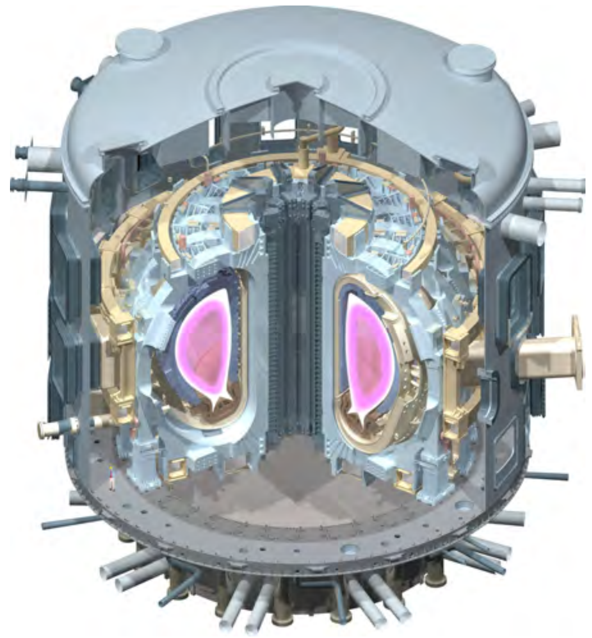
Nuclear Fusion – Status and Prospects

The ITER international experimental reactor will put fusion research on the way to demonstrating an energy-yielding plasma. In a world-wide cooperation the seven parties to the project involving Europe, Japan, Russia, USA, China, South Korea and India is being build ITER at Cadarache in France.


Graphic: ITER

The ITER international fusion test device in design (height: 30 metres)

Fusion conditions

The aim of fusion research is to utilise the energy source of the sun and stars here on earth: A fusion power plant is to derive energy from fusion of atomic nuclei. Under terrestrial conditions this can most readily be achieved with the two hydrogen isotopes, deuterium and tritium. These fuse to form helium, thus releasing neutrons and large quantities of energy: One gramme of fuel could yield in a power plant 90,000 kilowatt-hours of energy, i.e. the combustion heat derived from 11 tons of coal. The basic substances needed for the fusion process, viz. deuterium and lithium, from which tritium is produced in the power plant, are available throughout the world in almost inexhaustible quantities.

Like a coal fire, a fusion fire does not happen on its own, but only when the appropriate ignition conditions are present. As regards the fuel – a low-density, ionised gas, a "plasma" – it needs an ignition temperature of 100 million degrees. This high temperature precludes the plasma from being directly confined in material vessels. Any wall contact occurring would immediately cool the hot gas. Instead, use is made of magnetic fields which confine the fuel as thermal insulation and keep it away from the vessel walls.

The principle of deriving energy in this way was first realised in the JET (Joint European Torus) device at Culham, UK, the world's largest fusion experiment at present. It was jointly planned and built by Europe's fusion scientists and has also been jointly operated since 1983. All scientific and technical objectives specified in the planning have meanwhile been attained or even exceeded. In 1997 a transient fusion power of 16 megawatts was achieved. More than half the power needed to heat the plasma was regained through fusion.

However, the JET plasma with its volume of 80 cubic metres is too small to provide a net energy gain. This will be the role of the ITER (Latin for the "way") international experimental reactor. In its plasma volume of about 830 cubic metres a fusion power of 500 megawatts is to be produced, this being ten times as much as is needed to heat the plasma.

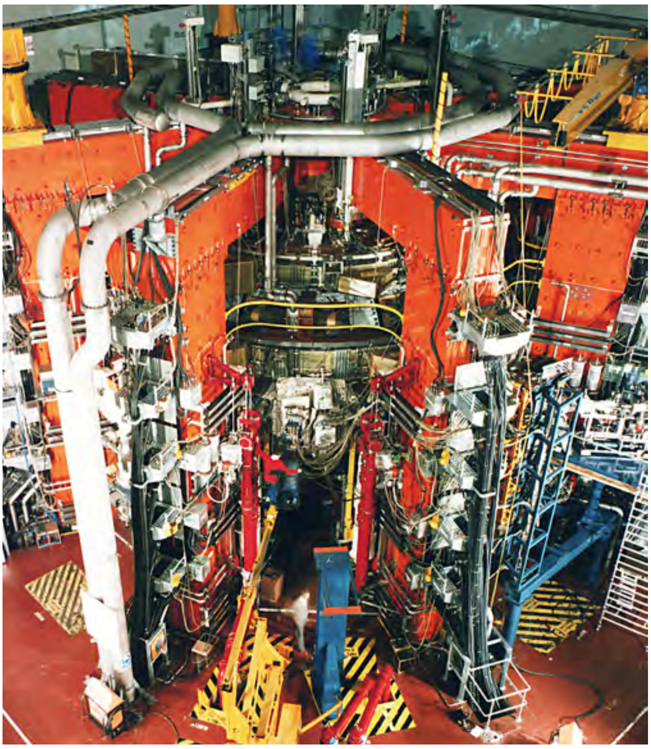


Photo: JET

The JET European joint experiment, the largest fusion experiment in the world


Photo: ITER

Full-size prototype of sector of the ITER plasma vessel, built in Japan according to the ITER design of 1998

The ITER international fusion test device

The ITER project was initiated in 1985 as a symbol of the ending of the Cold War in talks between the then Soviet Secretary-General, Gorbachev, and the Presidents of France and the USA, Mitterand and Reagan. In spring 1988, European, Japanese, Russian and, till 1997, US fusion scientists commenced with the planning work at Max-Planck-Institut für Plasmaphysik (IPP), Garching, as host laboratory.

After interruptions due to lengthy delays in reaching political decisions between the launching of the project, the design planning and the detailed planning, the construction plans at the meanwhile three ITER centres at Garching (Germany), Naka (Japan) and San Diego (USA) were completed in 2001. Essential components have been built as prototypes and tested. In 2003 China and South Korea joined the project; the USA also rejoined. After prolonged negotiations on the siting of the test device – in Japan or Europe – the partners agreed in 2005 to the European proposal: Cadarache in France. Shortly thereafter India joined the project.

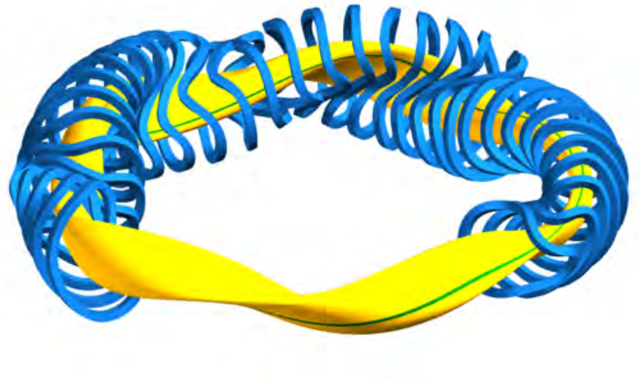
Negotiations on the legal and organisational structure of the project were completed in Oktober 2007 with the establishment of the international ITER Organisation. Meanwhile, the construction preparations have begun and the first industry contracts have been awarded. The contributions of the seven partners will be provided essentially in the form of finished components manufactured in the respective countries and then delivered to Cadarache. After a construction time of about ten years the first plasma is expected in 2019. Some 1000 scientists, engineers, technicians and other personnel will then work on the device for approx. twenty years.

The most widely operated devices: tokamaks

JET and ITER are fusion devices of the "tokamak" type, at present the most widely operated and best understood concept in the world. They generate their magnetic field cage partly with external magnet coils that encompass the plasma vessel. The rest is produced by an electric current flowing in the plasma that is induced there in pulsed mode by a transformer. Without auxiliary facilities tokamaks can therefore only operate in pulsed mode.

The European Fusion Programme is conducting research on several, differently specialised tokamaks: While the JET large-scale device is concerned with the plasma behaviour in the vicinity of ignition, it is more special questions that are being treated in the smaller national experiments, viz. ASDEX Upgrade at Garching, TEXTOR at Jülich, Tore Supra, operating with superconducting coils, at Cadarache in France, and FTU at Frascati in Italy. For example, ASDEX Upgrade, Germany's largest fusion device, is predominatly devoted to preparations for ITER: These include looking for optimised operating modes, i.e. developing plasma states with improved thermal insulation and extending the pulse length till continuous operation is achieved. The know-how acquired with ASDEX Upgrade, which has already been largely integrated in the ITER planning, will thus also govern the scientific operation of the device.

View into the plasma vessel of the ASDEX Upgrade tokamak, Germany's largest fusion device, at Max-Planck-Institut für Plasmaphysik in Garching



Plasma and magnet coils of the Wendelstein 7-X stellarator, now being built at the Greifswald branch of Max-Planck-Institut für Plasmaphysik

The alternative: stellarators

Unlike tokamaks, fusion devices of the "stellarator" type can operate in continuous mode from the outset: They function without plasma current, using a field generated exclusively with external coils. This calls, however, for magnetic coils of much more complex shape than in tokamaks.

In Europe, the TJ-II stellarator is being operated at Madrid and Wendelstein 7-X is being built at Greifswald. Upon completion in 2014 the latter will be the world's largest experiment of the stellarator type – but with a plasma volume of 30 cubic metres much smaller than ITER. Wendelstein 7-X is to demonstrate this alternative concept's suitability for a power plant: An improved magnetic field is to overcome the difficulties encountered in previous stellarators; the quality of the plasma equilibrium and confinement is to equal that of a tokamak. And with discharges lasting up to 30 minutes Wendelstein 7-X is to demonstrate the essential property of the stellarator, viz. continuous operation. But there is no intention of going for an energy-yielding plasma. As the latter's properties can be largely transferred from the tokamak to the stellarator, this objective is reserved for the tokamak ITER.

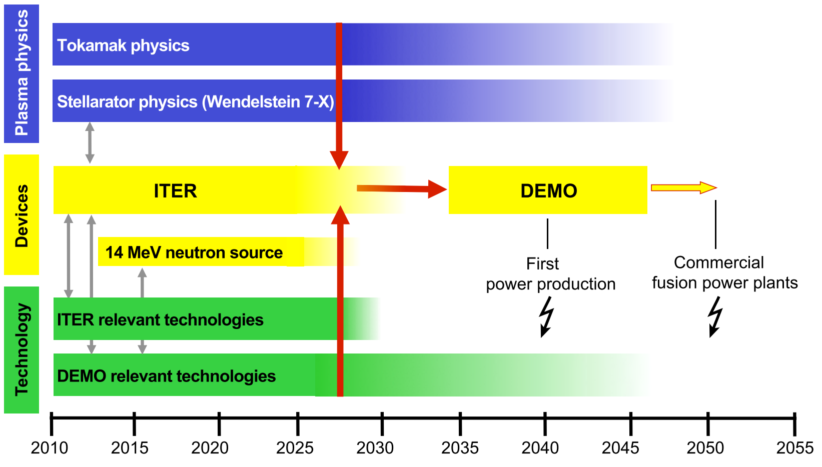
Fusion power plants as of mid-century

The ITER tokamak is to show that an energy-yielding fusion fire is possible. The technological side presents further challenges, primarily in materials research: Parallel to ITER it is necessary to promote – by means of, for example, a neutron source – development of neutron-resistant structure materials with low activation potential and heat and erosion-resistant materials for the plasma vessel. ITER is then to be followed by a DEMO demonstration reactor providing all the functions of a power plant. If Wendelstein 7-X can experimentally confirm the good properties calculated for it, this demonstration power plant could also be a stellarator. On the basis of twenty years each for planning, building and operating ITER and its DEMO successor a fusion power plant could thus provide economically useful energy towards the middle of the century.

This future power plant is to be built up in layers like an onion: The ring-shaped plasma at the core is surrounded by a so-called "first wall", then by the "blanket" and the vacuum vessel, around which the superconducting magnets are strung along. As the superconducting magnets operate at low temperature, the entire core section is enclosed in a cryostat.

The deuterium and tritium fuel is injected deep into the plasma in the form of frozen pellets. About 35 grammes of fuel per hour is needed by a power plant to produce 1000 megawatts of electric power. Till ignition, start-up heating provides the plasma for a few seconds with a power of 50 or 100 megawatts. The fast helium nuclei resulting from the onset of nuclear reactions are captured in the magnetic field as charged particles and transfer their energy to the plasma through collisions. The external heating can ultimately be largely switched off; the plasma continues to burn by itself and maintains the high fusion temperature through self-heating.

The neutrons produced leave the plasma without hindrance and are slowed down in the blanket, the inner shell of the vessel wall, where they deposit their kinetic energy in the form of heat. In the blanket the neutrons additionally produ-



The way to fusion power

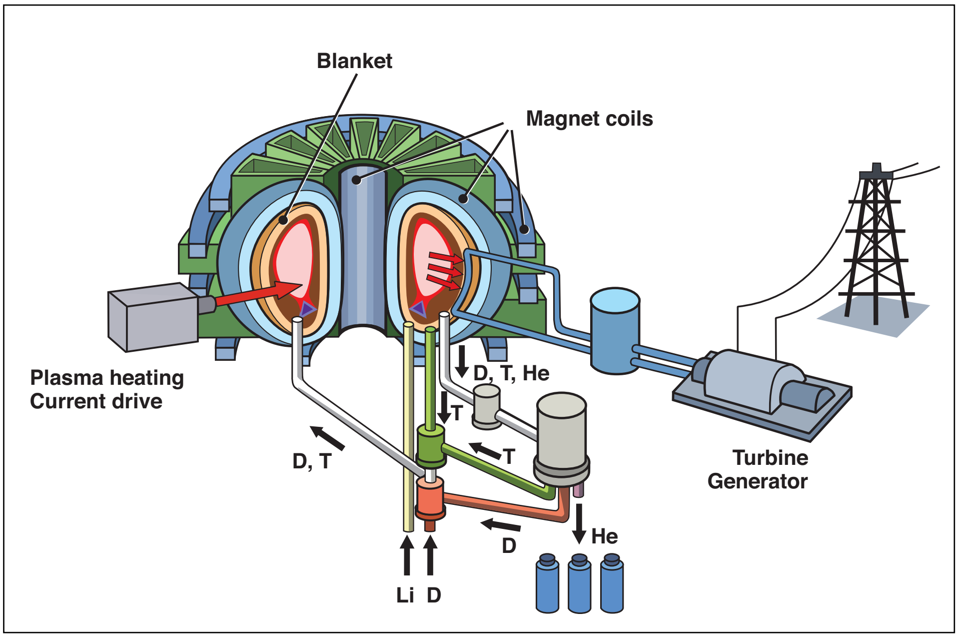
ce from lithium the tritium fuel component, which is removed by means of a flushing gas and returned to the fuel cycle. The "ash" of the fusion reaction, helium, is removed by the so-called divertor. The heat deposited in the blanket and divertor is transported by a coolant - helium or water - to the steam generator in order to produce electricity, which is then fed to the grid.

The conventional components of the power plant - stream generator, turbine and power generator - are hardly different to similar components in present-day coal-fired or nuclear power plants.

Safety and environmental properties

The question of safety concerns the radioactive tritium and the high-energy fusion neutrons, which activate the walls of the plasma vessel. A naturally prescribed property of a fusion power plant is: It can be so designed that it does not contain any energy sources which – if they get out of control – could destroy a safety sheath from inside. An accident with catastrophic consequences is impossible for fundamental physical reasons.

Climatically harmful emission does not occur. The walls of the plasma vessel are left over as radioactive waste and have to be put into intermediate storage at the end of their service life. The activity of the waste rapidly decreases, after about a hundred years to a ten-thousandth of the initial value. After a decay time of one to five hundred years the radiotoxic content is already comparable to the hazard potential of the entire coal ash from a power plant of equal power, which always contains radioactive materials. If appropriate recycling techniques are applied, there would no longer be any waste after a decay time of a hundred years. The entire material would then be cleared or approved for re-use in new power plants. By virtue of these favourable properties and its almost inexhaustible fuel reservoir fusion cold be one of the pillars of a permanent energy supply.



Graphic: IPP, Karin Hirl

Layout of a fusion power plant

With about 1500 megawatts of electric power, fusion power plants would primarily serve the base load and could be incorporated in the grid system of the power supply like present-day large-scale power plants. Fusion power plants would also earn their place in a power industry highly dominated by renewable energies: as a buffer for the weather-dependent wind and solar power plants. They could be used just as well for producing hydrogen.

A study on the development of the European energy market as of 2050 shows that fusion as a new and comparatively capital-intensive technology can penetrate the European market if the emission of carbon dioxide is to be appreciably reduced. In 2100 fusion could then cover about 20 to 30 per cent of Europe's power requirements.

As opposed to many of today's power plants, the cost with fusion fuel is almost negligible; the capital outlay is essentially incurred by the construction of the devices themselves. Since this eliminates the market dependence of the cost of fuel during operation, it is anticipated that price stability will be much higher.

The importance of the fusion option becomes obvious primarily in the global perspective, in view of the world's growing population: In countries with rapidly increasing economic activity such as India and China it is almost only coal-fired power plants that are being planned for the next few decades. Power plants and infrastructure are being designed for lifetimes of about forty years, by which time the DEMO fusion demonstration power plant is to start power production.

Max-Planck-Institut für Plasmaphysik (IPP)
Garching, Greifswald / Germany
www.ipp.mpg.de