinguishing fusion reactions in case of malfunction

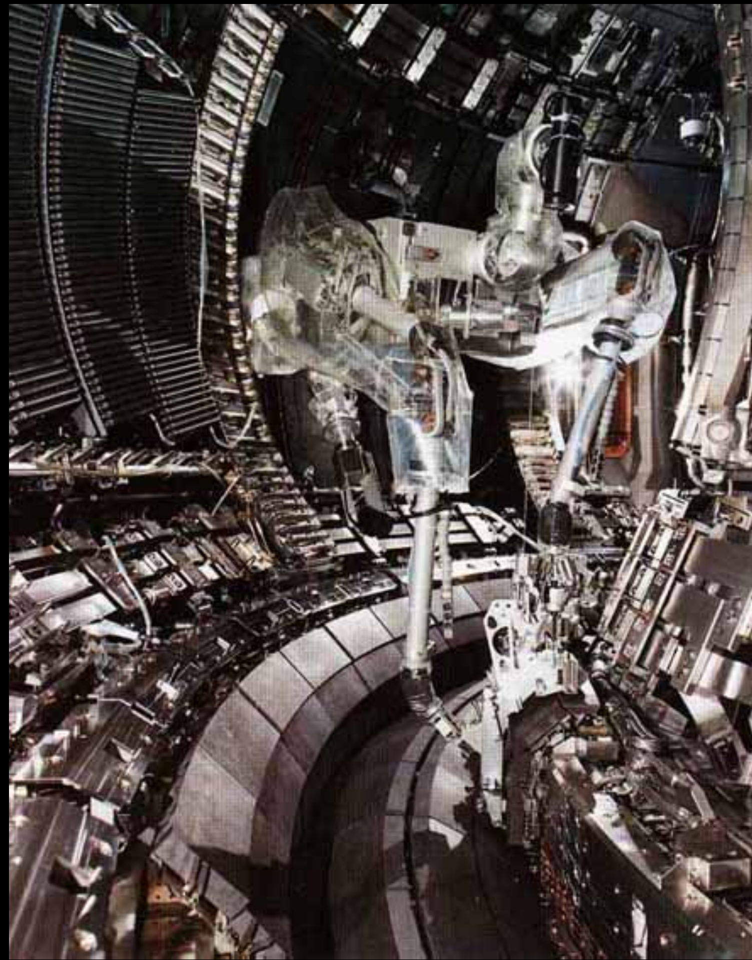
Tritium is produced and used inside the reactor,
no transport of radioactive fuel is needed.

Fusion: safety and environmental issues

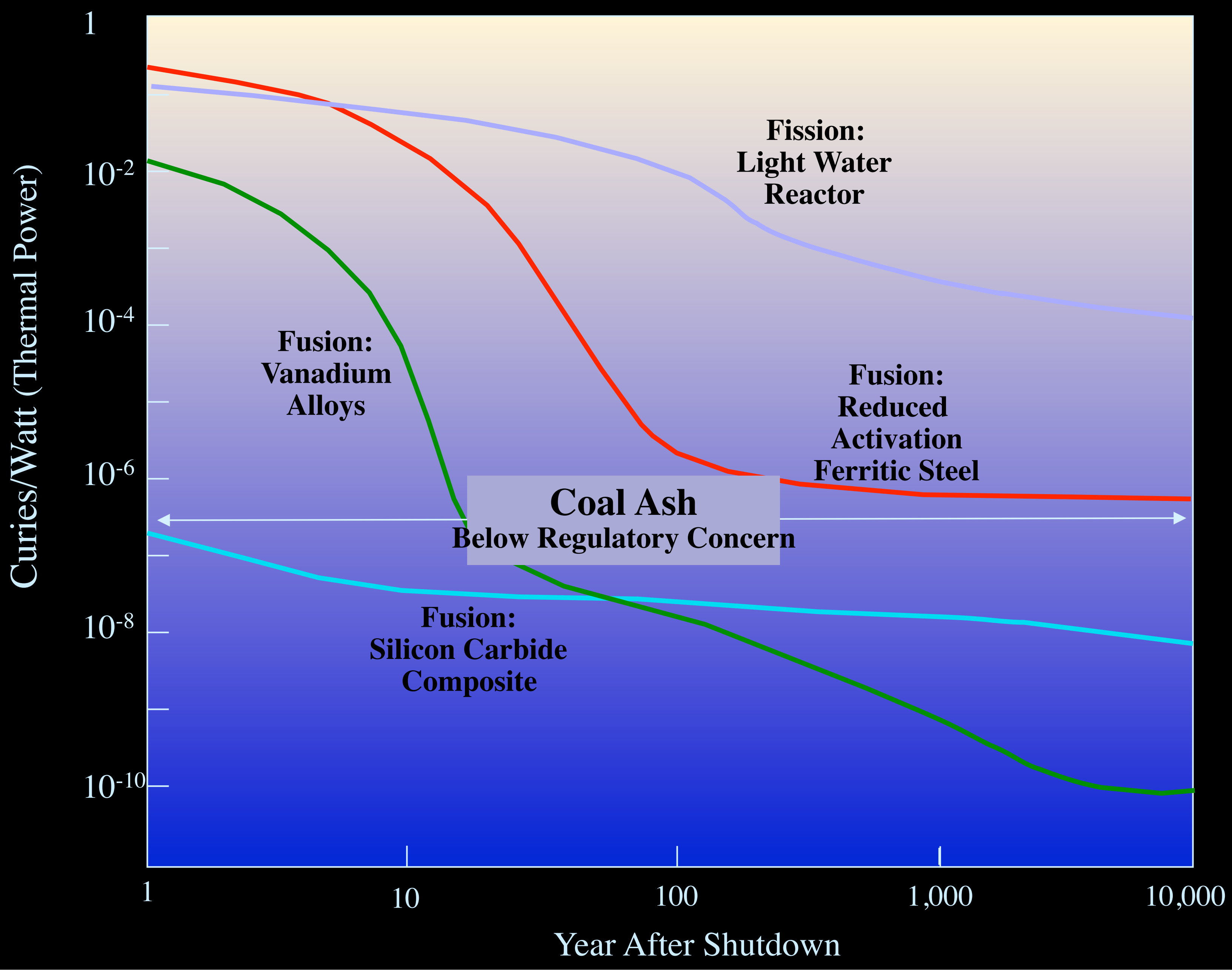
- **T-fuel is radioactive** (beta decay, 12 y halftime, extremely unlikely loss of 1 kg T causes, however, only 50 mSv 1 km away; evacuation not needed)

- **Reactor walls activated** (initial activity as for fission, but within 10-100 y the activity is 4-5 orders of magnitude lower than that of fission)

- **Disruptions** can cause wall damage or harm supraconducting magnets



Comparison - radioactivity from fission and fusion after shutdown



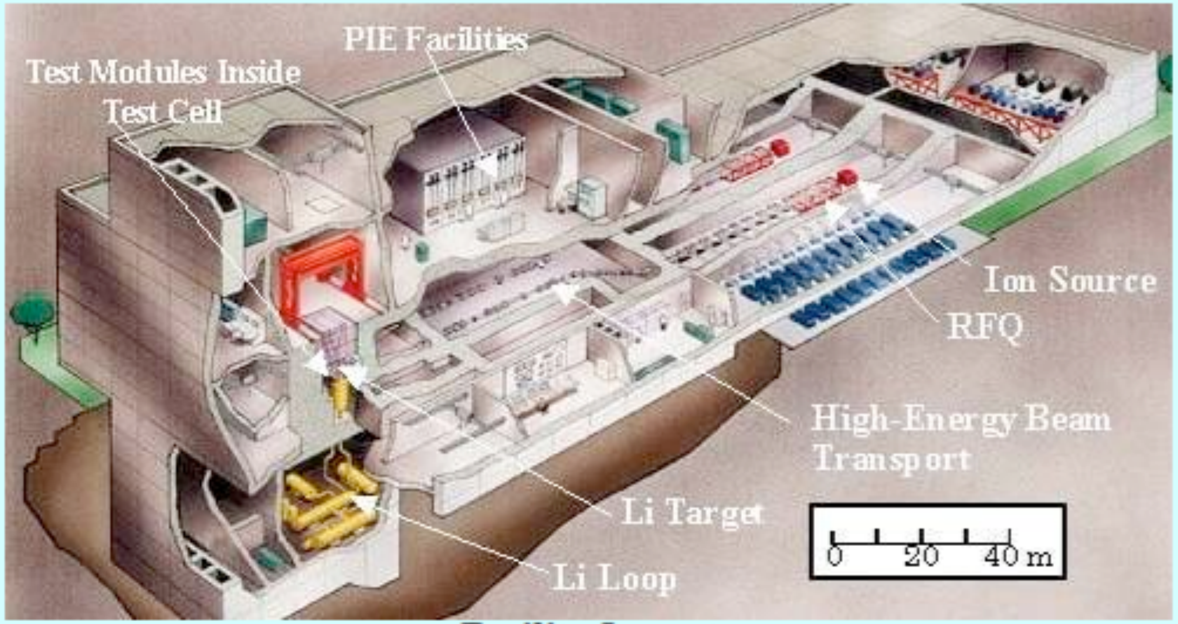
Conclusion – safety and environment

The European Safety and Environmental Assessment of Fusion Power (SEAFP) finds that

fusion has potential for becoming a safe, sustainable energy source with low external costs

IFMIF -

International Fusion Material Irradiation Facility
- Material test facility

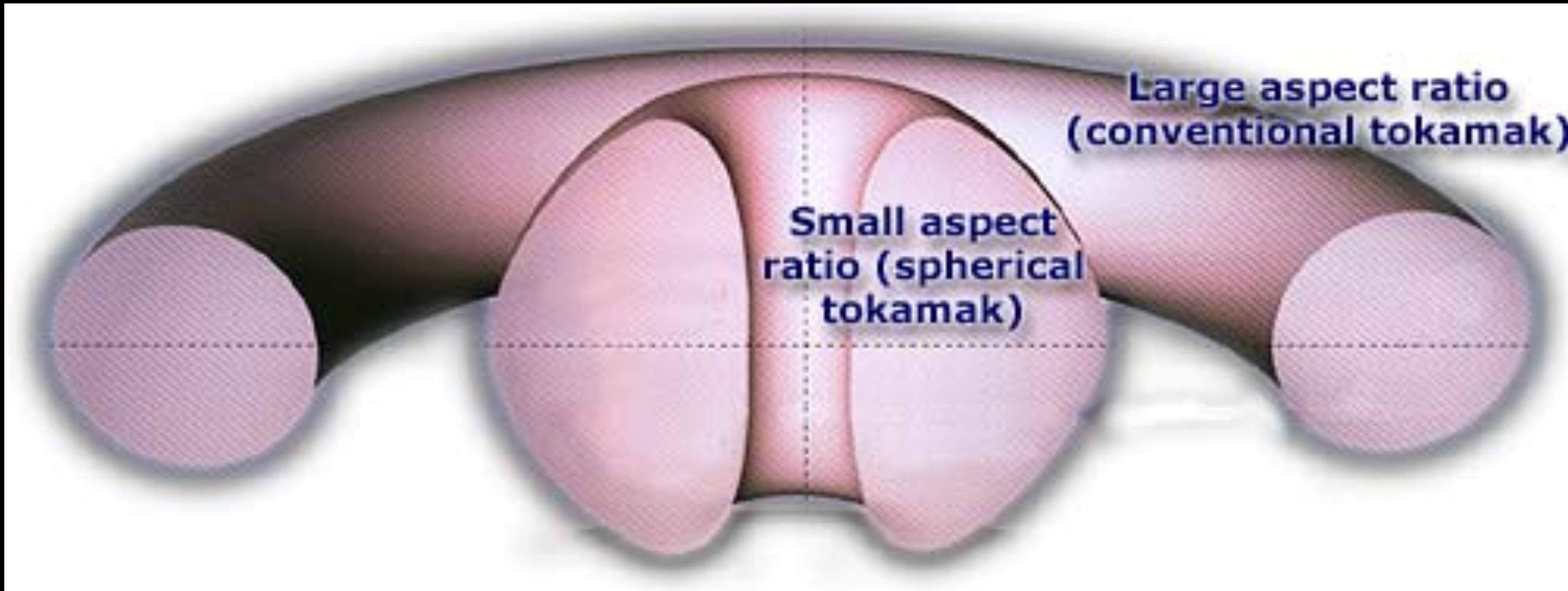


Facility Layout

JAEA, Japan:

2 parallel, 50 m, 40 MeV, 250 mA D-accelerators
Liquid Li - target (20 m/s)
Neutron flux: 2 MW/m^2 in 0.5 l volume, 14 MeV, 20 dpa/y

Can we improve the tokamak?



UKAEA

Spherical Tokamak

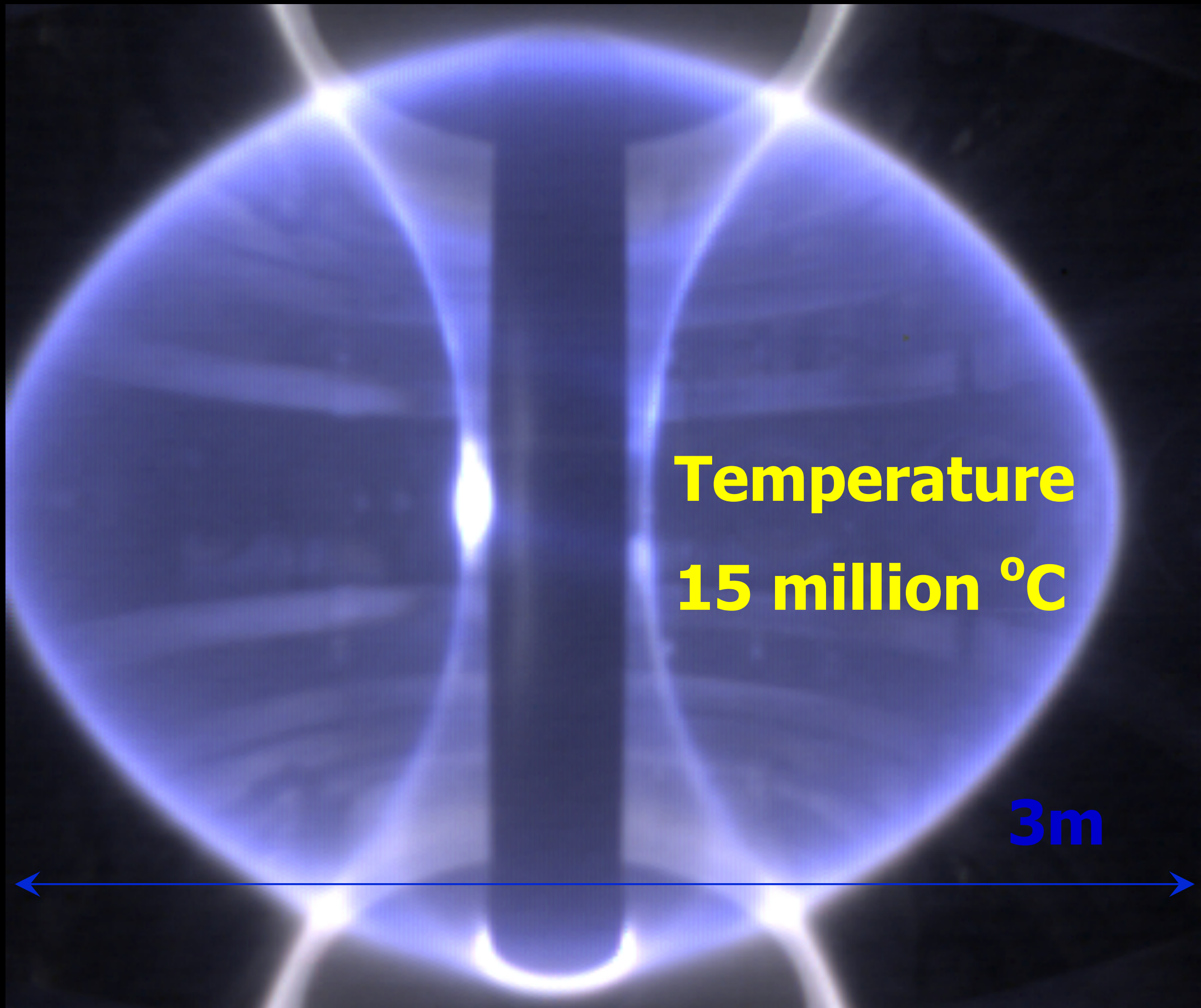
Advantages:

- Smaller than standard tokamak (lower cost)
- Higher plasma pressure
- No disruptions
- Good energy confinement

Disadvantages:

- Inner conductor exposed to heat and neutrons
- Neutron economy is an issue

A MAST plasma



MAST - Culham, England

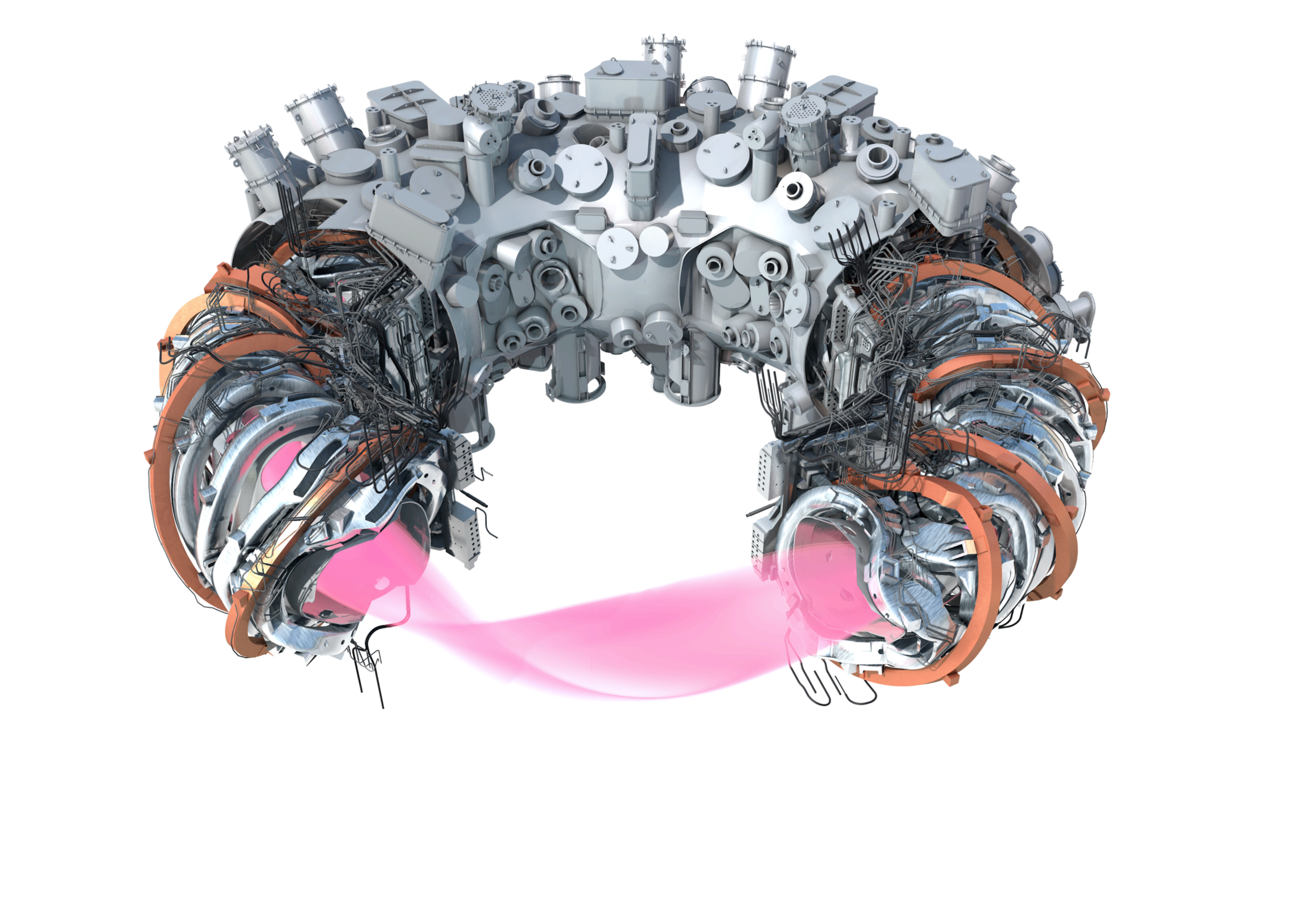
Stellarator

Advantages:

- No plasma current
- Continuous operation
- Godd confinement of particles and energy
- Modular reactor – simple service

Disadvantages:

- Limited plasma pressure
- Complex 3D theory and experimental diagnostics



Wendelstein VII-X
Stellarator in Greifswald,Germany

Stellarator – Wendelstein 7-X

Max-Planck-Institut für Plasmaphysik
EURATOM Assoziation

Superconducting coils

Max-Planck-Institut für Plasmaphysik
EURATOM Assoziation

Reversed-field Pinch (RFP)

Advantages:

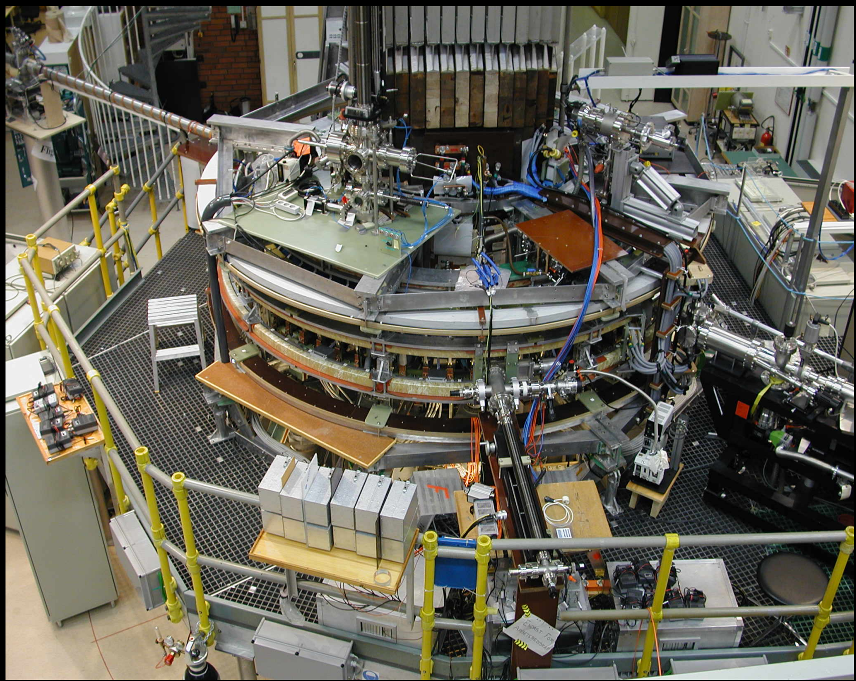
- Smaller than standard tokamak (lower cost)
- Higher plasma pressure
- Lower magnetic field
- Ohmical heating to ignition possible

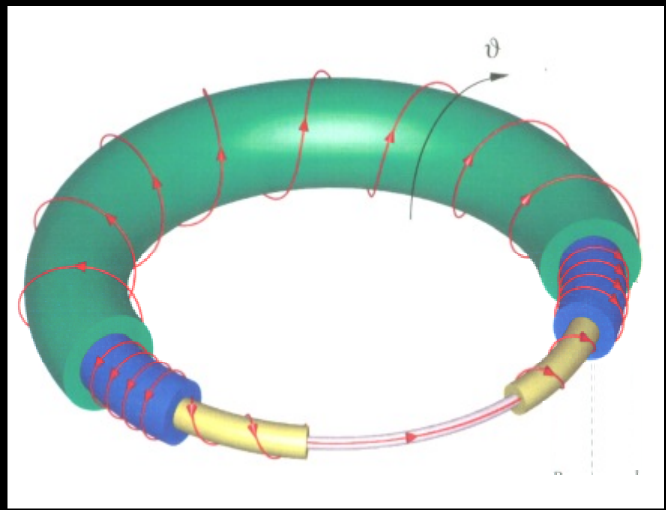
Disadvantages:

- Limited energy confinement
- Instabilities and current profile must be controlled

EXTRAP T2R

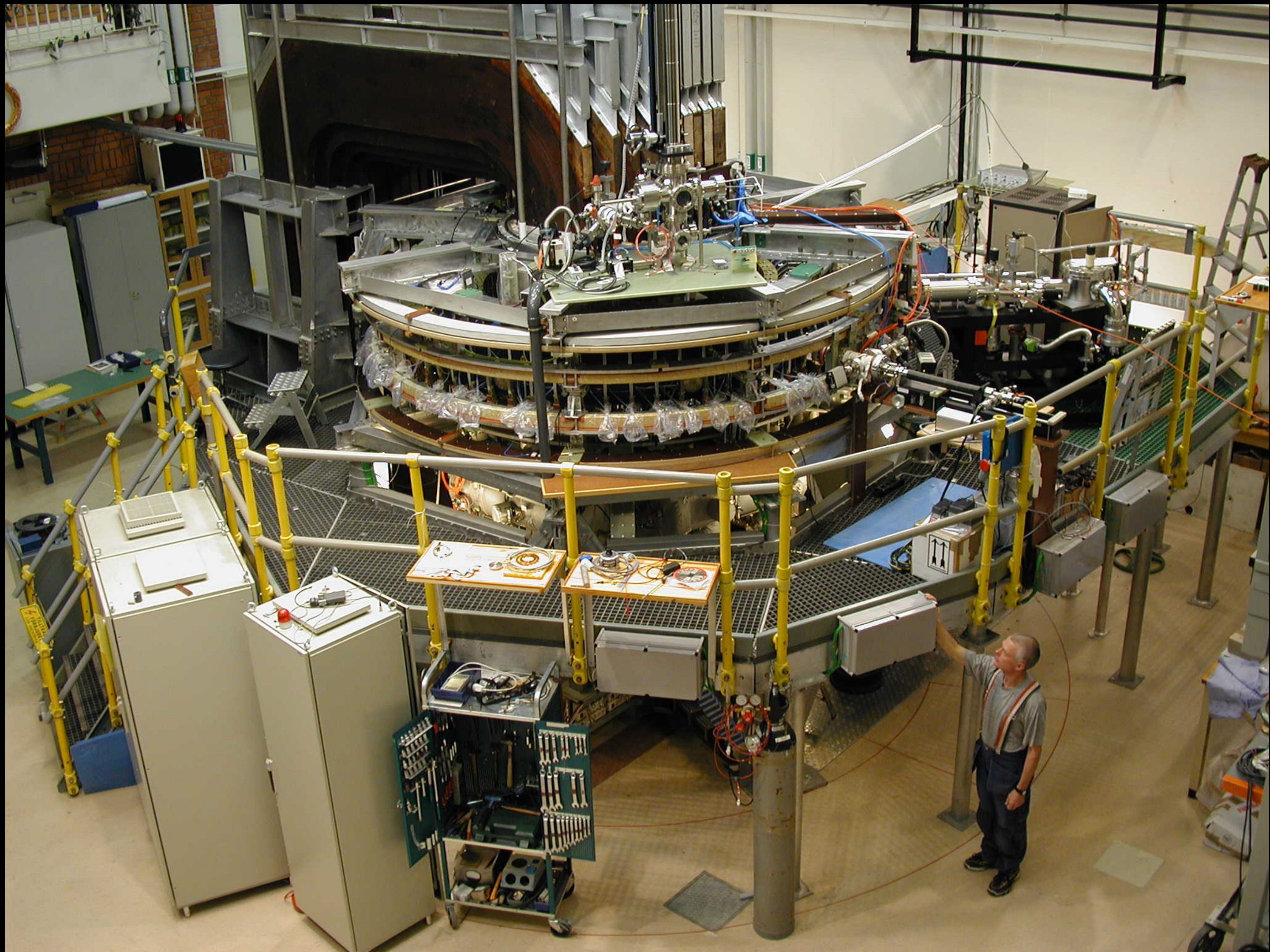
- One of several specialized experiments in the EU fusion programme
- Experimental group at KTH consists of about 10 persons (researchers, Ph D students, engineers and technicians)
- Research budget ca 10 Mkr/y
- Funding: KTH (60%), VR (20%), EU (20%).



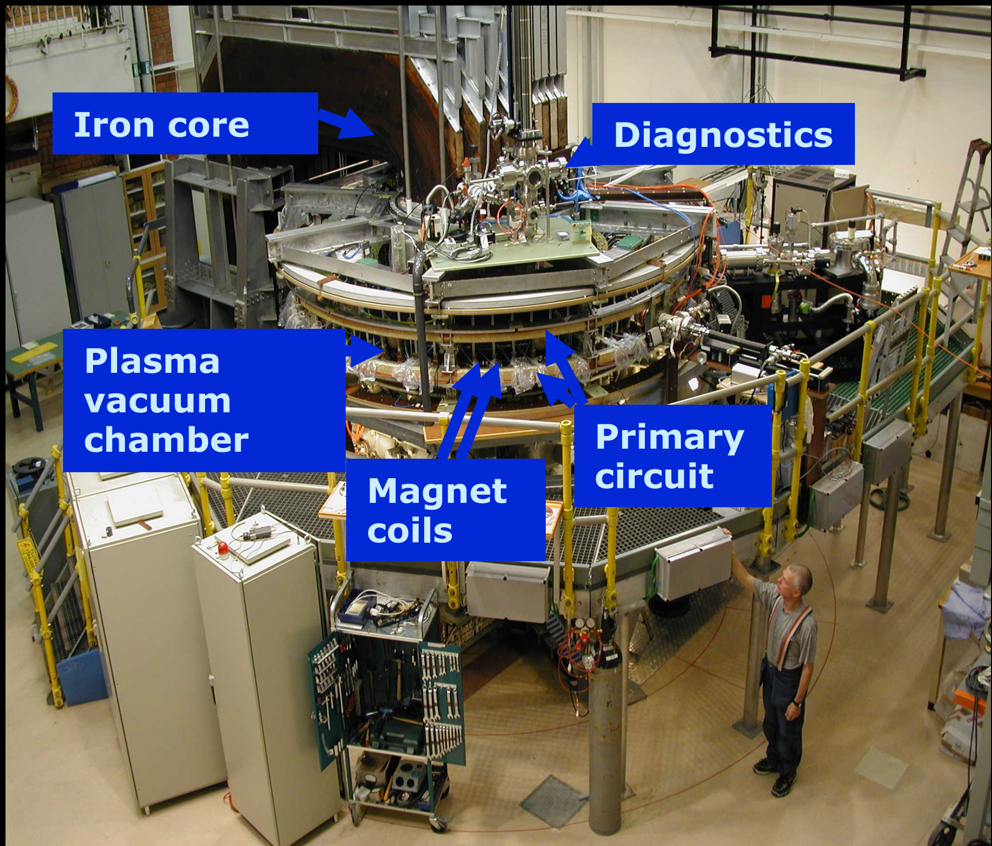


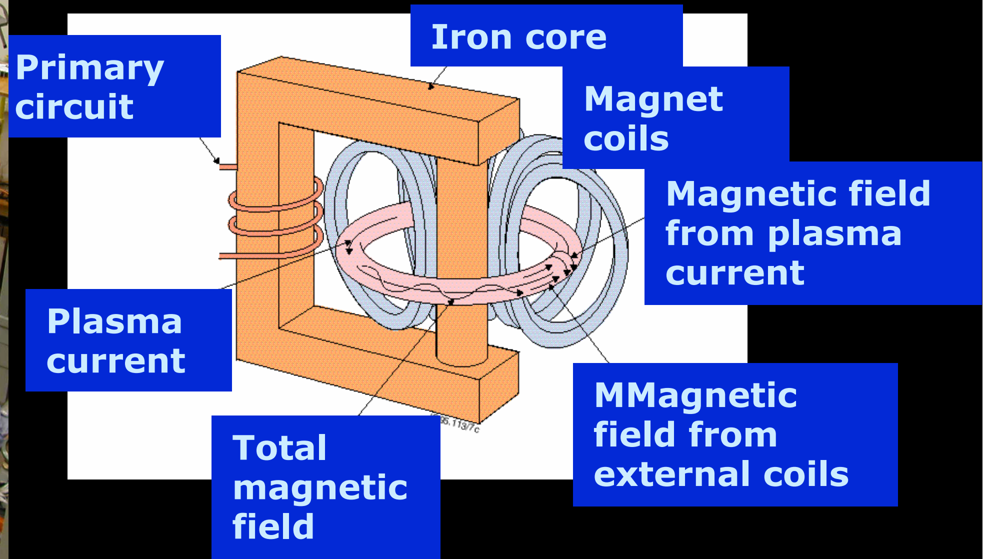
EXTRAP T2R, Alfvénlaboratoriet, KTH

Scandinavia's only fusion experiment – reversed-field pinch



Fusion experiment EXTRAP T2R at KTH





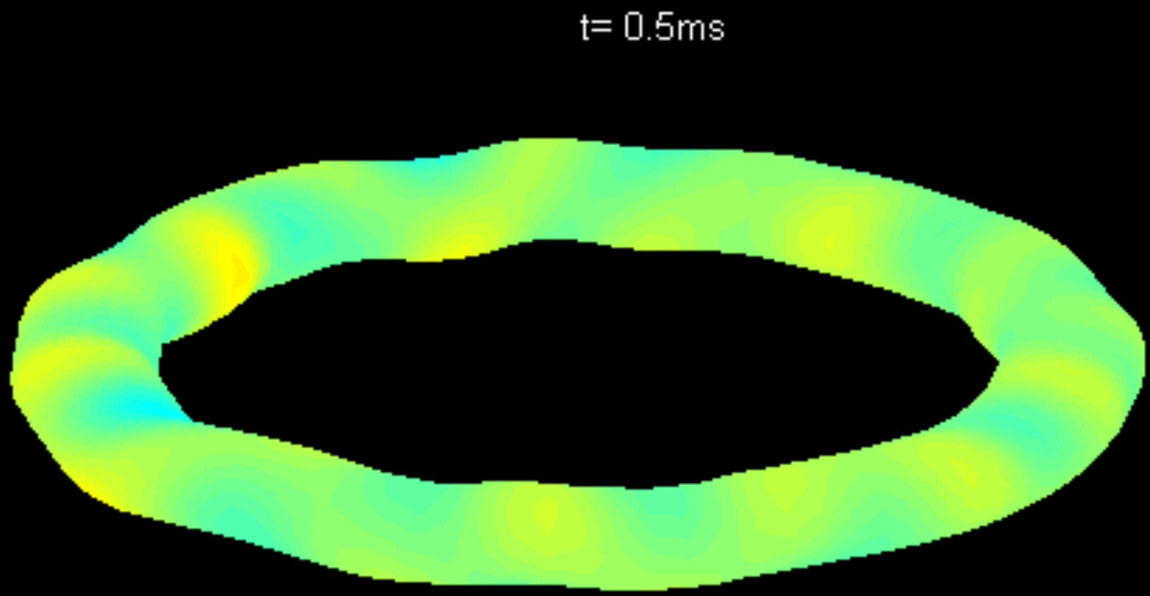
PLASMA INSTABILITIES

One of the main problems to develop a fusion reactor are plasma instabilities.

They can:

- **reduce plasma temperature**
- **damage the wall material**
- **produce a sudden termination of the plasma**

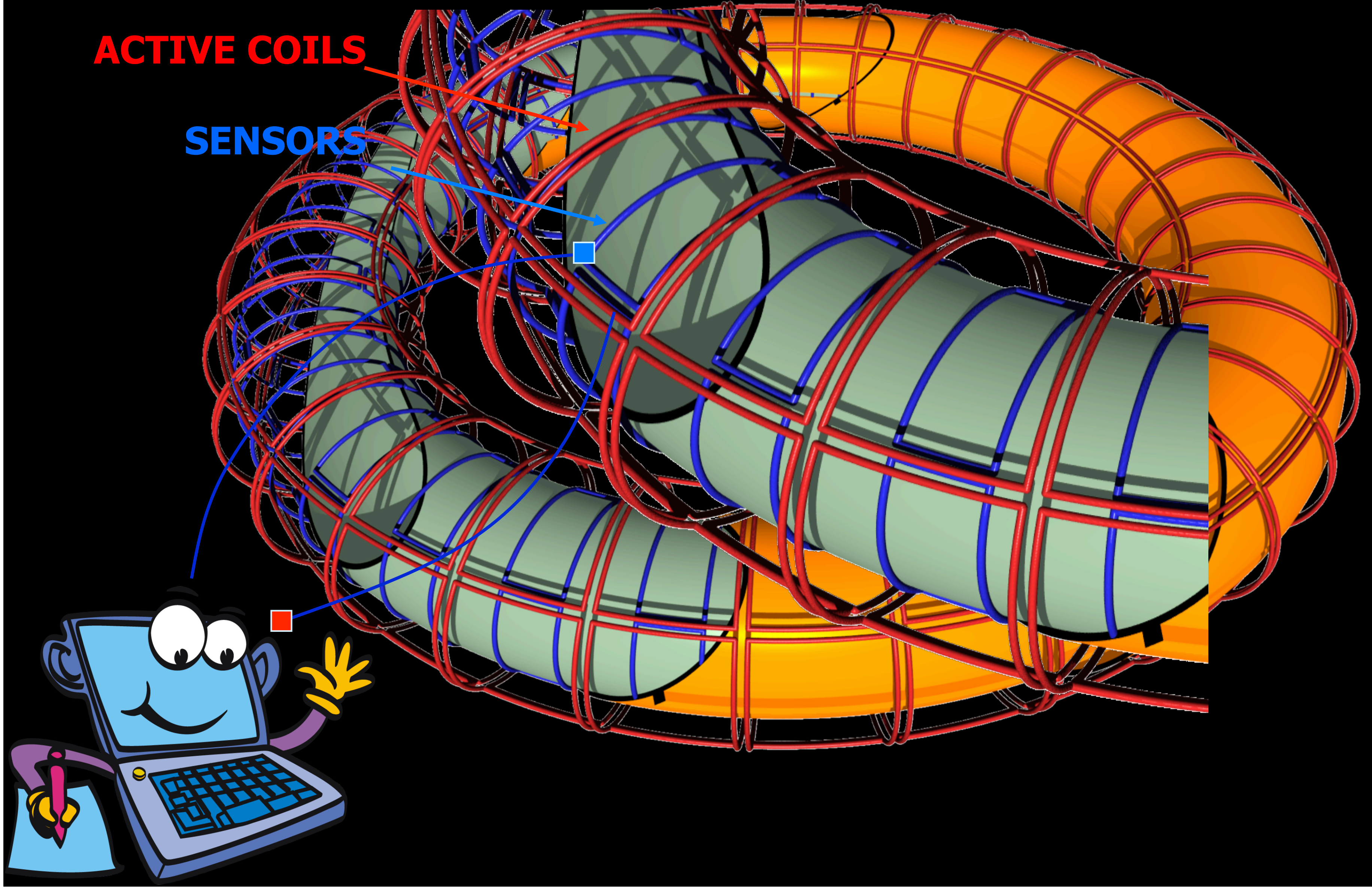
Example of an instability: Resistive Wall Mode (RWM)



Experimental data from EXTRAP T2R

EXTRAP T2R CONTRIBUTION

Here we are developing and improving methods to suppress/control instabilities



Distributed R&D 26 Associations in an Integrated Programme

EUROPEAN COMMISSION
Community Research

- Euratom - CEA (1958) France
- Euratom – ENEA (1960) Italy (incl. Malta)
- Euratom - IPP (1961) Germany
- Euratom - FOM (1962) The Netherlands
- Euratom - FZJ (1962) Germany
- Euratom - Belgian State Belgium (1969) (incl. Luxembourg)
- Euratom - RISØ (1973) Denmark
- Euratom – UKAEA (1973) United Kingdom
- Euratom - VR (1976) Sweden
- Euratom - Conf. Suisse Switzerland (1979)
- Euratom - FZK (1982) Germany
- Euratom –CIEMAT (1986) Spain
- Euratom – IST (1990) Portugal

- Euratom - TEKES (1995) Finland (incl. Estonia)
- Euratom - DCU (1996) Ireland
- Euratom - ÖAW (1996) Austria
- Eur - Hellenic Rep (1999) Greece (incl. Cyprus)
- Euratom - IPP.CR (1999) Czech Rep.
- Euratom - HAS (1999) Hungary
- Euratom – MEdC (1999) Romania
- Euratom – Univ. Latvia Latvia (2002)
- Euratom - IPPLM (2005) Poland
- Euratom - MHEST (2005) Slovenia
- Euratom – CU (2007) Slovakia
- Euratom – INRNE (2007) Bulgaria
- Euratom – LEI (2007) Lithuania

Focus areas of magnetic fusion research

1) Instabilities – difficult to confine a plasma at high density and temperature with moderate magnetic fields

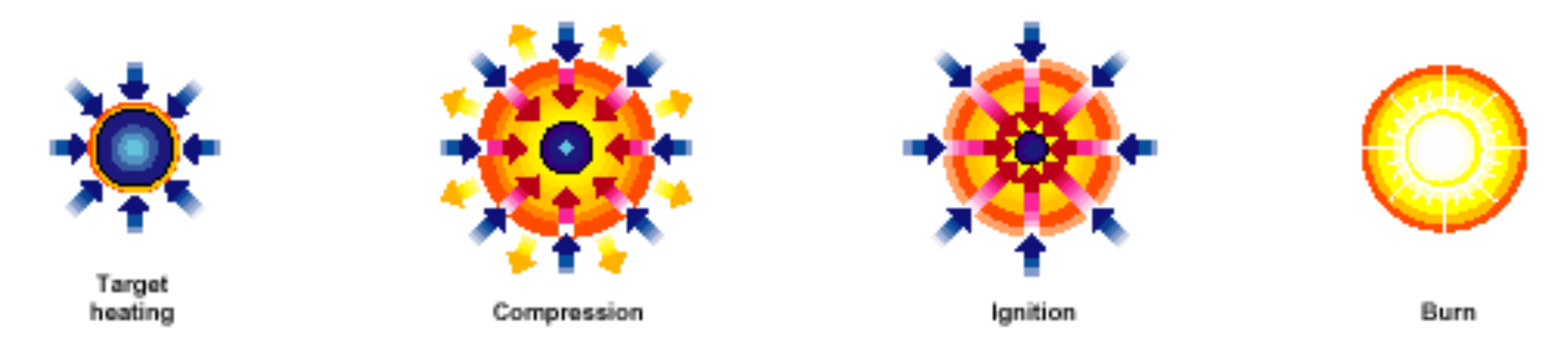
2) Turbulence – breaks up field lines and limits confinement time

3) Heat flow – high volume to surface ratio implies strong heat flow against wall

4) Neutron impact – the wall materials must withstand strong neutron flows

Inertial confinement

- Beams of laser light or heavy ions targeted on small pellet of 'fuel' (hydrogen isotopes).
- Surface heating ablates material leading to compression of pellet by rocket action.
- At sufficient temperature and density: fusion occurs.
- For economic power production, need to repeat 5-10 times s^{-1}.

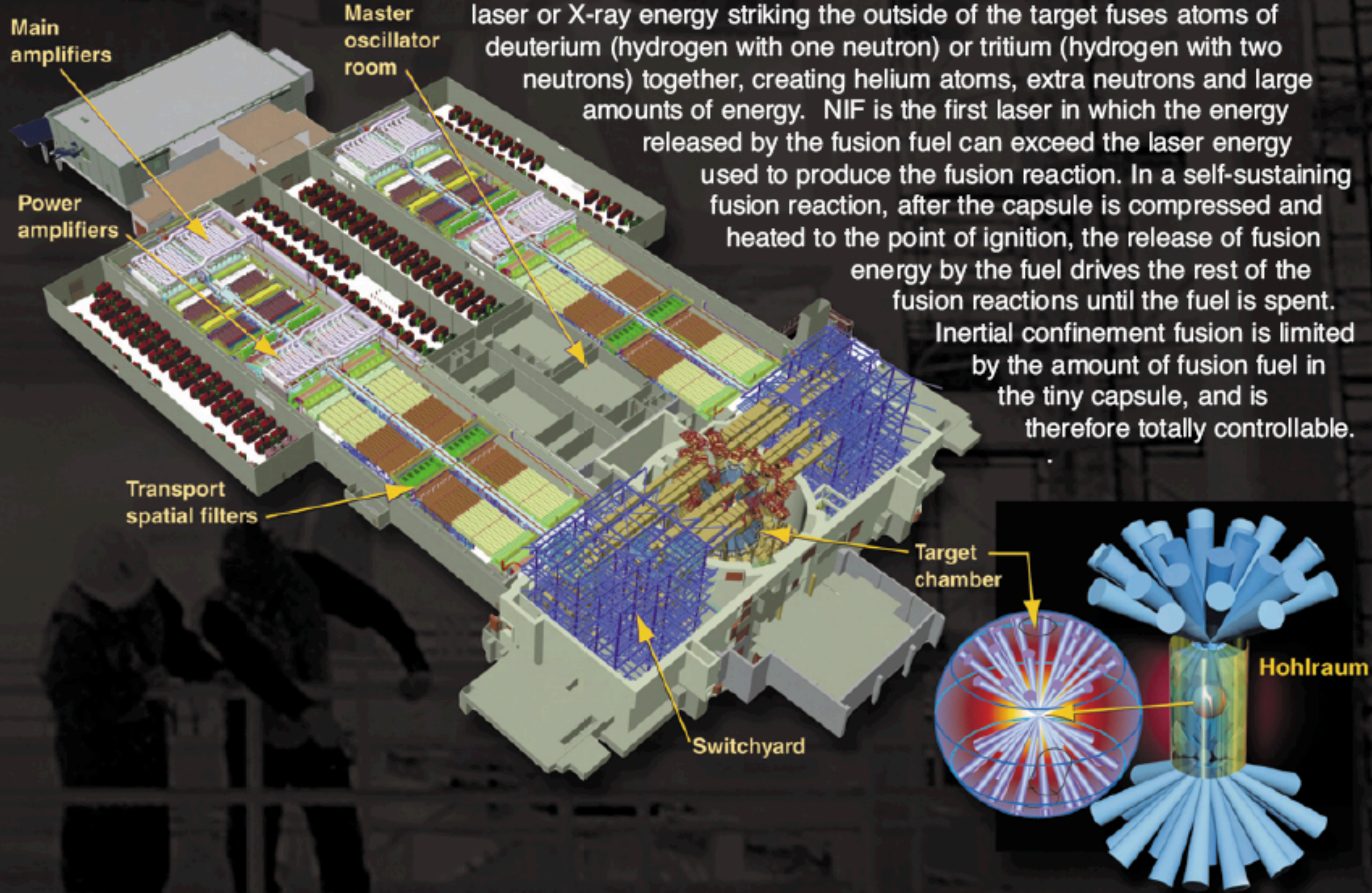


National Ignition Facility (NIF), Livermore, CA (tröghetsfusion)

Inertial Confinement Fusion: How to Make a Star

Inside the 30-foot-wide target chamber, a gold cylinder the size of a dime receives energy from all 192 laser beams simultaneously: about 1.8 million joules over a few billionths of a second (about 500 trillion watts, which is nearly 1,000 times the power generated in the United States over the same time period). This cylinder then produces X-rays that compress and heat a fusion capsule inside the cylinder to temperatures and pressures approaching those in a nuclear explosion or in the sun, igniting the fusion fuel in a self-sustaining reaction and creating a miniature star in the laboratory.

NIF will employ a process called inertial confinement fusion, in which either laser or X-ray energy striking the outside of the target fuses atoms of deuterium (hydrogen with one neutron) or tritium (hydrogen with two neutrons) together, creating helium atoms, extra neutrons and large amounts of energy. NIF is the first laser in which the energy released by the fusion fuel can exceed the laser energy used to produce the fusion reaction. In a self-sustaining fusion reaction, after the capsule is compressed and heated to the point of ignition, the release of fusion energy by the fuel drives the rest of the fusion reactions until the fuel is spent. Inertial confinement fusion is limited by the amount of fusion fuel in the tiny capsule, and is therefore totally controllable.

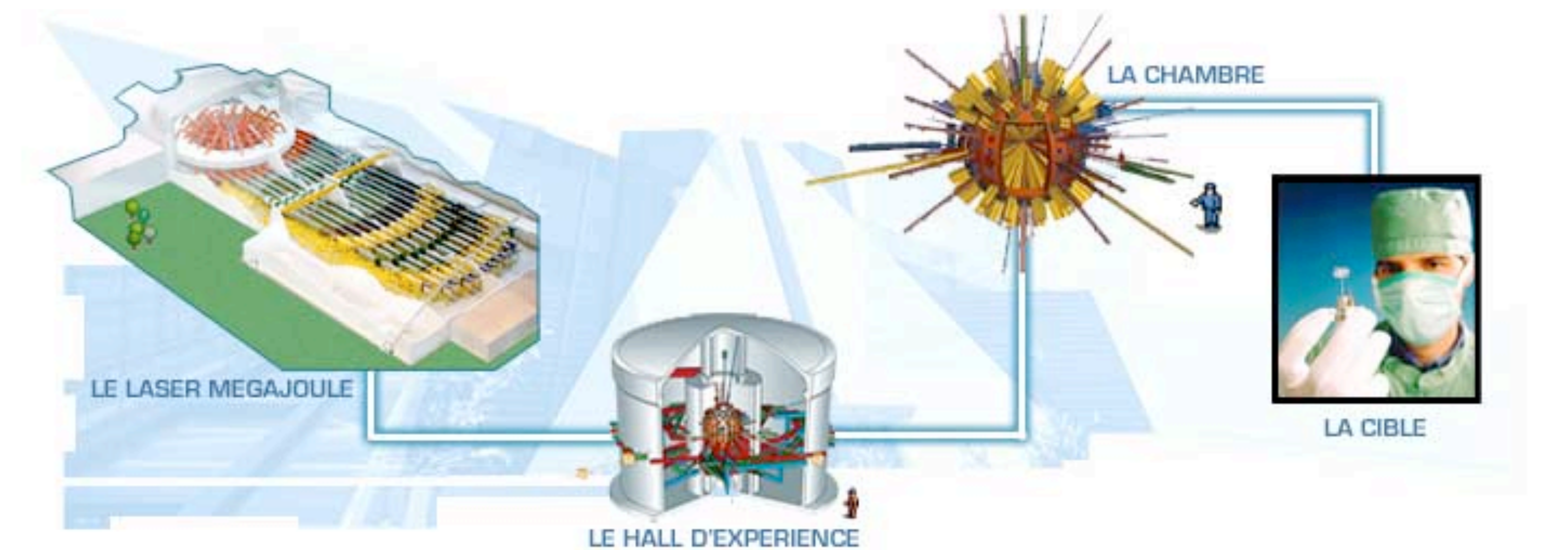


National Ignition Facility (NIF), Livermore, CA (tröghetsfusion)

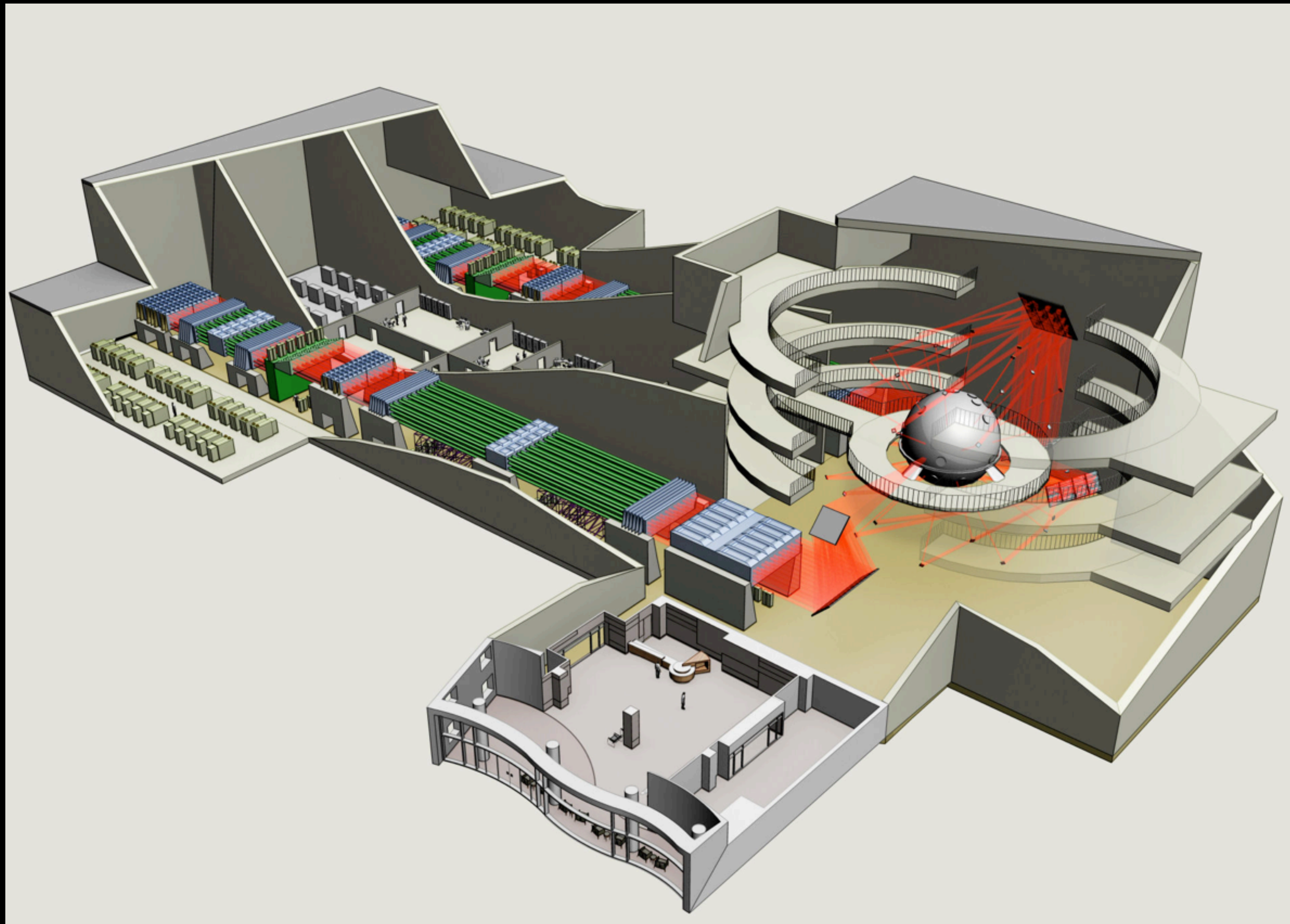
Laser Mégajoule, Bordeaux, Frankrike (tröghetsfusion)

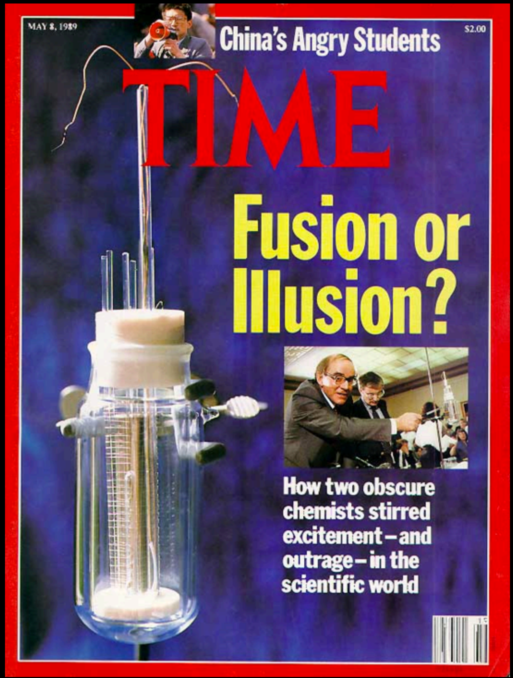
Du laser à la cible

Avec 240 faisceaux lasers regroupés en 60 « quadruplets », concentrés sur une cible de 2,5 mm de diamètre, placée dans une chambre de 10 m de diamètre ; elle-même située dans un hall d'expérience cylindrique de 60 m de diamètre et de 40 m de haut, au centre d'un bâtiment de plus de 300 m de long : **le LMJ est un formidable amplificateur d'énergie lumineuse.** Entre la lumière issue de la source laser, dont l'énergie est comparable à celle que l'on trouve dans les lecteurs de CD, et la chambre d'expérience, **l'énergie aura été amplifiée de plus de mille milliards de fois.**

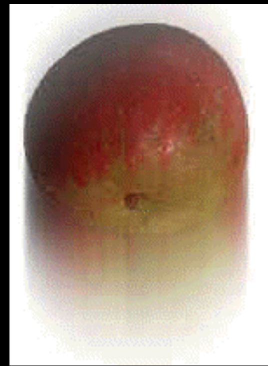


HiPER, Europa
(High Power laser Energy Research Facility)

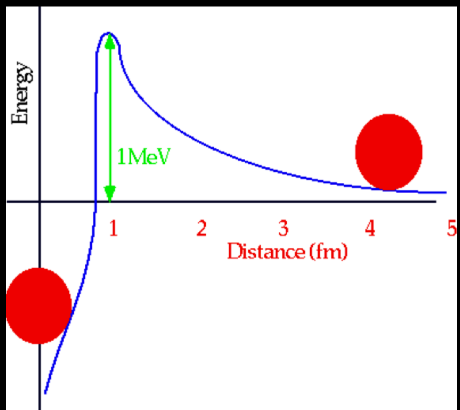




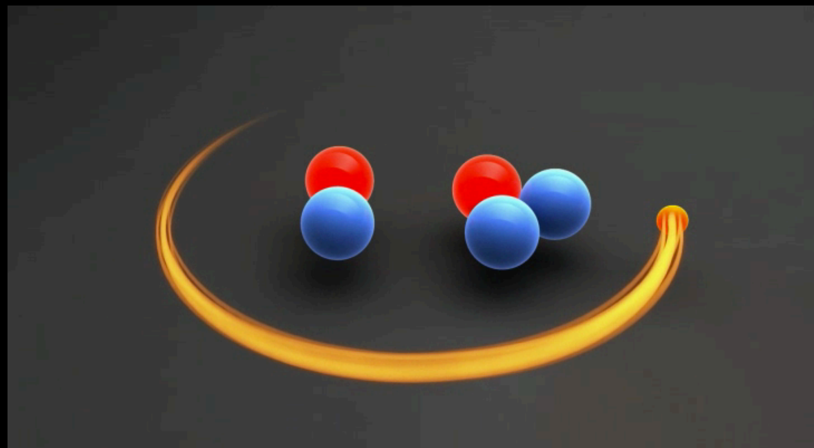
"Kall fusion"



Äpplen faller inte uppåt…

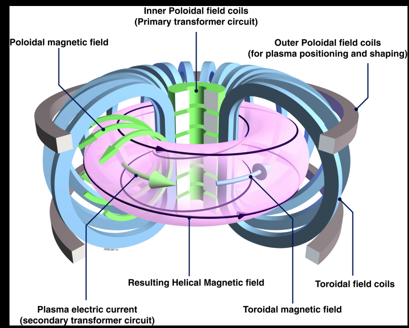


Coulomb-potentialen mellan två positiva laddningar kräver HÖGA partikel-energier…

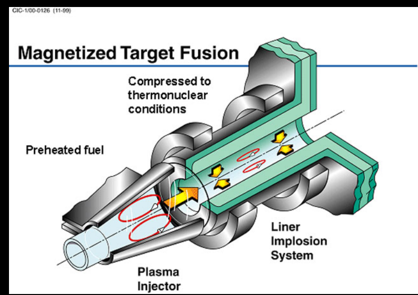


Muon-katalyserad fusion enda tänkbara kall-fusionsprincipen, men fungerar inte heller…

Fusion conditions

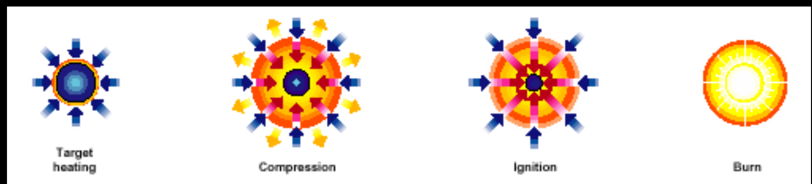


MCF (magnetic confinement fusion):
$n=10^{20}$ particles m^{-3}, $t_E=10$ s



MTF (magnetized target fusion):
$n=10^{25}$ particles m^{-3}, $t_E=10^{-4}$ s

ICF (inertial confinement fusion):
$n=10^{31}$ particles m^{-3}, $t_E=10^{-10}$ s



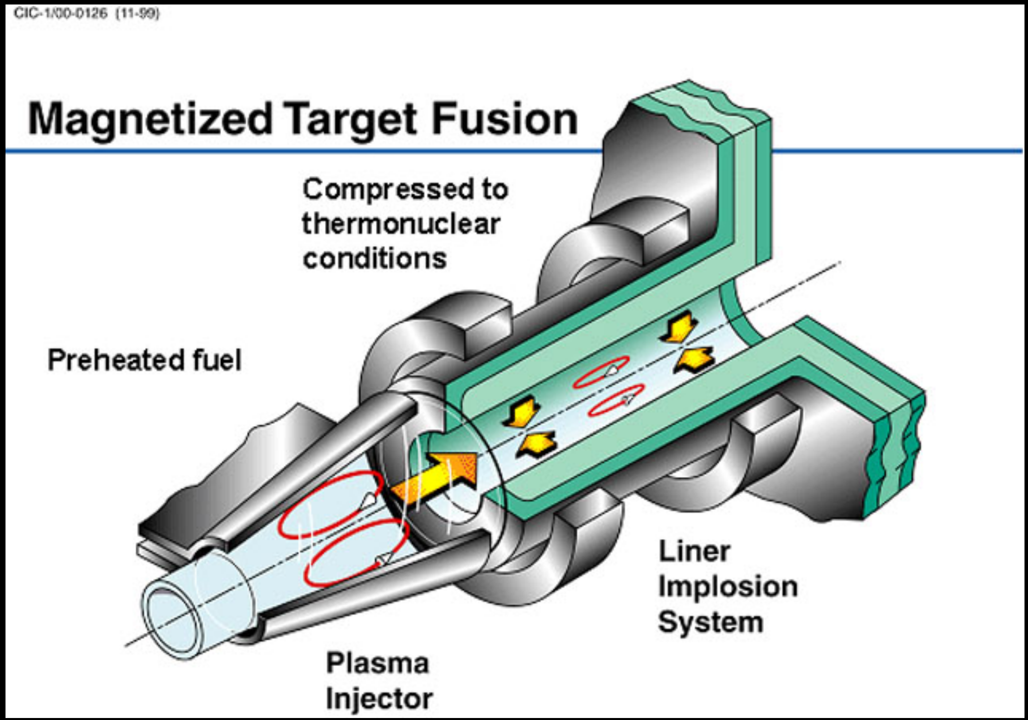
Magnetized Target Fusion

Advantages:

- Much smaller than standard tokamak
- Low cost

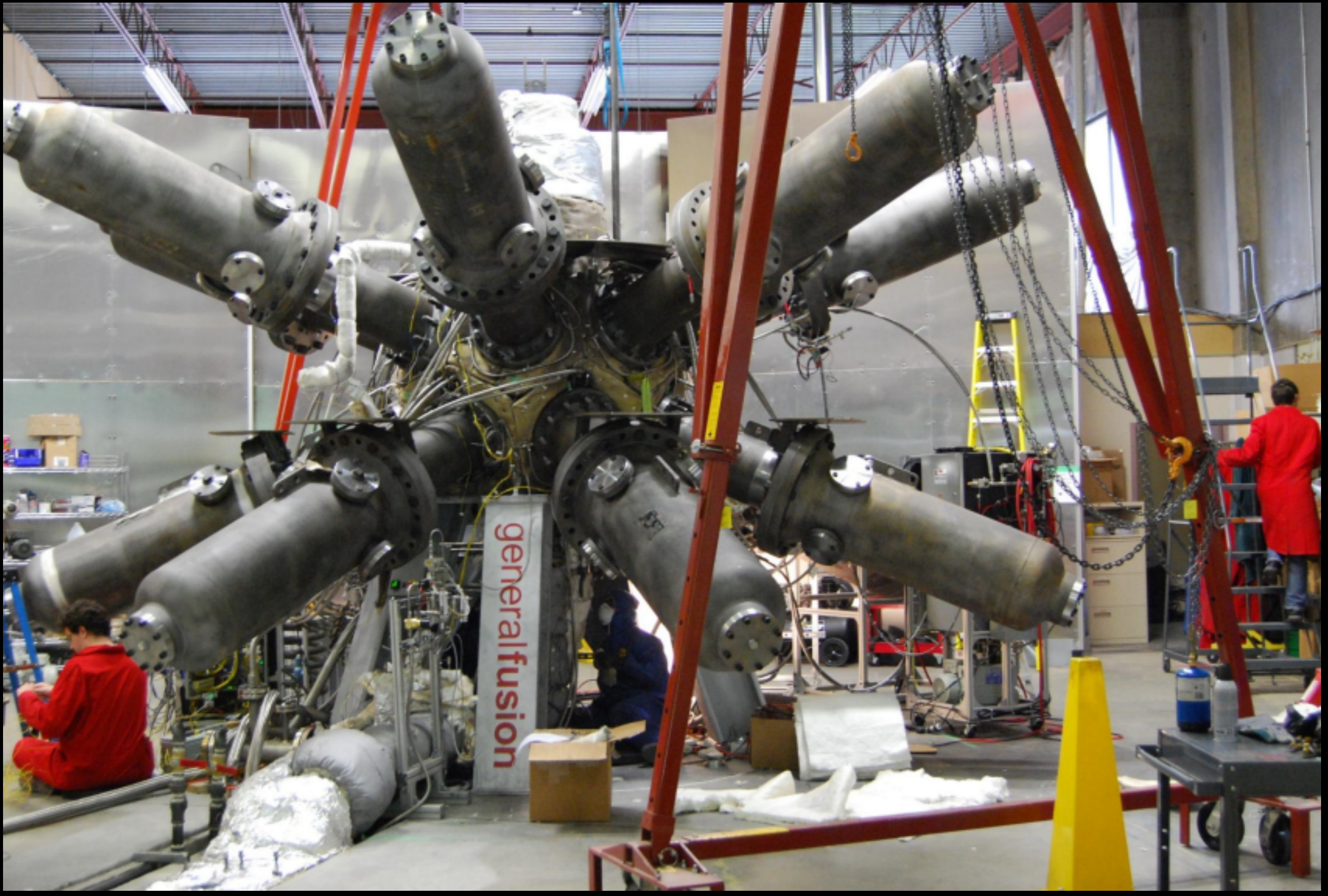
Disadvantages:

- Pulsed
- Dwell time still too short



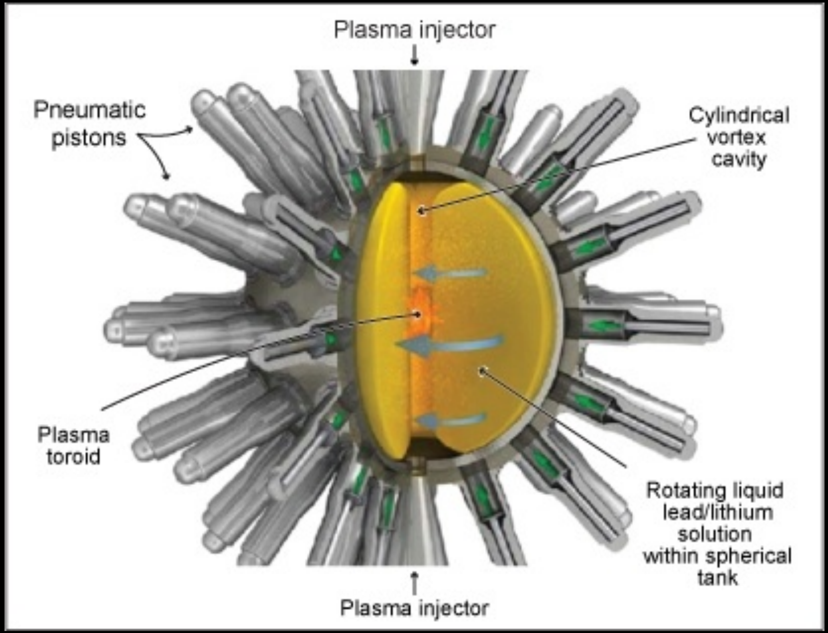
Magnetized Target Fusion

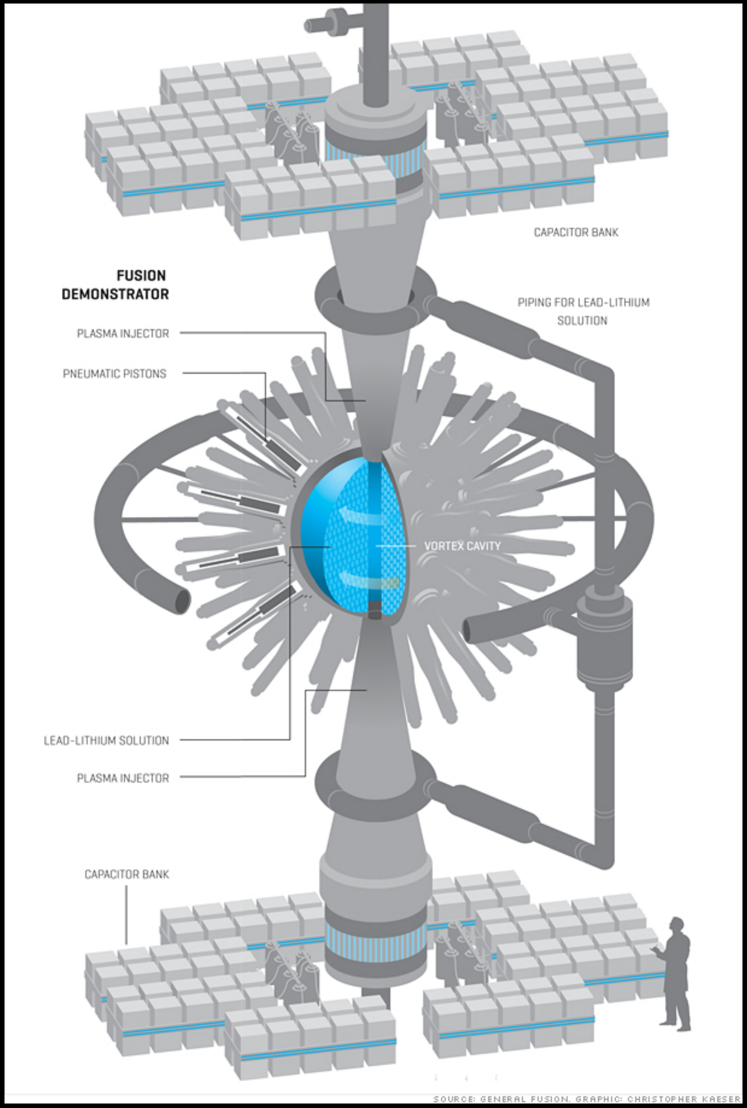
General Fusion



Magnetized Target Fusion

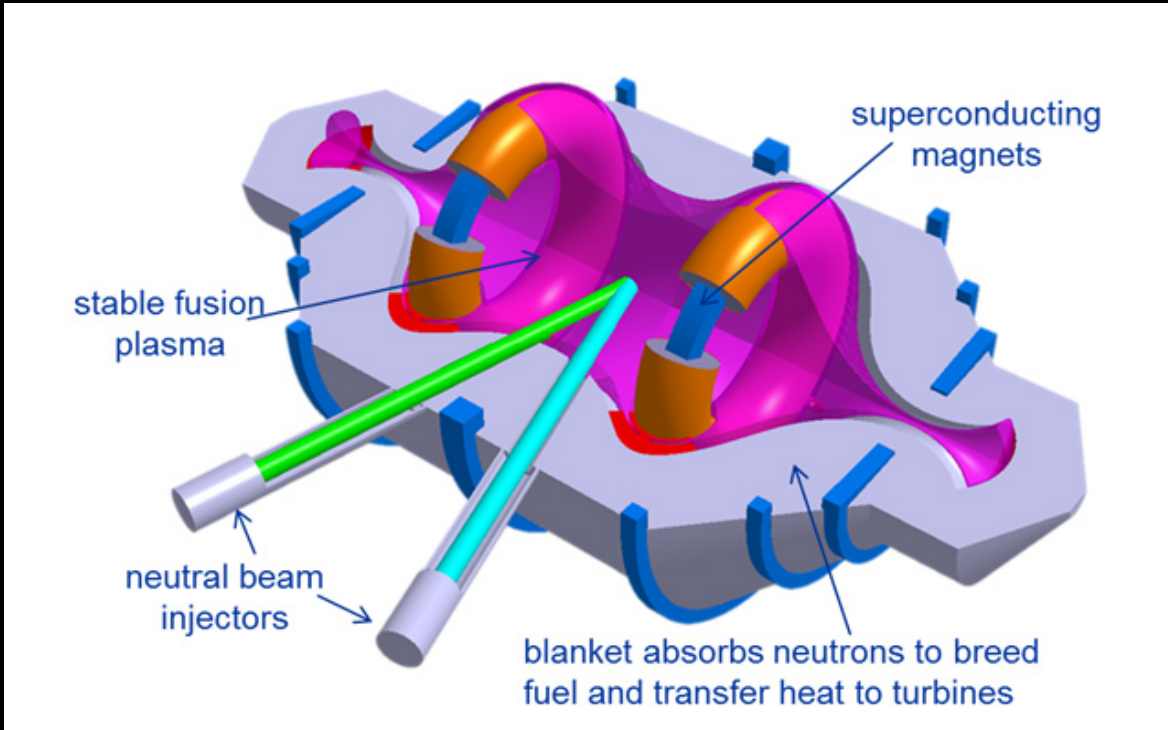
General Fusion

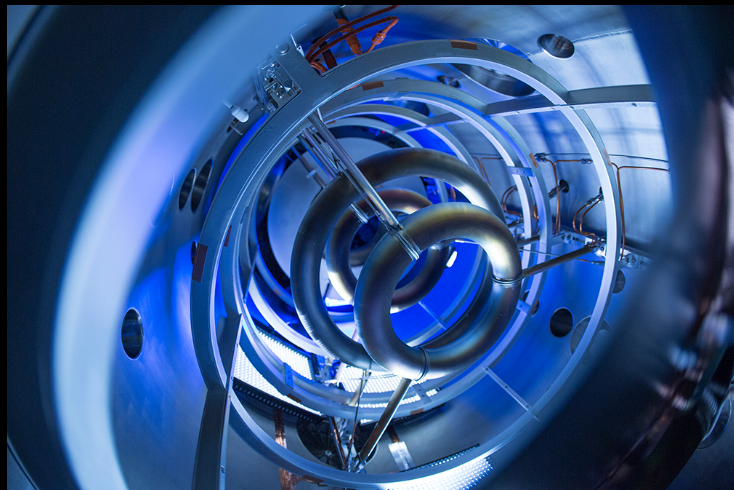




Lockheed Martin

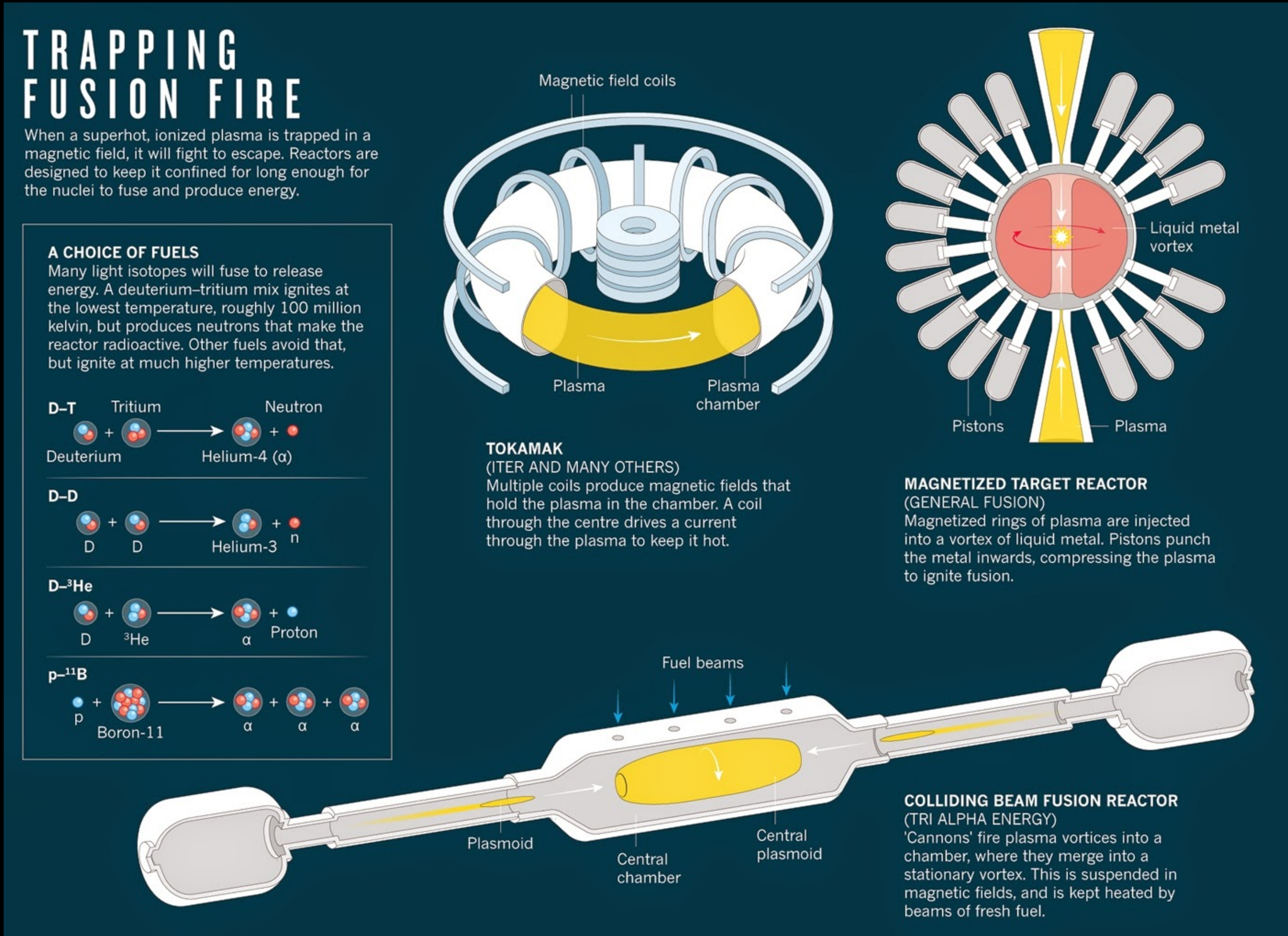
Mirror fusion plasma





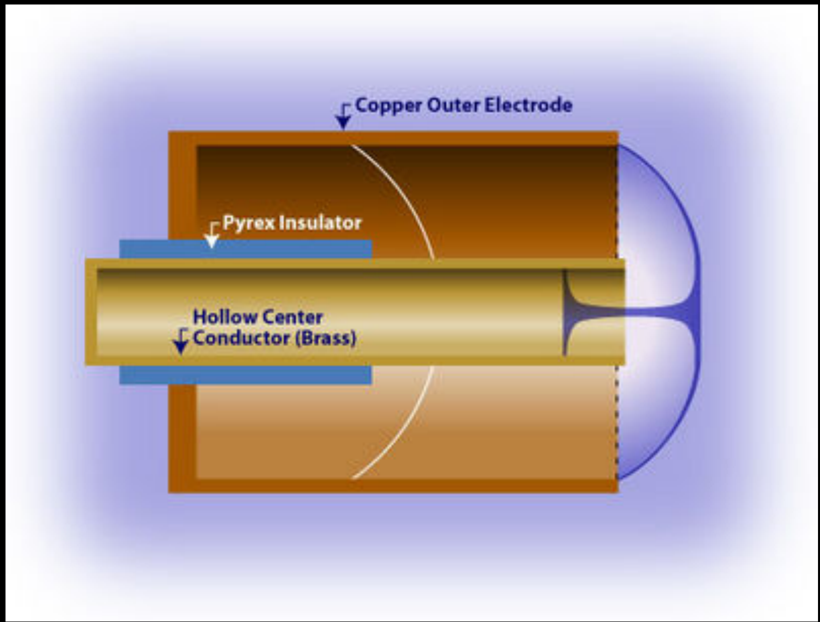
Tri Alpha

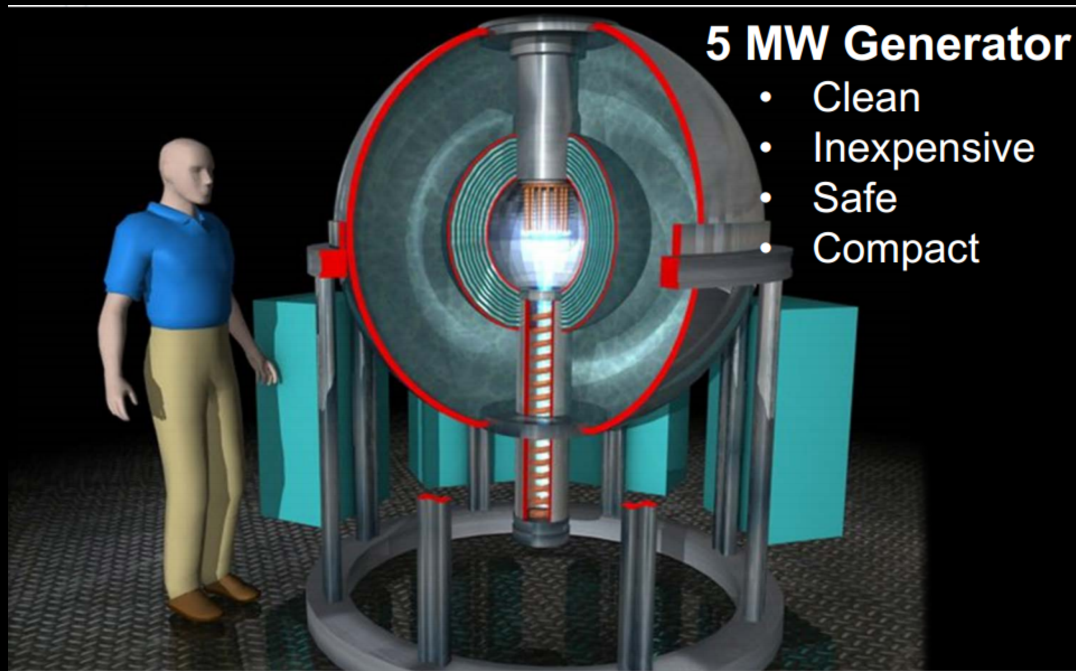
Colliding p-B plasmas



Plasma focus

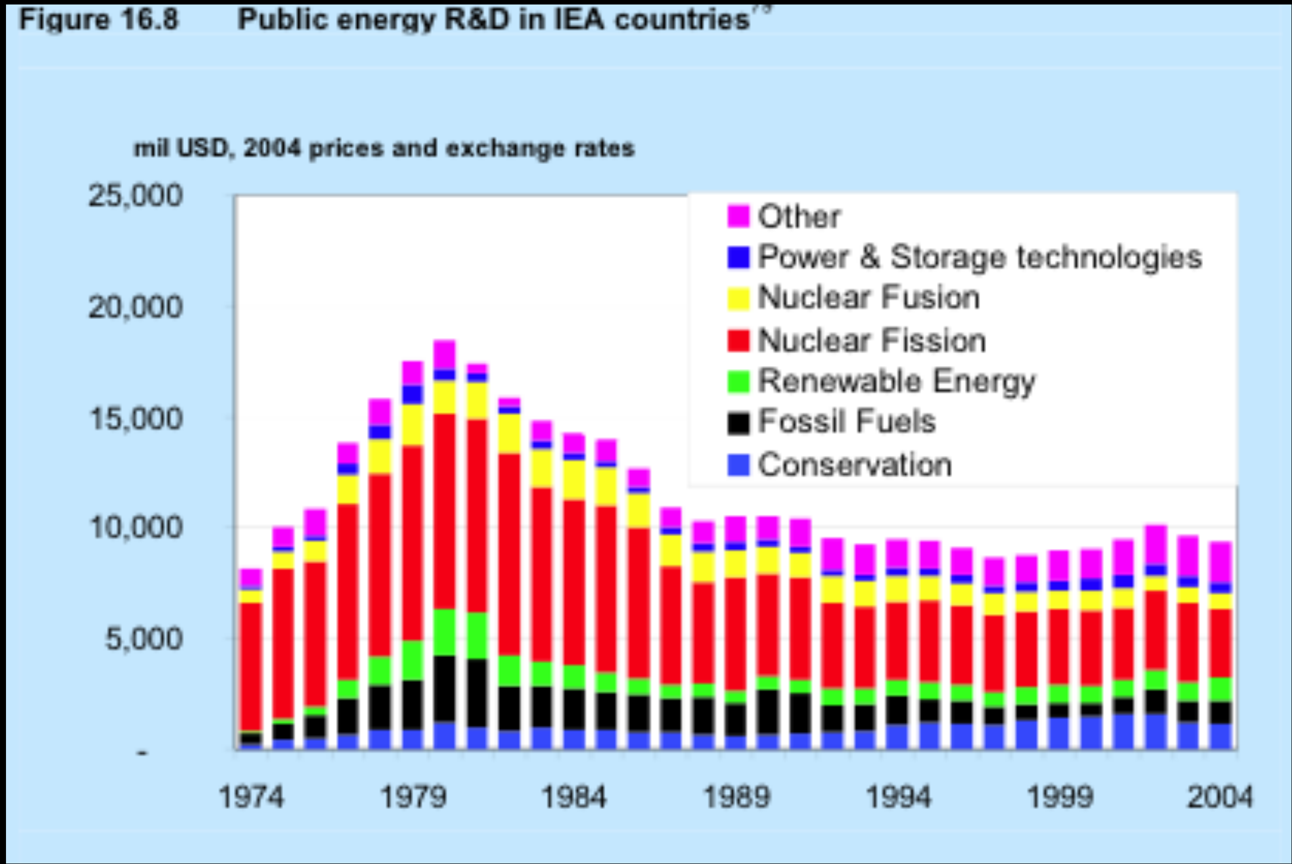
A good neutron source





What are the costs for fusion?

Stern report 2006 - “The Economics of Climate Change”



In a 700 page report, on connection between world economy and global heating, Stern emphasizes the importance of a new policy for investment in innovations within the energy field:

"Globally, support for energy R&D should at least double, and support for the deployment of new low-carbon technologies should increase up to fivefold."

DEMO parameters: factors in Cost of Electricity

- DEMO Phase 2 is the last stage before Commercial Power Plant - we must consider Cost of Electricity (CoE).
- PPCS studies reveal Relatively simple scaling can be developed for Cost of Electricity (CoE).
- CoE depends on:
  - capital cost and hence size of 'nuclear island' (magnets,vacuum vessel, vessel contents)
  - Operational parameters:

$$\mathrm{CoE} \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{P_e^{0.4}\,\beta_N^{0.4}\,n^{0.3}}$$

Availability

Thermodynamic efficiency

Net electrical power

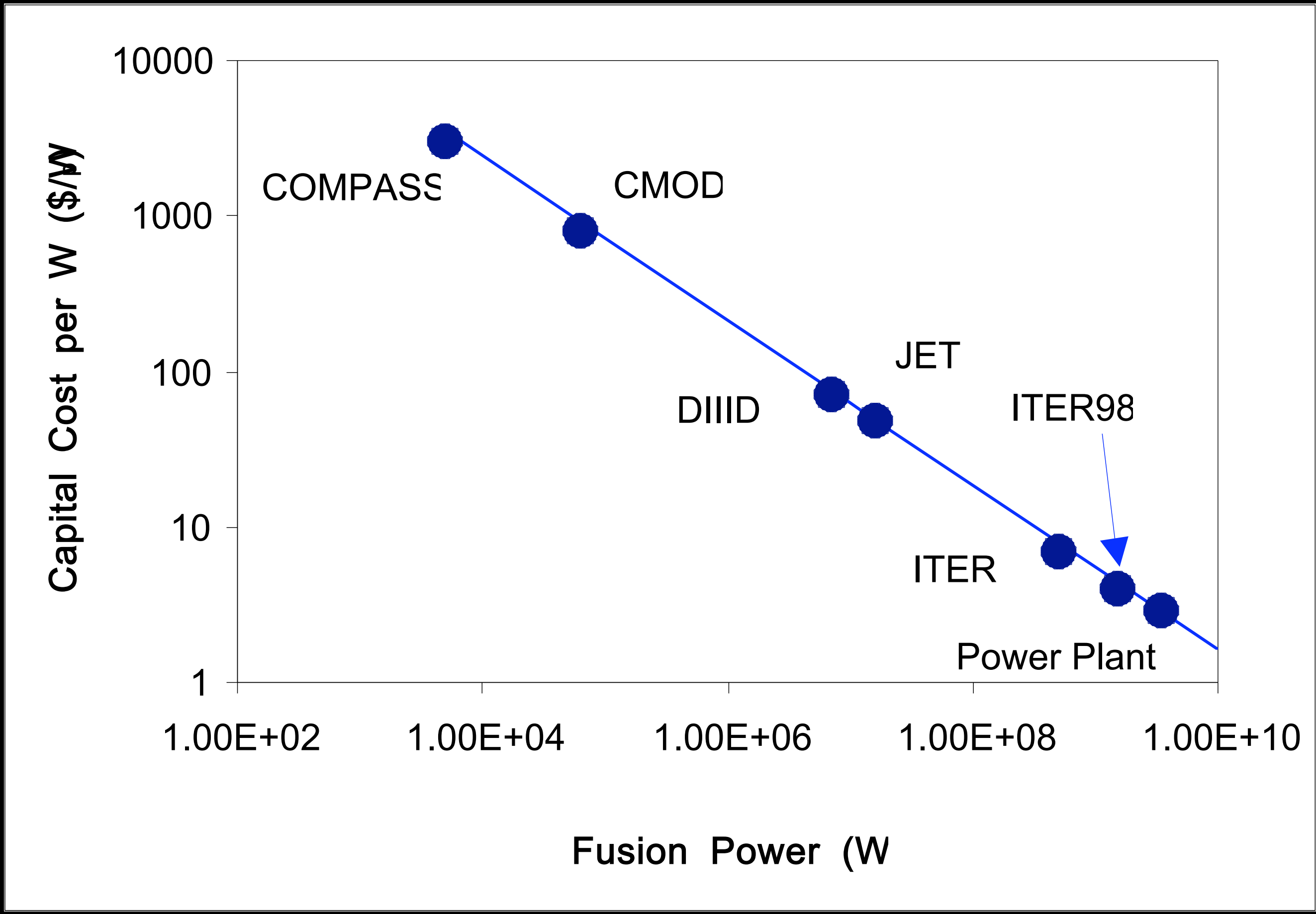
Physics - high β, high density

UKAEA

UKAEA Fusion Working with Europe

Economy for fusion

Direct costs (COE), according to EFDA SERF-study:
ca 0.06-0.08 €/kWh electricity



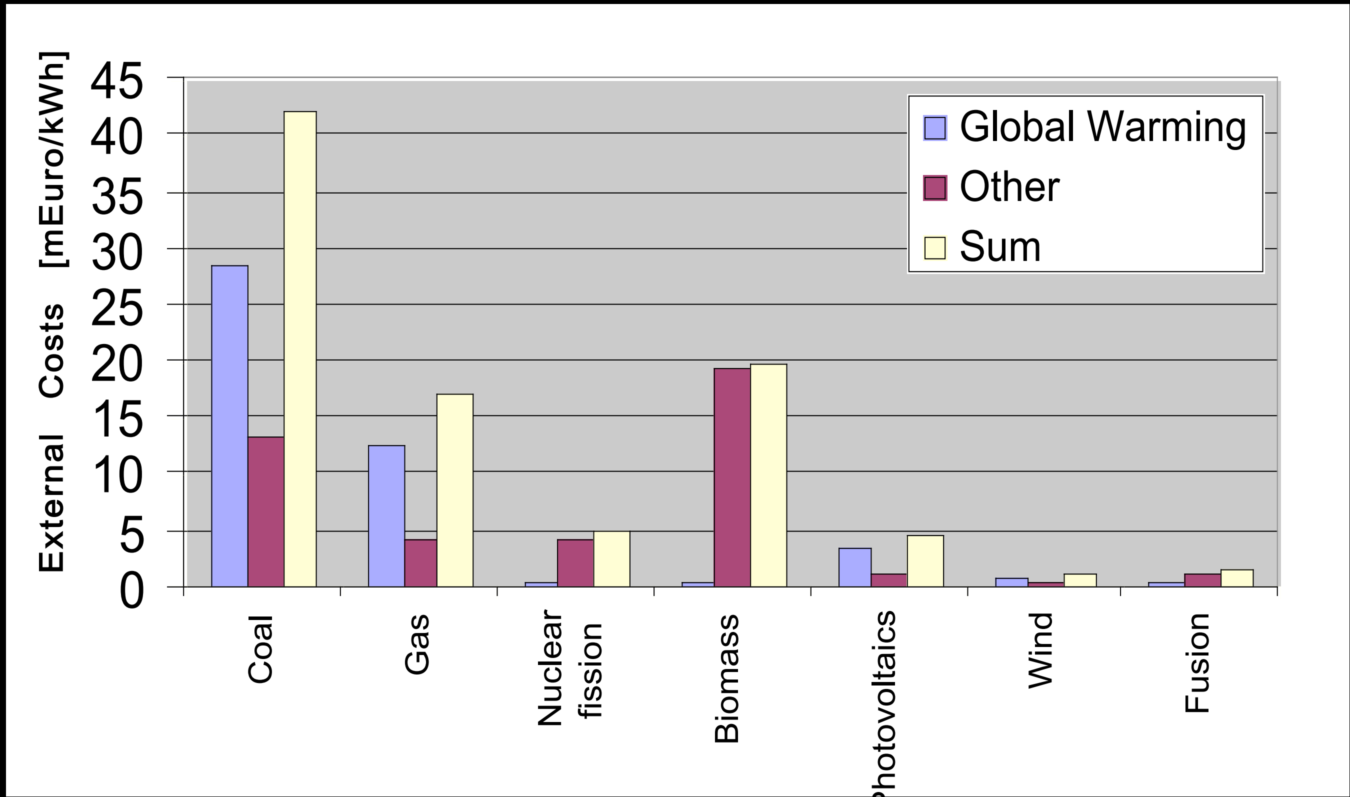
Direct costs: construction, maintenance, fuelling, shutdown.

Energiequelle	Kapitalkosten in Euro pro kW	Produktionskosten in Euro per kWh	Übliche Größe des Kraftwerks in kW	Emission von Treibhausgasen in °C equiv. pro kWh	Landverbrauch in km² pro 1.000 MW
Ölprodukte	1.000	0,25	1-10.000	200	1
Kohle	800 - 1.100	0,05	1.000 - 1.000.000	270	1-2,5 plus Minen
Gas	300 - 600	0,035 - 0,05	1.000 - 1.000.000	180	1
Kernspaltung	1.000 - 1.500	0,05 - 0,08	250.000 - 1.000.000	6*	1 plus Minen und Sicherheitszonen****
Wasserkraft	1.400	0,05	10.000 - 20.000.000	20*	30 - 40
Solar PV (photovoltaisch)	4.000 - 6.000**	0,25	0,01-10	25*	23
Wind	700 - 1.200**	0,06 - 0,10	0,1-100.000	34*	490
Biomasse	1.300 - 1.700	0,05 - 0,10	1-150.000	10*	2.000
Fusion	6.000***	0,05 - 0,10***	1.000.000 - 3.000.000	9*	1

Direct costs for different energy sources

(Energy Information Agency, EFDA)

External costs, electricity production



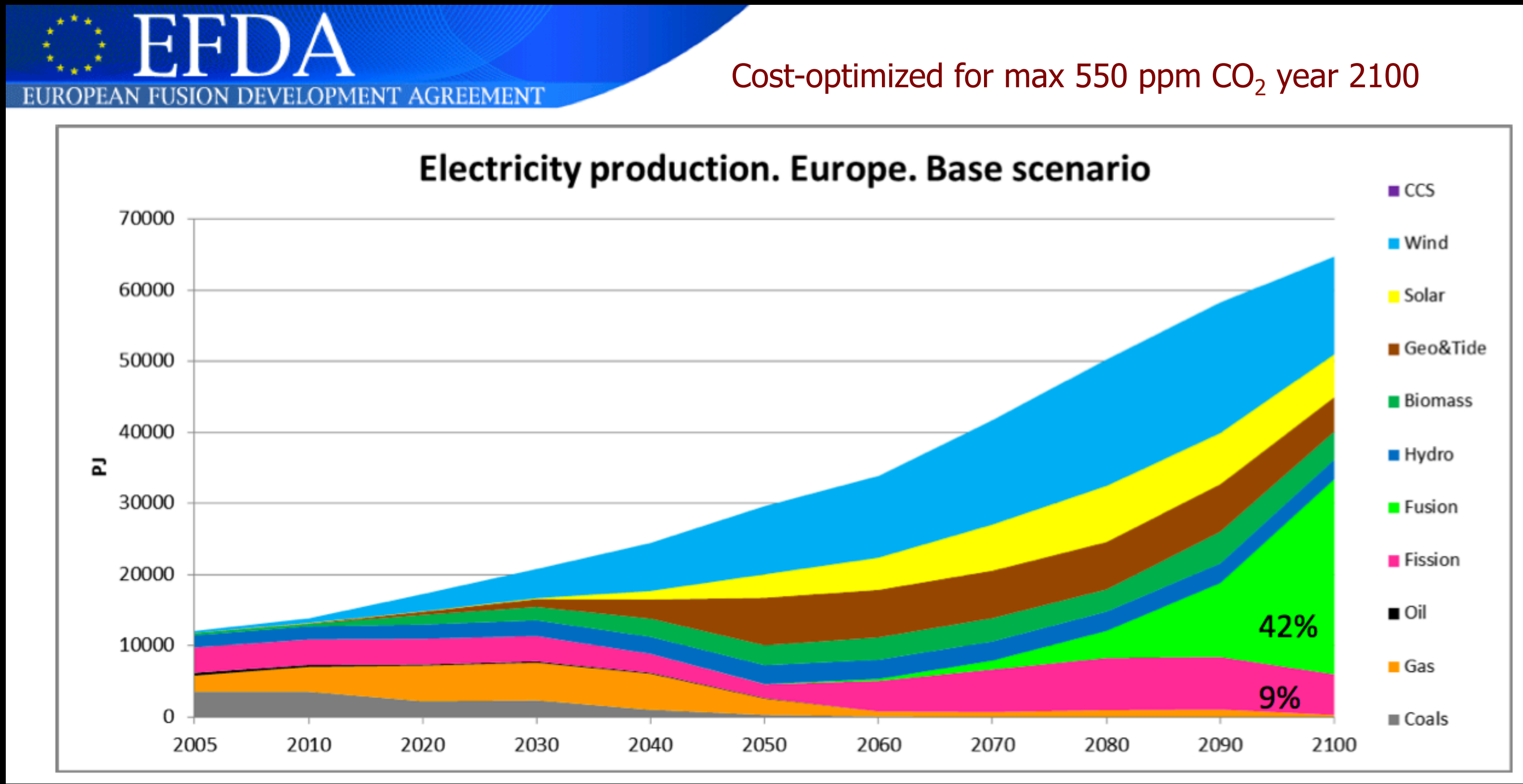
External costs: greenhouse gas effects on environment, pollution, waste management, radioactivity, accidents.

Only windpower has lower external costs than fusion!

From EFDA SERF-study (2007)

Conclusions

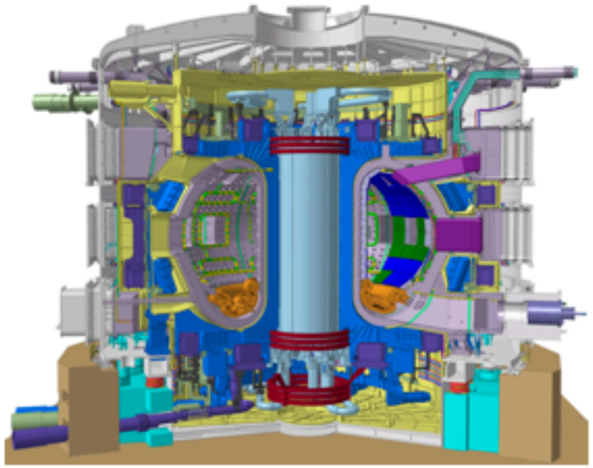
Fusion energy is needed
- and is on its way



- **Unique sustainable and clean base load power that, with renewables, can phase out fossil fuels**
- **Fuel for millions of years, over the whole planet**
- **Good economy when external costs are included**

ENERGY AND FUSION RESEARCH - AN INTRODUCTORY COURSE

This introductory course will present the state of today's fusion research and provide insight into the physics and technology of fusion.



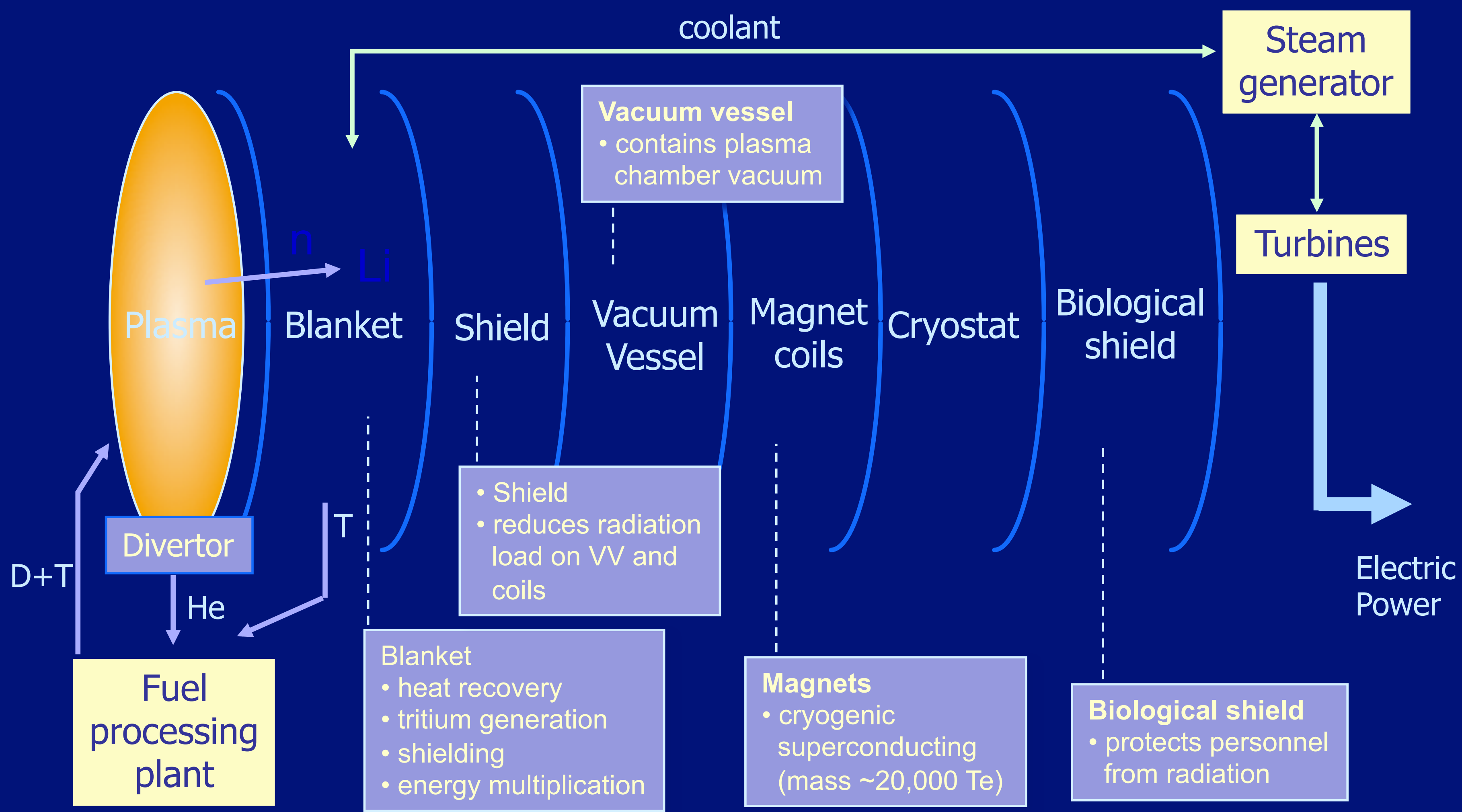
The development of fusion has now reached a state when it may be said that fusion power will indeed be realized. In this course, different solutions to "the greatest technological challenge ever pursued" will be presented.

As a background, we will discuss the energy problems that threat to become critical towards the mid-century, unless new energy sources are developed. Comparisons with the non-fossil energy sources that are known today will be made.

That was all,

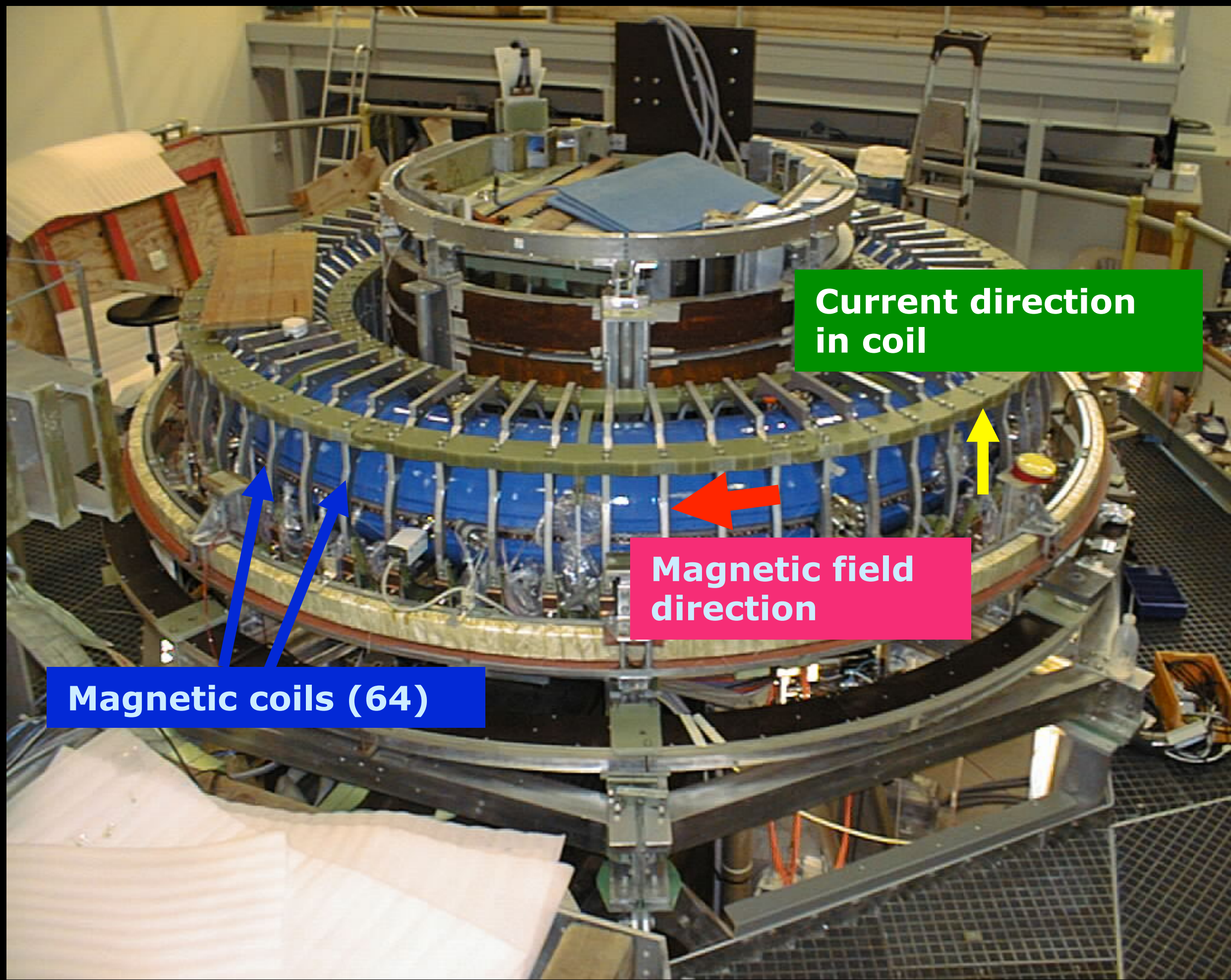
thank you!

Fusion Power Plant operation

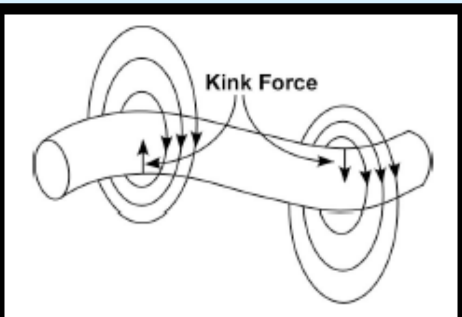


UKAEA

Magnetic coils for plasma confinement

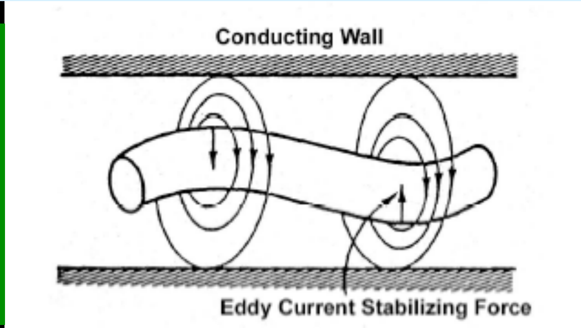


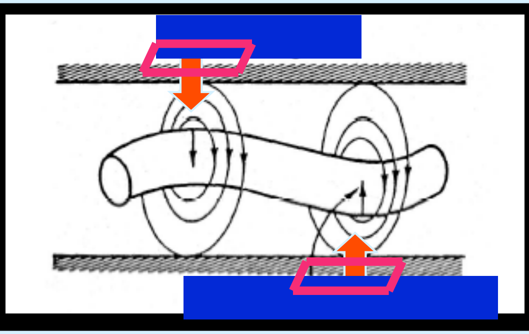
Plasma instabilities
- and feedback stabilisation



1. Plasma instability: small perturbations lead to growing deformations

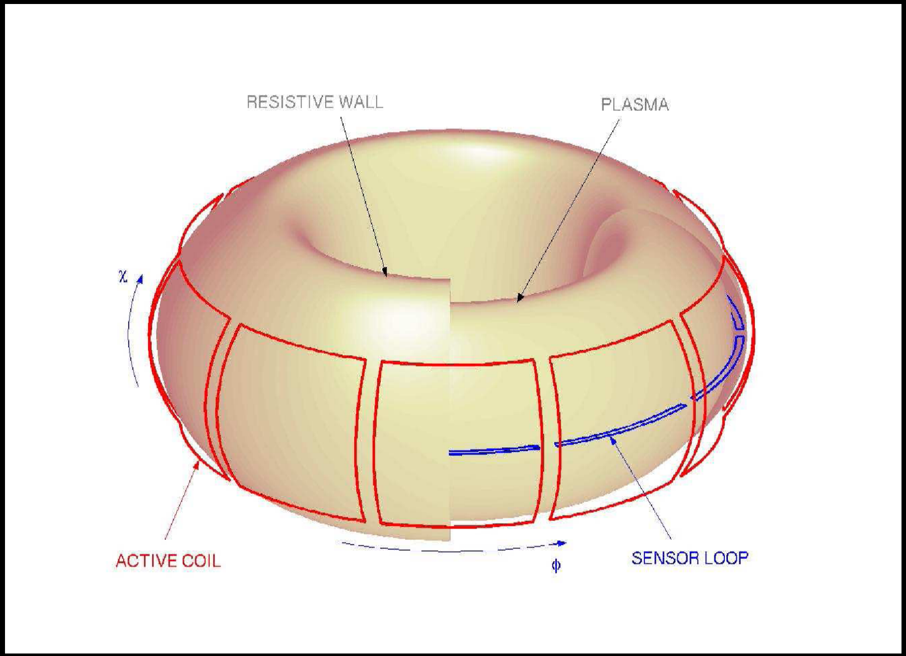
2. Passive stabilisation: an electrically conducting shell confines the magnetic field and provides damping of the perturbation by the magnetic pressure at the wall

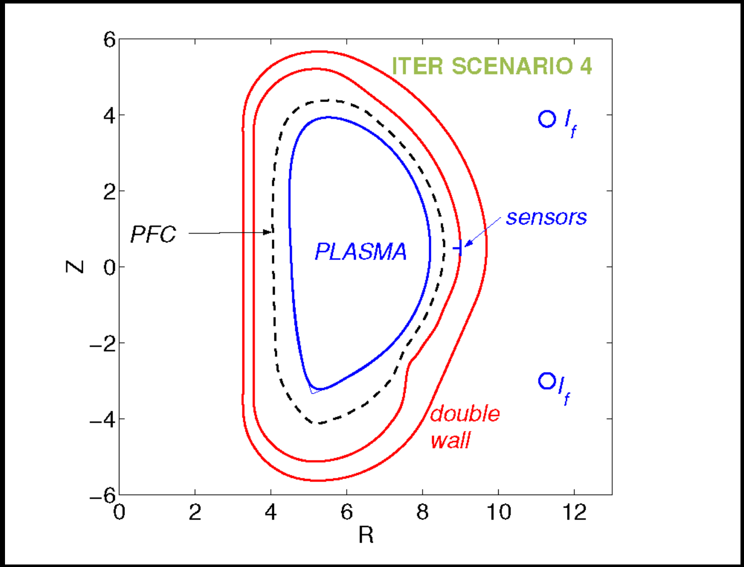




3. Active stabilisation: The perturbation can be completely damped when the shell is combined with outer magnetic coils that provide magnetic return forces on the plasma

Potential for ITER

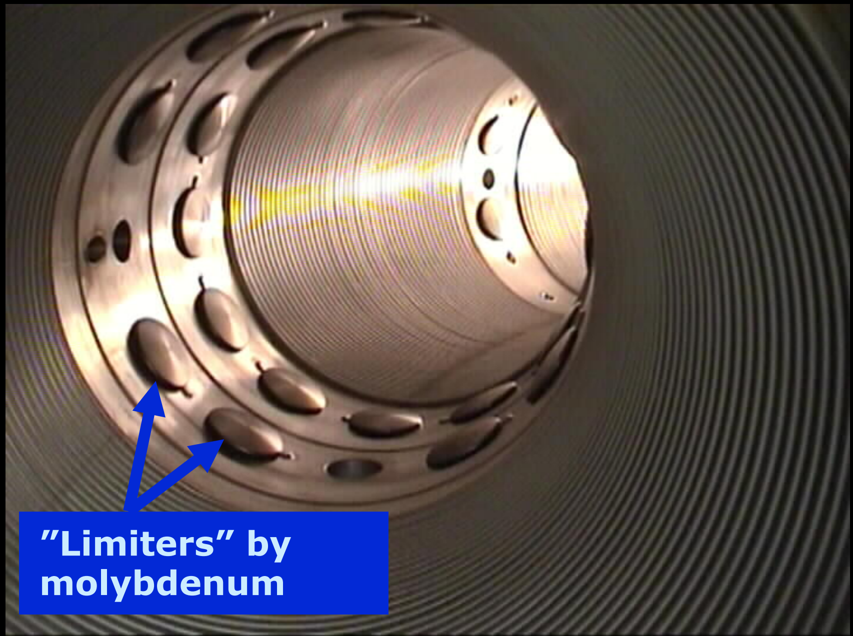


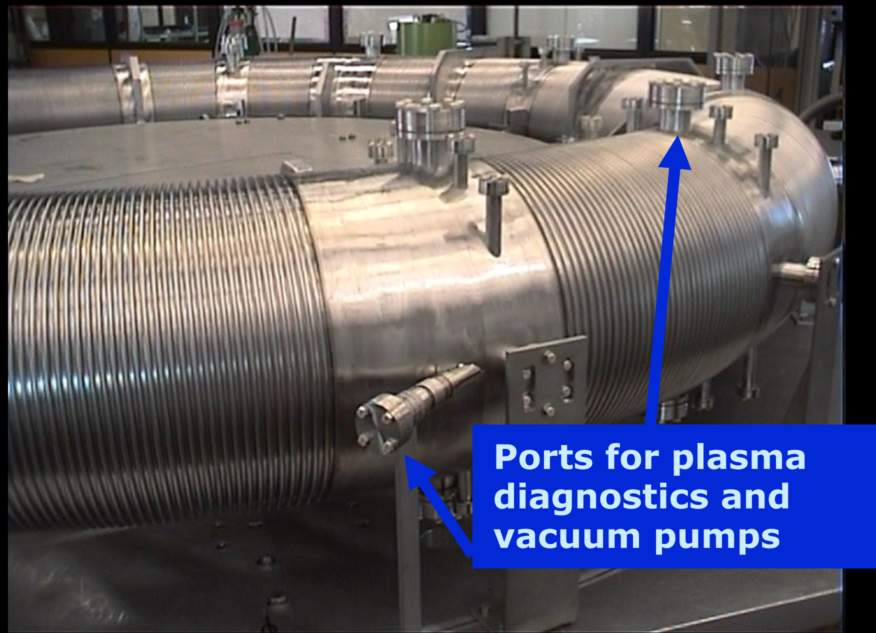


- Active plasma control in ITER can improve plasma stability
- Higher plasma pressure can be confined
  => more fusion reactions per second results.

Vacuum chamber

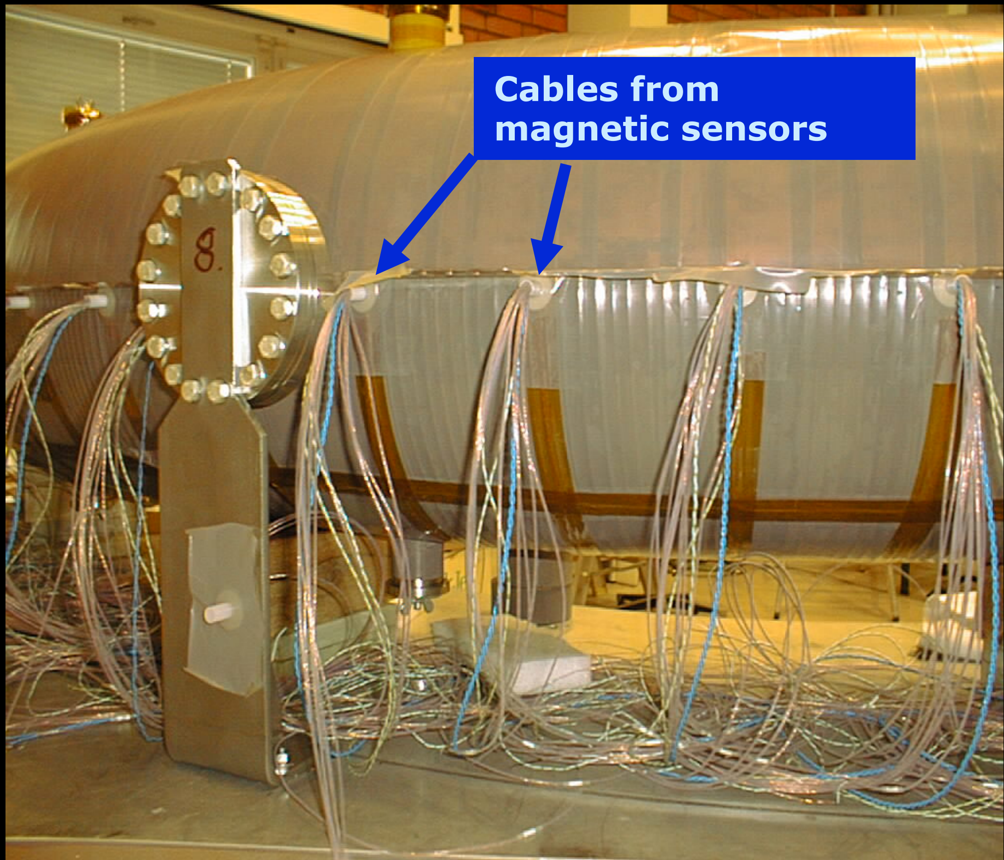
The vacuum chamber is made of stainless steel - as a thin-shell, ring-shaped bellow





Plasma – wall interaction is minimized by ”limiters” by molybdenum, ”catching” the heat flow from the plasma

Sensors for magnetic field mesurements

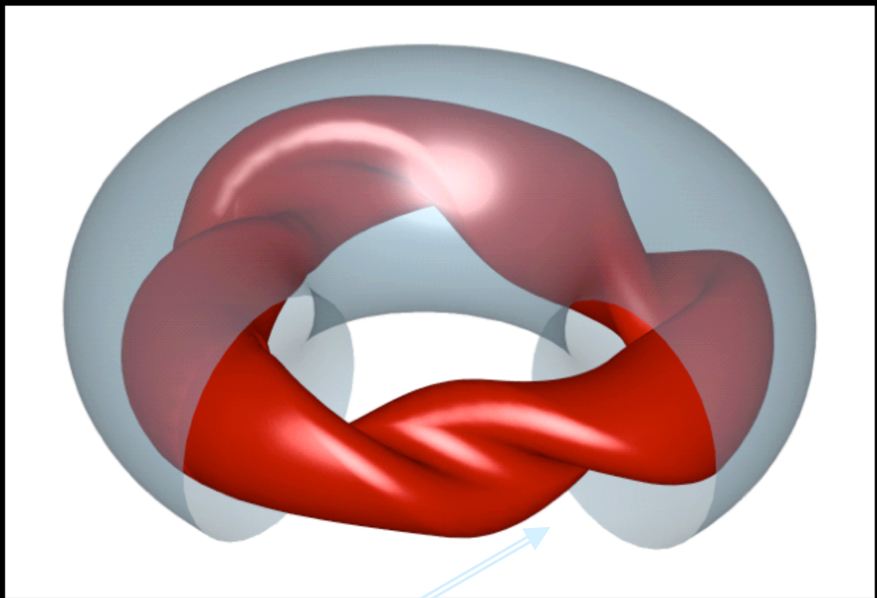


Some 900 magnetic field sensors (electrically insulated)

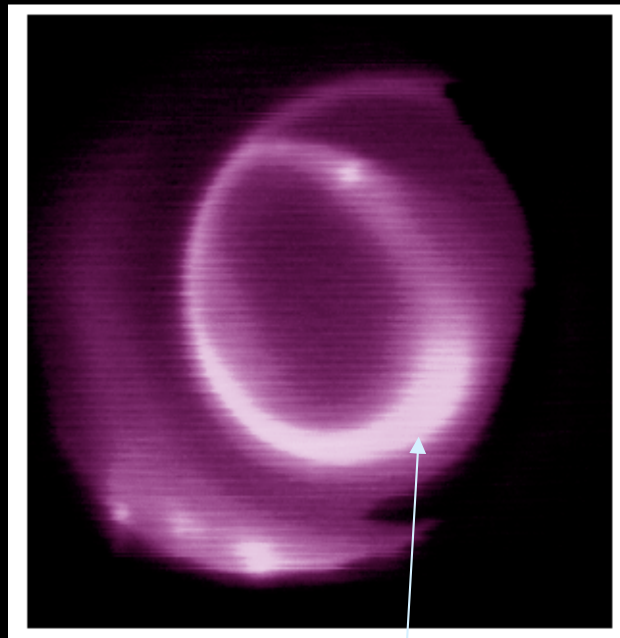
Placed on outside of vacuum chamber

Plasma perturbation in EXTRAP T2R

The plasma deformation
grows in time
(exaggerated here)



Camera view for
picture at the right



Experiment, showing light
from parts of wall that are
in contact with the plasma