EUROPEAN COMMISSION

Community research

FUSION RESEARCH

An Energy Option for Europe's Future

GENERAL INFORMATION

EURATOM

Interested in European research?

RTD info is our quarterly magazine keeping you in touch with main developments (results, programmes, events, etc.).
It is available in English, French and German. A free sample copy or free subscription can be obtained from:

European Commission
Directorate-General for Research
Information and Communication Unit
B-1049 Brussels
Fax (32-2) 29-58220
E-mail: research@cec.eu.int
Internet: http://europa.eu.int/comm/research/rtdinfo/index_en.html

EUROPEAN COMMISSION

Directorate-General for Research
Directorate J - Energy
Unit J6 Fusion Association Agreements

Contact: Hugues Desmedt

European Commission

Office MO75 00/31

B-1049 Brussels

Tel. (32-2) 29-98987

Fax (32-2) 29-64252

E-mail: hugues.desmedt@cec.eu.int

EUROPEAN COMMISSION

FUSION RESEARCH

An Energy Option for Europe's Future

2004

Directorate-General for Research
Fusion energy research

Europe Direct is a service to help you find answers
to your questions about the European Union

Freephone number:
00 800 6 7 8 9 10 11

A great deal of additional information on the European Union is available on the Internet. It can be accessed through the Europa server (http://europa.eu.int).

Cataloguing data can be found at the end of this publication.

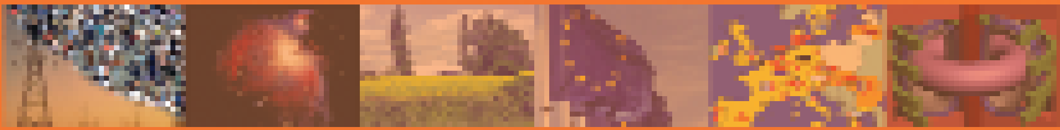
Luxembourg: Office for Official Publications of the European Communities, 2004

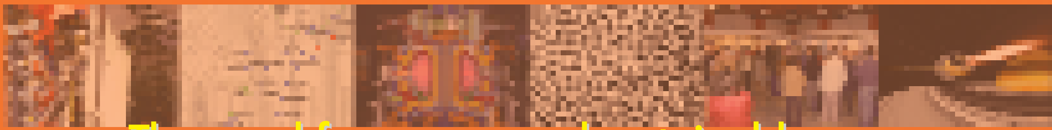
ISBN 92-894-7714-8

Printed in Belgium

PRINTED ON WHITE CHLORINE-FREE PAPER

Contents





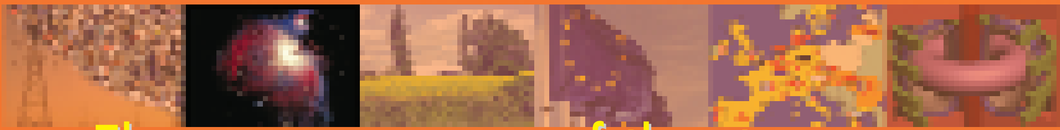
The need for secure and sustainable energy

The European Union (EU) economy depends on a secure and sufficient supply of energy. Today this demand is mainly satisfied by fossil fuels (oil, coal and natural gas), which account for 80% of the total energy consumption. Almost 67% of the fossil fuels we use are imported. Overall, imported fossil fuels currently provide about 50% of the EU's energy needs, and by 2030 this is expected to increase to about 70%, in particular from oil.

Secure and sustainable energy sources are required to maintain our standard of living. European researchers are developing a range of environmentally acceptable, safe and sustainable energy technologies. Fusion is one of them.

For the long term, fusion will provide an option for a large scale energy source that has a low impact on the environment and is safe, with vast and widely distributed fuel reserves.

This booklet describes the work being carried out by European researchers to realise the objective of making fusion energy available for the benefit of society.

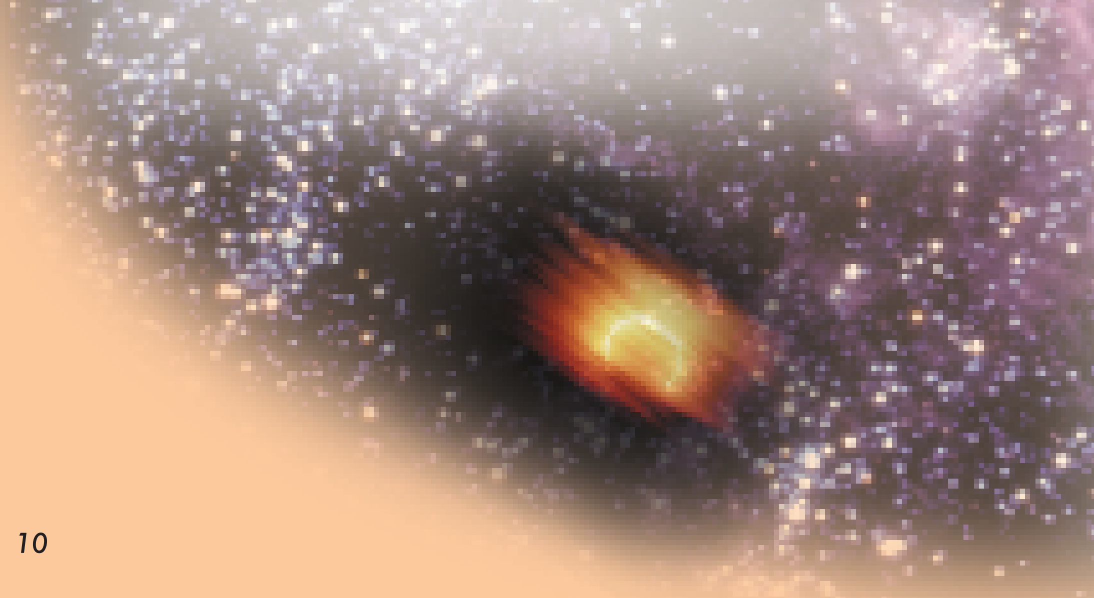


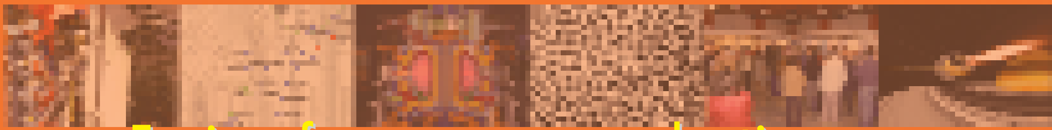
The energy source of the stars

Fusion is the process which powers the sun and other stars. Nuclei of low mass atoms "fuse" together and release energy. In the core of the sun, the huge gravitational pressure allows this to happen at temperatures of around 10 million degrees Celsius.

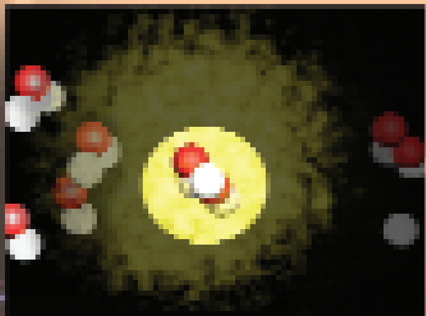
At the much lower pressures (10 billion times less in the sun) that we can produce on earth, temperatures above 100 million degrees Celsius are required for fusion energy production rates of interest.

Gas raised to these temperatures becomes a "plasma", where the electrons are completely separated from the atomic nuclei (ions). Plasma is the fourth state of matter with its own special properties. The study of these properties is the focus of plasma physics research. Although the plasma state is exotic on Earth, more than 99 % of the universe is made up of plasma.



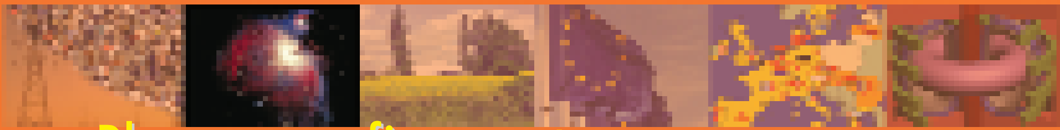


Fusion for energy production



The fusion reactions between two isotopes of hydrogen - deuterium (D) and tritium (T) - provide the basis for the development of a first generation fusion reactor, as other fusion reactions require even higher temperatures. Each reaction produces an alpha particle (i.e. helium) and a neutron with a high energy which can be used to heat the steam cycle of a power station for generating electricity. To supply a city with a population of about one million with electricity for one year, a fusion power plant would require a small truck-load of fuel.

Deuterium is a naturally occurring, non-radioactive isotope and can be extracted from water (on average 35 g in every cubic metre of water). The required non-naturally occurring tritium will be produced from lithium (a light and abundant metal) inside the fusion reactor. When a high energy fusion neutron strikes a lithium atom, tritium is produced and further energy is released. The tritium is recycled back into the reactor as fuel.

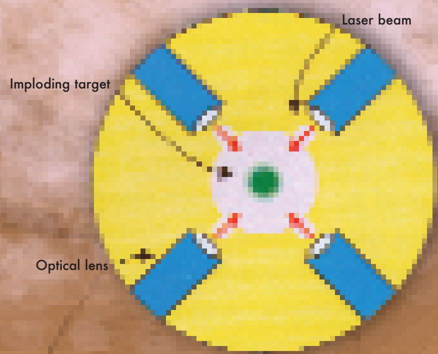


Plasma confinement

Magnetic confinement fusion

To reach temperatures of 100 million degrees Celsius, powerful heating of the plasma is required and the thermal losses must be minimised by keeping the hot plasma away from the walls of its container. This is achieved by placing the plasma in a toroidal "cage", made by strong magnetic fields which prevent the electrically charged plasma particles from escaping (the fusion neutron is not confined because it has no electrical charge). This is called "toroidal magnetic confinement fusion". It is the most advanced technology and forms the basis for the European fusion programme.

A different approach is used in the so-called "inertial confinement fusion". Here, ultra high power lasers or ion beams compress and heat a very small D-T pellet to about 10,000 times solid density, until fusion reactions occur. The European fusion programme maintains a watching brief on this field.



Inertial confinement fusion

Safety aspects of fusion

A fusion reactor is like a gas burner: the fuel which is injected in the system is burnt. There is very little fuel in the reaction chamber (about 1 g of D-T in a volume of 1,000 m^3) at any single moment and, if the fuel supply is interrupted, the fusion reactions last for only a few seconds. Any malfunction of the device would cause the plasma to cool and the reactions to stop.

The basic fusion fuels, deuterium and lithium, as well as the reaction product, helium, are non-radioactive. The radioactive intermediate fuel, tritium, is produced as it is needed to maintain the fusion process in the reactor chamber. Therefore, with a fusion power plant there is no need for the regular transport of radioactive fuel.

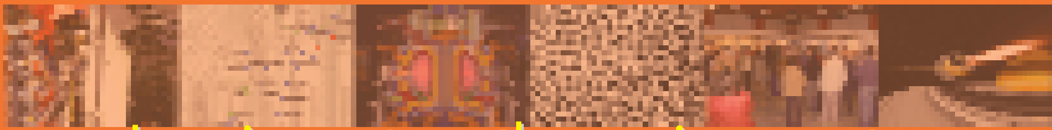
Safety aspects of fusion (continued)

Tritium Handling Facility

Tritium decays quite quickly (it has a half-life of 12.6 years) and the decay produces an electron (beta radiation) of very low energy. In air, this electron can travel only a few millimetres and cannot even penetrate a sheet of paper. Nevertheless, tritium is harmful if it enters the body and so the proper safety features are designed into the fusion power plant.

A fusion reactor can be designed such that the "worst case" scenarios of any in-plant accident will not require the evacuation of nearby population.

European Tokamak Facility JET (Culham-UK)



Low impact on the environment

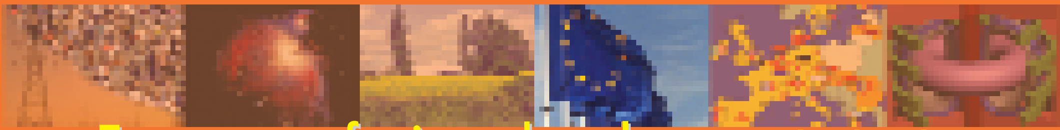
Fusion power stations will differ from today's power plants mainly in the reactor core. The energy generated by the fusion reactions will be used in the same way as today, e.g. for the generation of electricity and as heat for industrial use.

The fuel consumption of a fusion power station will be extremely low. A 1 GW electric fusion plant will need about 100 kg deuterium and 3 tons of natural lithium to operate for a whole year generating about 7 billion kWh. A coal fired power plant would require about 1.5 million tons of fuel to generate the same energy!

Fusion reactors do not produce greenhouse gases and other pollutants which can harm the environment and/or cause climate change.

The neutrons generated by the fusion reaction activate the materials around the plasma. A careful choice of the materials used for these components will allow them to be either cleared from regulatory control, or recycled about 100 years after the end of operation. For these reasons, waste from fusion plants will not be a burden for future generations.

Fusion power stations will be particularly suited for base load energy generation to serve the needs of densely populated areas and industrial zones. They can also produce hydrogen for a "hydrogen economy".



European fusion development strategy

The long-term objective of fusion R&D in the Member States of the European Union (plus countries associated to the Euratom Framework Programme) is "the joint creation of prototype reactors for power stations to meet the needs of society: operational safety, environmental compatibility, economic viability".

The strategy to achieve this long-term objective includes the development of an experimental reactor ("Next Step") which is pursued in the international "ITER" collaboration, followed by a demonstration reactor ("DEMO"), which for the first time would be able to generate significant amounts of electricity and would be tritium self-sufficient. The construction of ITER, and later DEMO, will require the significant involvement of European industry and will be accompanied by complementary physics and technology R&D activities in the fusion laboratories and in universities.

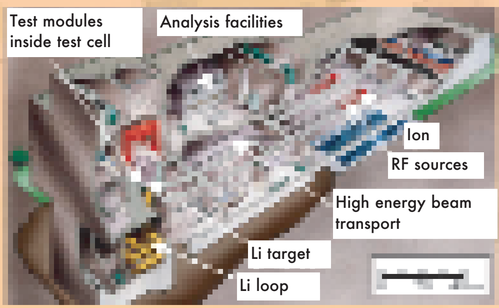
Participation (with international partners) in the design of the ITER device has been an important element of the European fusion research programme in recent years. The basic outline of this design follows that of the European JET device (Joint European Torus, Culham, UK), which achieved world record results with 16 MW of fusion power in 1997. The extrapolation to ITER is undertaken by extensive modelling using the comprehensive experimental data base from European and international fusion experiments.

Schematic of ITER

The ITER collaboration is carried out under the auspices of the International Atomic Energy Agency (IAEA, Vienna - A). The overall strategic objective of ITER is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.

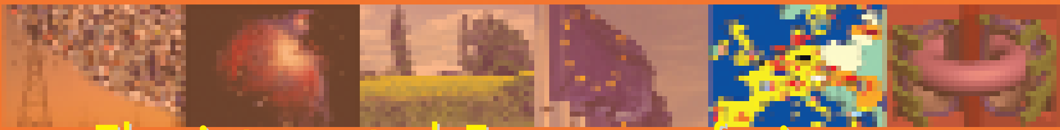
In parallel to ITER, work for DEMO is undertaken on R&D issues which have long lead times. One important objective is the development of advanced structural materials (in particular with low activation qualities) which are optimised for fusion reactor conditions.

Artist impression of the European site for ITER at Cadarache - F



Conceptual design of IFMIF

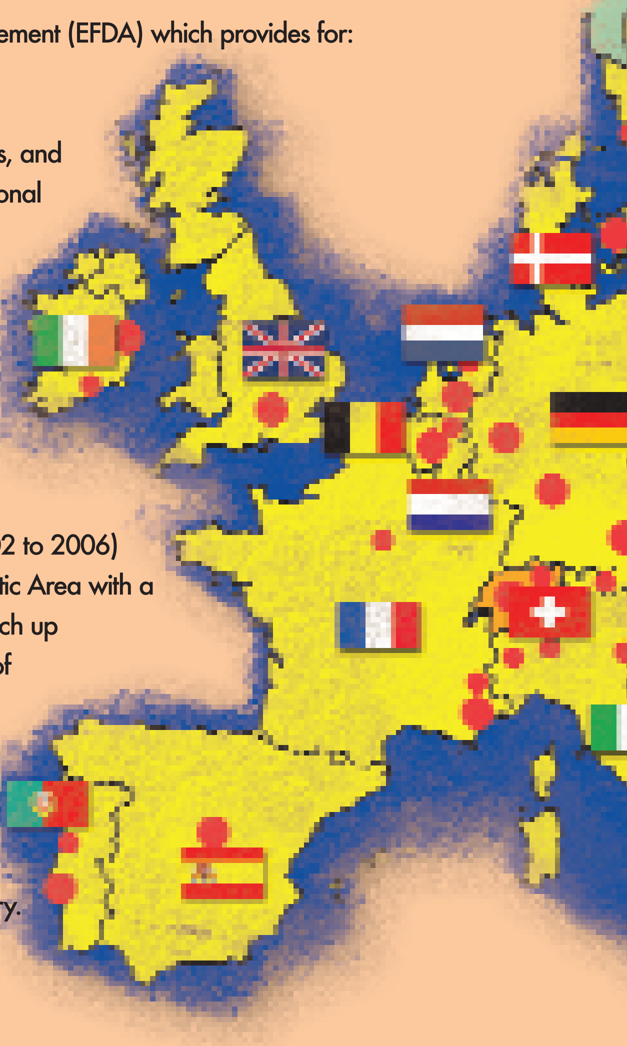
The qualification and validation of such materials needs a specific test facility, such as IFMIF (the International Fusion Materials Irradiation Facility) for which a conceptual design has been established.



The integrated European fusion research programme

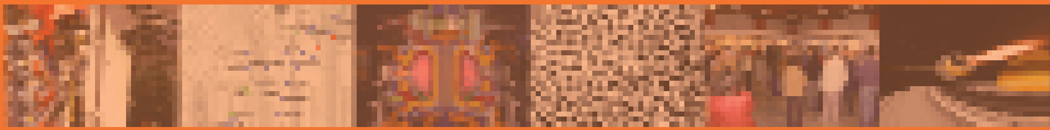
Based on the Euratom treaty, fusion research and development in Europe is co-ordinated by the European Commission and implemented through:

- Contracts of Association with research institutes or organisations in the Member States and countries associated to the Euratom Framework Programme (the Euratom Associations are represented in the map by red dots).
- The European Fusion Development Agreement (EFDA) which provides for:
  - Fusion technology activities by the Associations and industry,
  - the collective use of the JET facilities, and
  - European contributions to international collaborations such as ITER.
- Contracts of limited duration in countries which do not have a fusion "Association".
- An agreement for the promotion of mobility of researchers, and Euratom Fellowships.



In the 6th EU Framework Programme (2002 to 2006) Fusion Energy Research is a Priority Thematic Area with a Community budget of €750 million (of which up to €200 million may be used for the start of ITER construction).

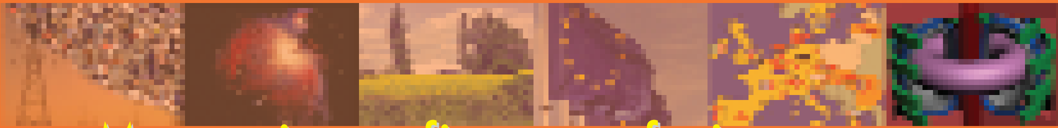
Behind the success of European fusion research stands the work of about 2,000 physicists and engineers in European associated laboratories and in European industry.



A key feature of the European fusion programme is its unique co-ordination which provides for an intensive use of all relevant R&D resources in pan-European collaborations on all the major research topics, in particular in the JET exploitation and in the technology programme of EFDA, which is strongly oriented towards ITER, but includes also work with a perspective towards DEMO.

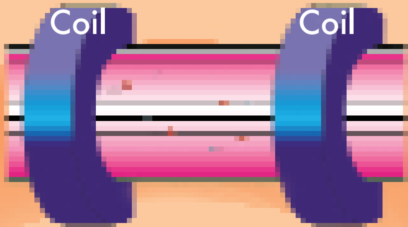
This single, co-ordinated fusion programme, with large and small laboratories directed towards a common programmatic objective, is an example of a European Research Area and has brought Europe to the forefront of international magnetic confinement fusion research. Achievements in Europe's associated fusion laboratories have enabled the construction of JET and progress towards ITER, which none of the Member States or Associated States would have been able to achieve alone.

Besides the major international collaboration on ITER, Implementing Agreements in the frame of the International Energy Agency (IEA, Paris - F) serve as a framework for collaborations with non-European partners to pool the best world expertise on specific topics of common interest. The same objective is also pursued with a number of bilateral and multilateral agreements for collaborations between European and non-European laboratories.



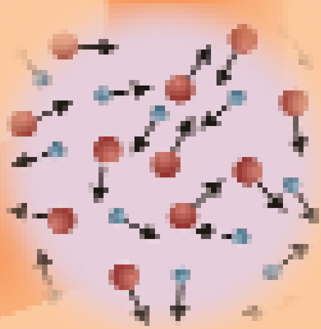
Magnetic confinement fusion

Magnetic confinement fusion makes use of strong magnetic fields to confine the plasma in a "vacuum vessel" which isolates the plasma from air. In an idealised situation electrically charged ions and electrons which make up the plasma cannot cross the magnetic field lines.



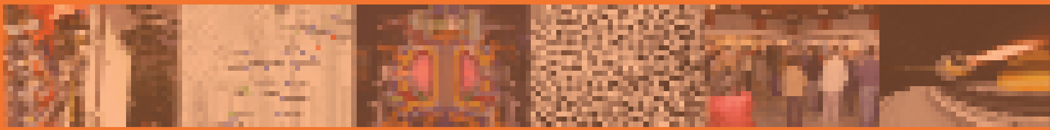
Plasma with magnetic field

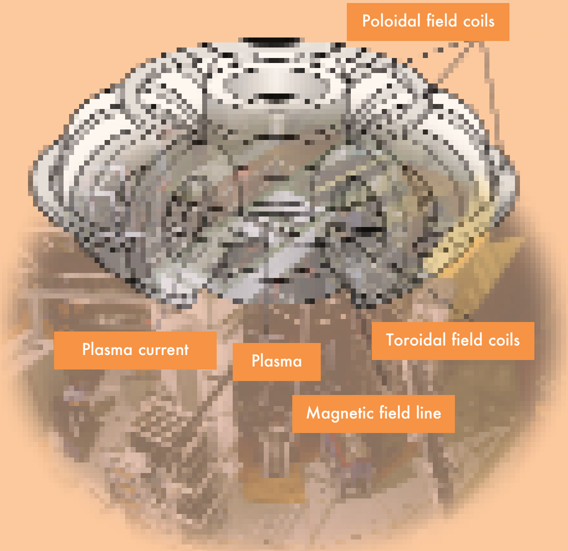
They can however move freely along the magnetic field lines. By bending the field lines around to form a closed loop, the plasma particles are, in principle, confined. Particles and their energy are kept well isolated from the wall of the burn chamber, thus maintaining the high temperature. In fact, in a real toroidal magnetic system there are losses of energy through various processes, such as radiation, and by particle collisions which cause particles to escape from the plasma across the magnetic field lines as time goes by.



Plasma without magnetic field

The magnetic fields are generated by large electrical currents flowing in coils located outside the reactor chamber. Frequently, currents generated in the plasma also contribute to the magnetic cage.





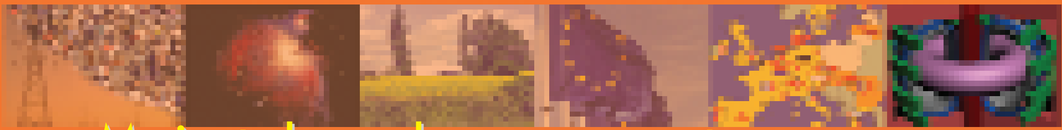
Schematic of tokamak

In the type of machine called the "tokamak", the plasma acts as the secondary winding of a transformer (the primary winding is an external coil) and a change of current in the primary winding induces a current in the plasma. As well as generating a magnetic field which plays a role in confining the plasma, this current also provides some heating, because of the plasma's electrical resistance.

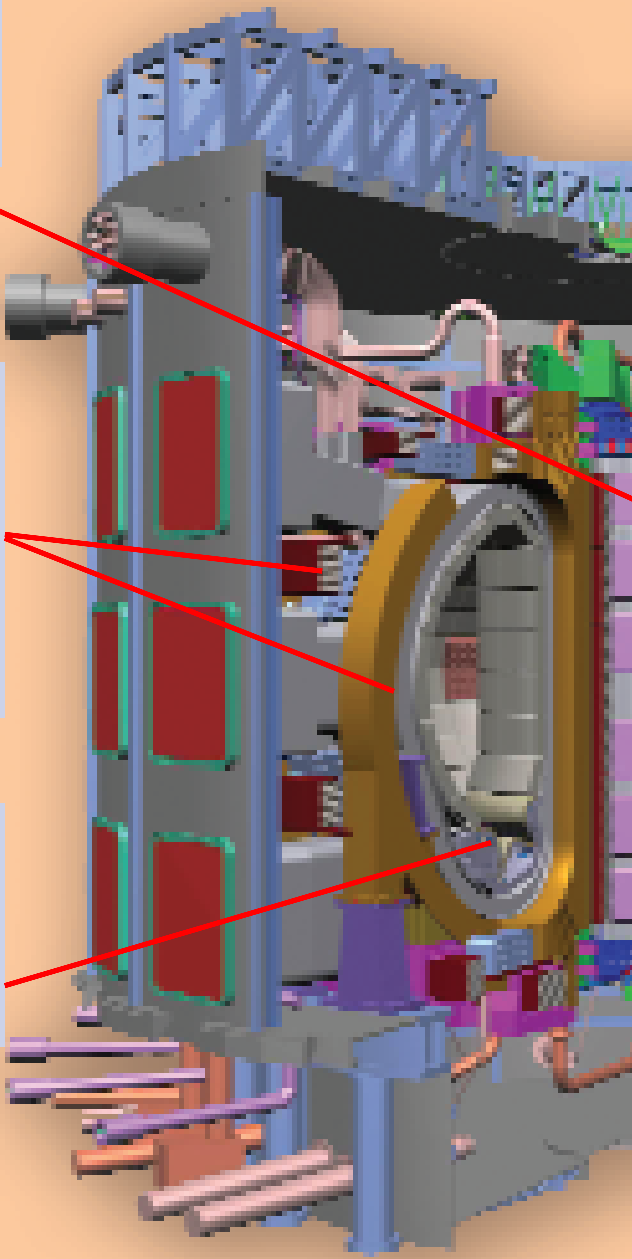
Since a transformer cannot generate a current continuously, the plasma current must be sustained by other means in order to achieve steady-state operation.

The type of machine called the "stellarator" uses the same principle of magnetic confinement, but by employing external coils of a complex shape it does not require a current to flow in the plasma. Stellarators therefore have an inherent potential for continuous operation.

Schematic of stellarator



Main tokamak components



Central solenoid

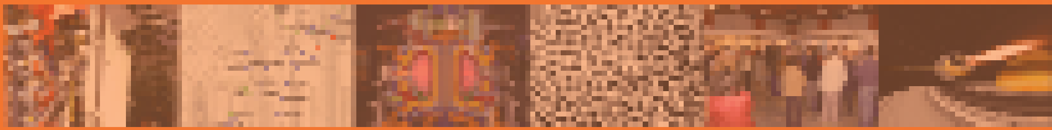
The primary circuit of the transformer. The plasma forms the secondary circuit.

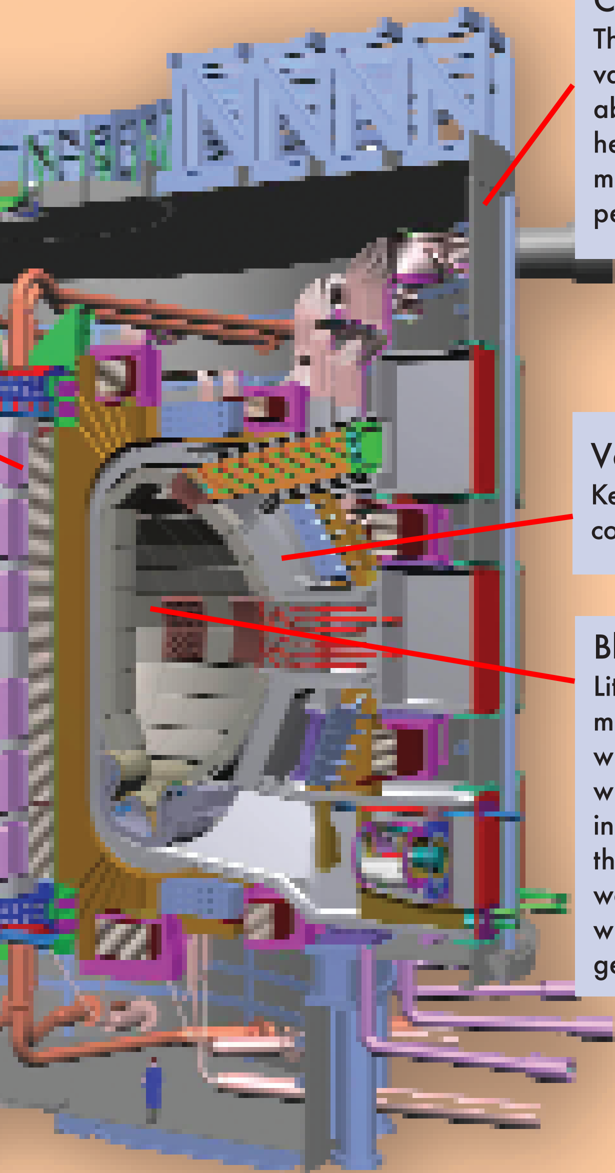
Toroidal field coils and poloidal field coils

These generate the strong magnetic field (typically about 5 tesla, which is about 100,000 times the earth's magnetic field) that confines the plasma and stops it touching the walls of the vacuum vessel.

Divertor

Removes the impurities and He from the vacuum vessel and is the only area were the plasma is deliberately allowed to touch the walls.





Cryostat

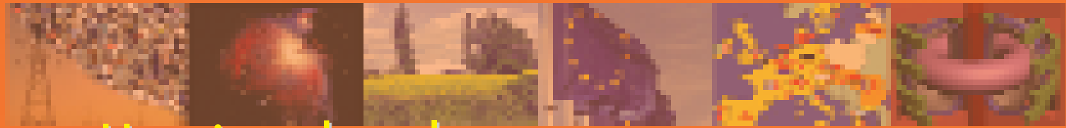
This encloses the coils and the vacuum vessel and is cooled to about -200 degrees Celsius to help keep the superconducting magnets at their operating temperature of -269 degrees Celsius.

Vacuum vessel

Keeps air from penetrating the containment region of the plasma.

Blanket module

Lithium is contained in the blanket modules. When neutrons react with lithium, tritium is produced which can be separated and fed into the plasma. The energy of the neutrons is removed to heat a water circuit and produce steam which will power the electrical generators.



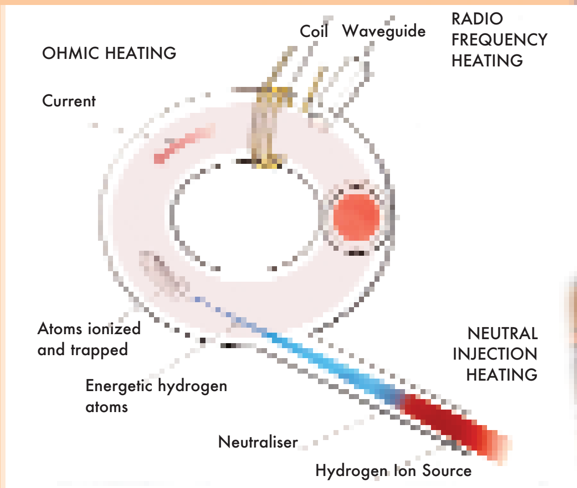
Heating the plasma

The current flowing in a tokamak plasma contributes to its heating. As the plasma temperature increases, this ohmic heating becomes less effective and brings the plasma only to temperatures of a few millions of degrees, i.e. about 10 times too low for the fusion reactions to occur in large numbers. To go higher, further heating is supplied through external sources.

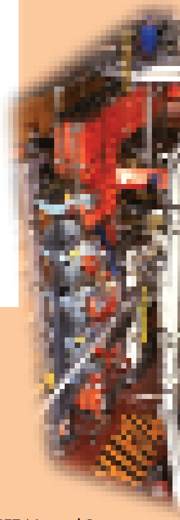
High-frequency heating uses high-power electromagnetic waves of different frequencies which transfer their energy to the plasma through resonant absorption.

Radio frequency antenna at Tore Supra (CEA, Cadarache - F)

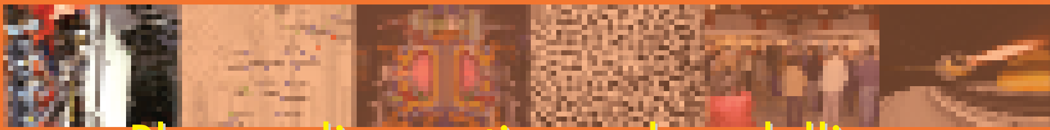
Three of these systems are being developed: Ion Cyclotron Resonance Heating (20 MHz to 55 MHz), Electron Cyclotron Resonance Heating (100-200 GHz, basically microwaves), and Lower Hybrid Heating (1-8 GHz).



Beams of energetic neutral particles are injected into the plasma, penetrate it, and transfer their kinetic energy to the plasma through collisions with the plasma particles.



JET Neutral Beam system

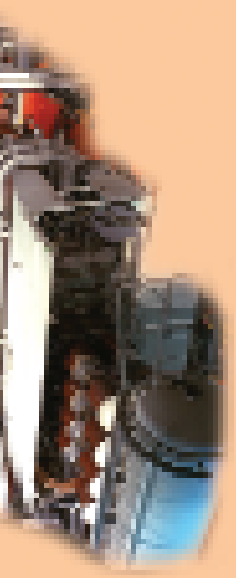


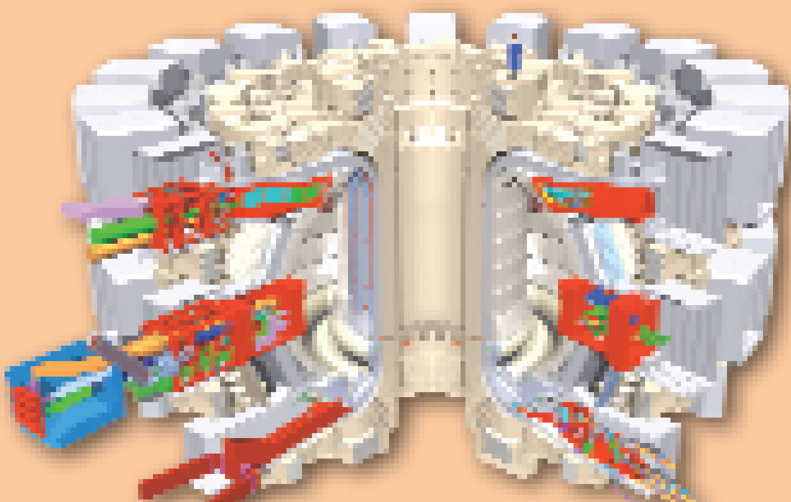
Plasma diagnostics and modelling

To understand how to design a fusion reactor it is necessary to understand the processes that are happening in the plasma. This requires sophisticated and complex measurement systems, which are referred to as diagnostics.

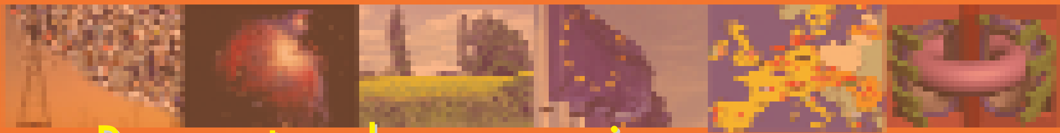
Diagnostics are being developed in European laboratories to monitor every aspect of the plasma from the temperature at the centre of the plasma, using very powerful lasers, to the amount of impurities in the plasma and where they are produced.

The data obtained from these diagnostics are used in the development of new computer codes that will ultimately be able to predict the performance of the device and ensure that the device is operating as expected.



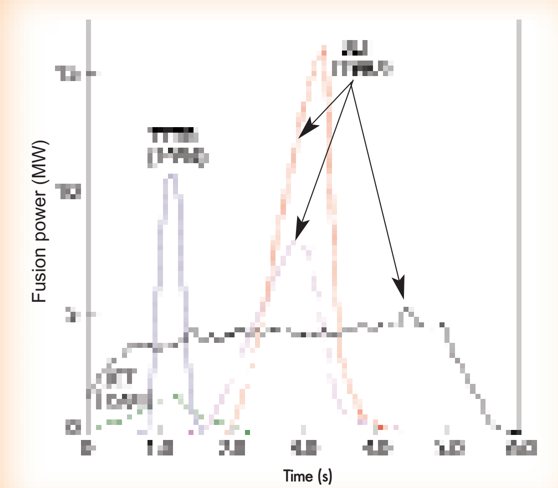


Schematic of ITER diagnostics



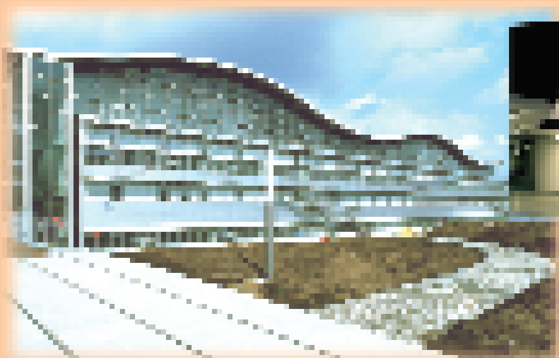
Recent advances in magnetic fusion

The European tokamak JET (Joint European Torus) located in Culham (UK) is the world's largest fusion facility and the only one currently capable of working with a D-T fuel mixture. JET has reached, or exceeded, all its original objectives and achieved the record generation of 16 MW of fusion power in 1997.



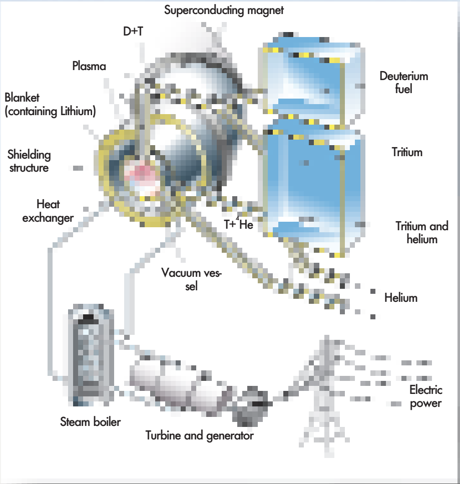
Fusion power achievements

Studies are also undertaken on a compact spherical variant of the tokamak and on the reversed field pinch. The largest new facility currently being constructed is the stellarator W 7-X in Greifswald (D).



IPP building (Wendelstein 7X) in Greifswald - D

The generation of fusion power



Skematic of future fusion reactor

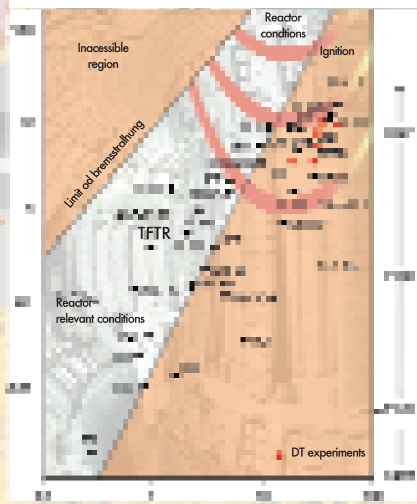
The high-energy helium nuclei (or alpha particles) generated by the D-T fusion reactions collide with other particles and heat the plasma. The neutrons released in the fusion reaction escape from the plasma and are slowed down in a "blanket" located around the plasma. Within this blanket lithium is transformed into tritium and the heat generated by the neutrons can be used to produce steam which drives turbines for electricity generation. When all plasma energy losses are compensated by alpha particle heating and no further external power is required, the plasma has reached a condition of self-sustained "burn", and requires essentially only fuel to be continuously fed to it.

A figure of merit, Q (the power amplification factor) is used to define the power gain of a fusion device.

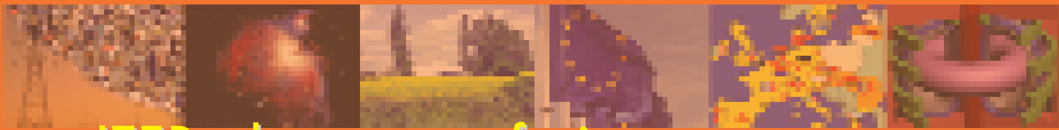
$$Q = \frac{\text{Power generated by fusion reactions}}{\text{Heating power injected}}$$

JET, has generated 16 MW of fusion power at Q = 0.65. The next machine, ITER, aims at Q = 10, while future fusion reactors may have Q values up to 40 or 50.

Progress of fusion research worldwide



Time (s)



ITER, the way to fusion energy

ITER is the next major milestone in the development of a nuclear fusion reactor.

The ITER project is based on an international collaboration. International plasma physicists and fusion engineers completed the design in 2001 and are now in the process of preparing for its implementation.

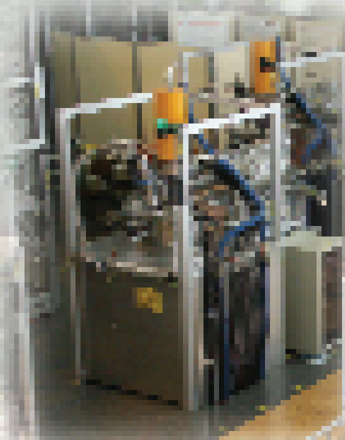
The overall programmatic objective of ITER is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes. ITER will accomplish this objective by demonstrating the controlled burn of deuterium-tritium plasmas, with steady state as an ultimate goal, and by demonstrating technologies essential for a reactor in an integrated system.

ITER will be capable of generating 400 MW of fusion power for a duration of 6 minutes, later to be extended towards steady state.

The capital cost of ITER amounts to about €4,6 billion (2000 values). Once agreement is reached among the international partners, construction of ITER will take 8 to 10 years and the device will then operate for a period of about 20 years.

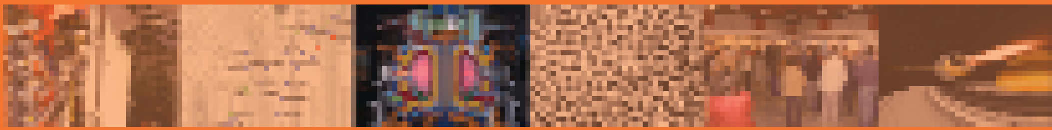
ITER is based on the scientific achievements of many machines around the world, with specific contributions from JET.

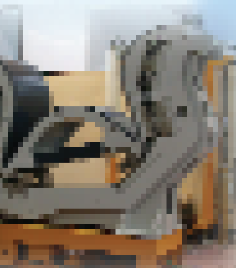
ITER divertor fu



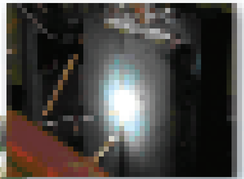
ITER Divertor remote handling test platform

Gyrotron High Frequency Microwave Source

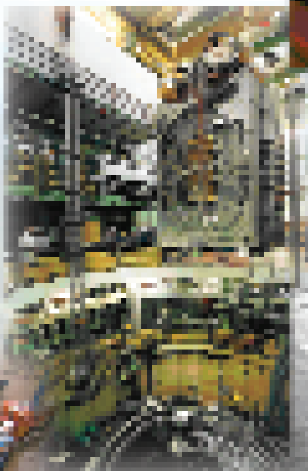


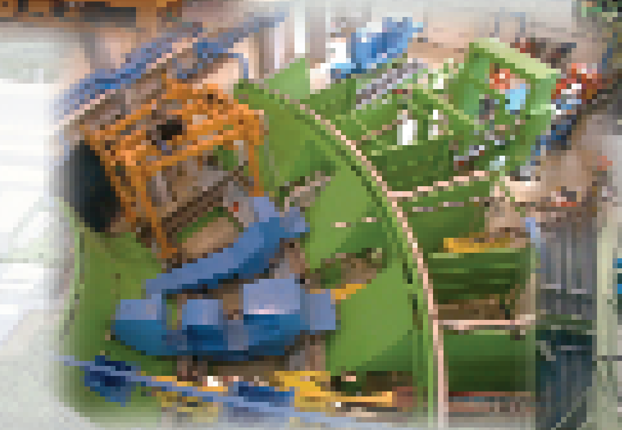


ull scale prototype

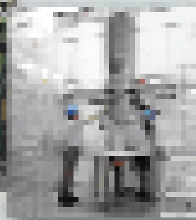


High power laser welding (11 kW) for vacuum vessel sectors

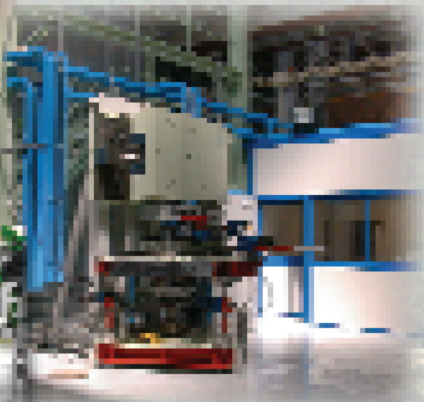


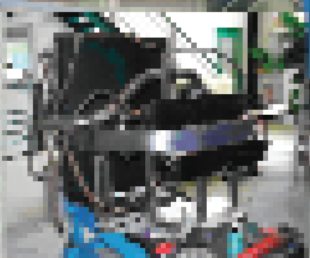


Testing on Toroidal Field model coil

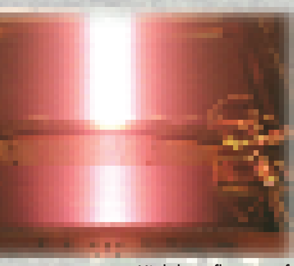


1 MW gyrotron





Blanket test facility



High heat flux test of protecting armour tiles

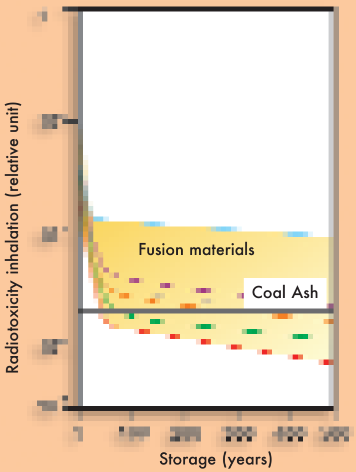
The full scale divertor vertical target mock-up tested at Framatome

Long-term technology activities

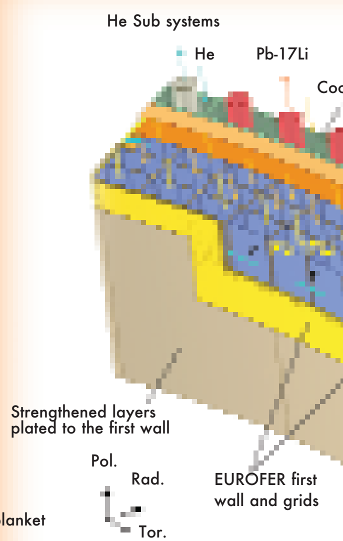
Apart from the work on ITER, there is much fusion technology research and development being carried out for DEMO. European breeding blanket studies concentrate on the use of helium-cooled lithium-lead (Pb-17Li) and on helium-cooled ceramic breeder pebbles. This research is critical for the development of the fusion reactor tritium cycle.

European structural materials development concentrates on reduced activation ferritic and martensitic steels (EUROFER) and, looking further ahead, is investigating silicon carbide composites.

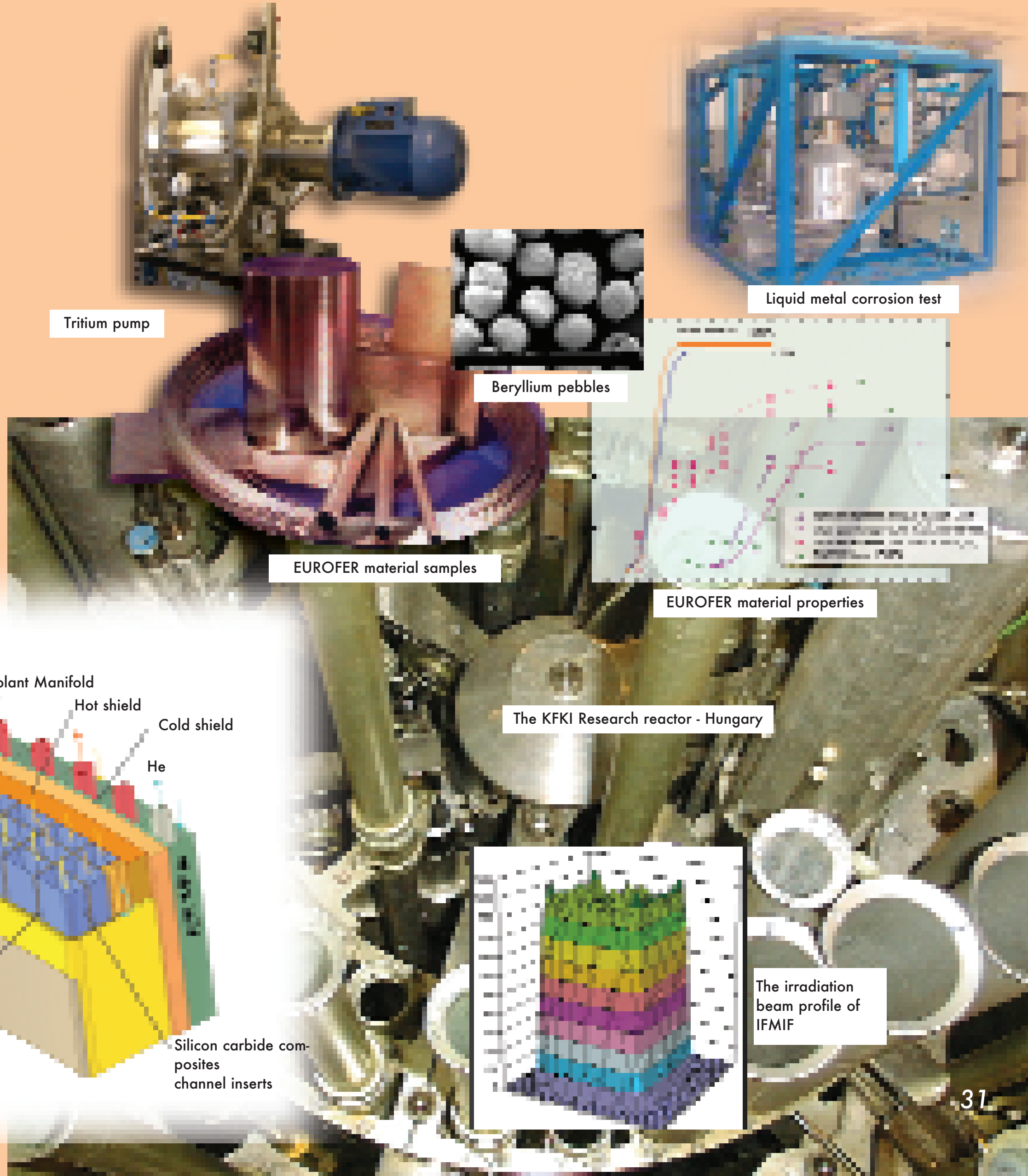
Safety and environmental questions are also tackled. These are mainly focused on improved concepts and the minimization of the activated materials. Socio-economic studies analyse economic aspects and long-term scenarios for fusion.



Calculated decay of radiotoxicity from different models of fusion power plants compared with the radiotoxicity of coal ash.



Concept for test blanket



Tritium pump

Liquid metal corrosion test

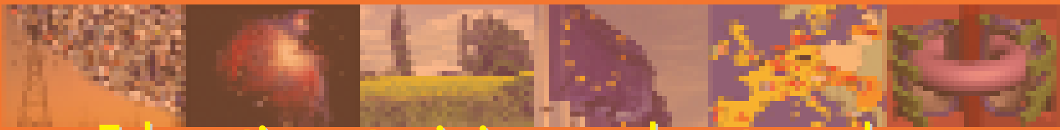
Beryllium pebbles

EUROFER material samples

EUROFER material properties

The KFKI Research reactor - Hungary

The irradiation beam profile of IFMIF



Education, training and outreach activities in Europe

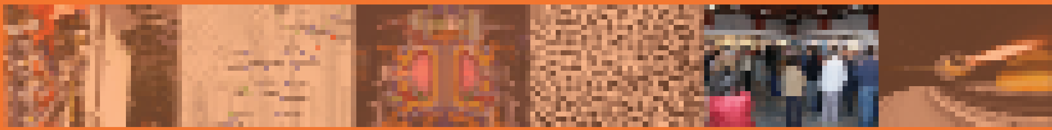
Education and training of young researchers is an important part of the work programme of the Associations. Many professional staff from the Associations have teaching responsibilities in academic institutions, mainly universities, and around 200 to 250 graduate and PhD students perform their research within the Association laboratories. Several Associations organise graduate courses and summer schools in fusion and plasma physics for graduate level students and recently graduated researchers.

The main summer schools organised by the Associations are:

- Carolus Magnus Summer School - The TEC group of Associations (B, D, NL),
- Culham Summer School - Association Euratom-UKAEA (UK),
- Volos Summer School - Association Euratom-Greece (GR),
- IPP CR Summer School - Association Euratom-Institute of Plasma Physics, (CZ).

An itinerant exhibition has been created and presented in many European cities to inform the general public and students about the fusion energy research activities in Europe.

Fusion Expo at Santander - Spain (Dec.2003)



Fusion Road Show

The Fusion Road Show, developed by the Association Euratom-FOM (NL), provides a good example of successful outreach activties undertaken by the fusion community. The road show consists of a series simple experiments to explain the basic principles linked together in an entertaining performance and accompanied by an explanatory presentation.

Through EFDA, the European fusion programme participate in EIROforum, a collaboration between seven European intergovernmental scientific research organisations that are responsible for infrastructures and laboratories. A primary goal of EIROforum is to play an active and constructive role in promoting the quality and impact of European Research. One specific aim is to co-ordinate the outreach activities of the organisations, including technology transfer and public education.

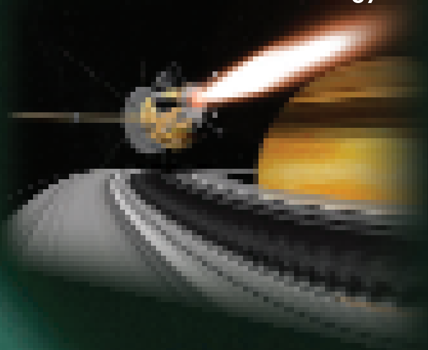
The seven EIROforum members are:

- CERN European Organisation for Nuclear Research,
- EFDA European Fusion Development Agreement,
- EMBL European Molecular Biology Laboratory,
- ESA European Space Agency,
- ESO European Southern Observatory,
- ESRF European Synchrotron Radiation Facility,
- ILL Institut Laue-Langevin.

Physics on Stage 3 - Teachers in action

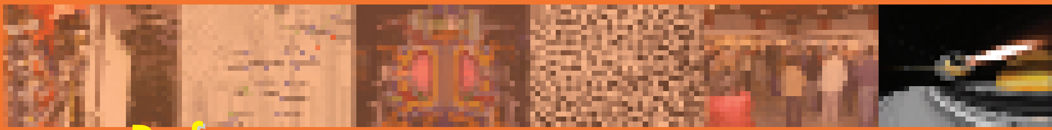
Fusion R&D spin-offs to other high-technology areas

Industry has been instrumental in helping to build devices and to develop the technologies needed in fusion R&D, and industry has benefited from this relationship by developing expertise and commercial products in various areas outside fusion. These spin-offs include plasma processing techniques, surface treatments, improved lighting, plasma displays, vacuum technology, power electronics and metallurgy.



Ion space motor

Knowledge transfer from fusion also occurs through researchers who move from the fusion research environment to other technology areas, bringing with them the skills they have developed in fusion. This kind of cross-fertilisation and interdisciplinarity is one of the important forces driving European scientific and technological progress.



References

Background reading:

" Towards a European Strategy for the Security of Energy Supply", Green Paper, European Commission, COM (2000) 769
http://europa.eu.int/comm/energy_transport/en/lpi_lv_en1.html

Relevant Websites:

http://europa.eu.int/comm/research/energy/fu/fu_en.html
http://www.efda.org
http://www.jet.efda.org
http://www.iter.org
http://www.fusion-eur.org
http://www.eiroforum.org

Contacts for further information:

C. Ibbott
European Commission
Directorate General RTD J6 Fusion Association Agreements
75 rue Montoyer B-1049 Brussels - Belgium
tel: +32 229 86721 - fax: +32 229 64252
e-mail: christopher.ibbott@cec.eu.int
http://europa.eu.int/comm/research/energy/fu/fu_en.html
+++
F. Casci
EFDA CSU Garching
Boltzmannstr.,2 D-85748 Garching bei Muenchen - Germany
tel: +49 89 3299 4237 - fax:+49 89 3299 4197
e-mail: federico.casci@efda.org - http://www.efda.org
+++
M.T. Orlando
Consorzio RFX - Management of Fusion EXPO
Corso Stati Uniti, 4, I-35127 Padova - Italy
tel: +39 049 829 5990 - fax: +39 049 829 5051
e-mail: mariateresa.orlando@igi.cnr.it - http://www.igi.pd.cnr.it

[illegible]

European Commission

Fusion Research An Energy Option for Europe's Future

Luxembourg: Office for Official Publications of the European Communities

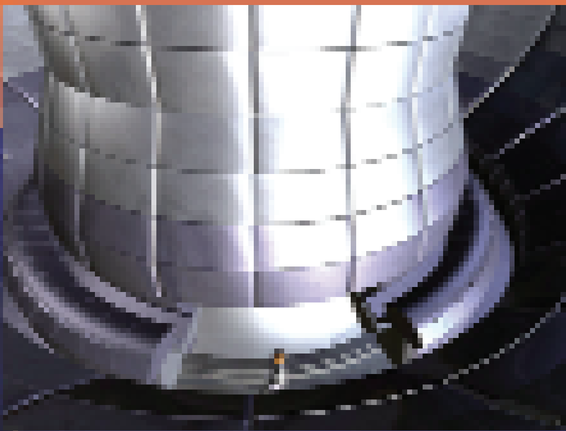
2004 — 40 pp. — format A5, 14,8 X 21.0 cm

ISBN 92-894-7714-8

About "The Starmakers"

The 8 minute "Starmakers" film describes ITER, a large experimental device that will be built in a world wide collaboration, as the "next step" on the route to fusion power. A virtual reality visit gives the audience a visual appreciation of this huge project. At the fusion EXPO, the movie, when viewed through passive polarised glasses, takes the audience on a spectacular 3D virtual reality journey. The version distributed here is 2D and does not require special glasses.

The movie has been produced by the Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne(CH), with financial support from the Directorate General for Research of the European Commission. The movie has been created numerically by Digital Studios SA (Paris -F) based on the computer aided design of the ITER device.



KI-60-04-256-EN-C

In its decision on the Euratom Specific Programme, the Council of Ministers said:
'Fusion energy could contribute in the second half of the century to the emission-free large-scale production of base-load electricity. The advances made in fusion energy research justify the further pursuit of a vigorous effort towards the long-term objective of a fusion power plant.'

This booklet describes fusion energy research and how it is co-ordinated and managed in Europe. The next generation fusion experiment, ITER, should pave the way in the second half of the 21st century for fusion to provide a significant contribution to the world's energy production.

The information in this booklet has been compiled from the research activities of the European fusion programme.

Publications Office
Publications.eu.int