MAX PLANCK INSTITUTE
FOR PLASMA PHYSICS

FUSION BASICS

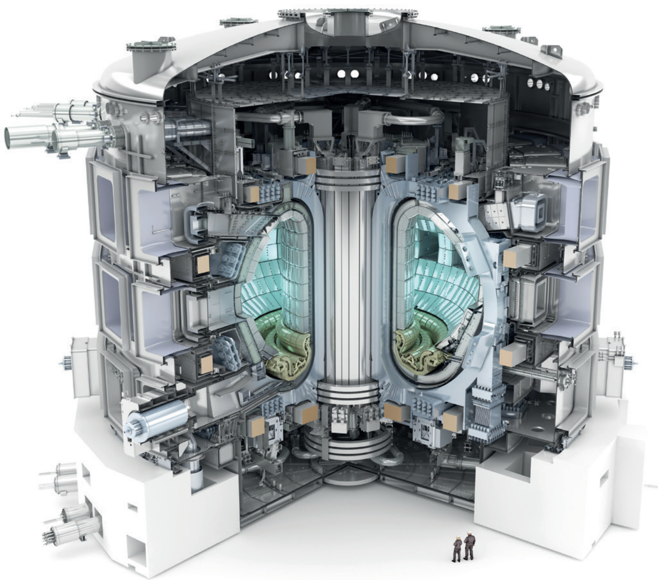
Nuclear Fusion Status & Prospects

The goal of fusion research is to harness the energy source of the sun and stars on Earth: A fusion power plant is to generate energy from the fusion of atomic nuclei.

Under terrestrial conditions, this is best achieved with the two types of hydrogen: deuterium and tritium. Deuterium is called heavy hydrogen because its nucleus contains a neutron in addition to a proton. Tritium is called super-heavy hydrogen because there are two neutrons in the nucleus.

Deuterium and tritium fuse to form helium, releasing neutrons that can transport large amounts of energy: One gram of fuel in a power plant could release the heat of combustion of approx. 11 tons of brown coal (lignite). Or, in a different calculation: one kilogram of fuel would cover the annual energy needs of 1,000 people in central Europe.

The basic materials necessary for this - deuterim and lithium, from which the latter is used to produce tritium at the power plant - are present on Earth in large quantities.



The ITER fusion test facility is currently being built in the south of France. (Graphic: Fusion for Energy)

Magnetic fusion vs. laser fusion

Fusion research focuses essentially on two concepts.

In magnetic fusion, plasma heated to more than 100 million degrees Celsius is confined in a magnetic field. Light atomic nuclei fuse in this plasma, releasing large amounts of energy.

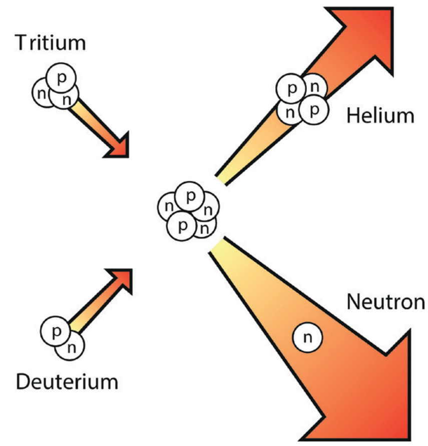
In laser fusion (also called inertial fusion), fusion is achieved by shooting high-energy laser beams at a small fuel pellet a few millimetres in size. At the end of 2022, US researchers from the Lawrence Livermore National Laboratory achieved an important scientific breakthrough; for the first time, they were able to release more fusion energy than they had invested in laser energy.

However, magnetic fusion is actually far ahead in the technological realisation of a power plant. That is why most research institutes and companies are pursuing this concept, for example, at the ITER international research reactor. ITER is currently being built by seven project partners (China, Europe, India, Japan, Russia, South Korea, and the USA) in Cadarache in southern France.

At the same time, China and the United Kingdom are investing in national programmes to build fusion power plants. There are also approx. 40 start-up companies that have raised billions of dollars from private investors for the construction of commercial nuclear fusion power plants.

Magnetic fusion and fusion conditions

Similar to a coal fire, a fusion fire does not ignite independently, but only under suitable ignition conditions. The fuel – a very thin, ionized gas, i.e. „plasma“ – has an



Neutrons are released in fusion reaction, whose kinetic energy can be converted into electricity. The energy of the helium that is also produced is to be used in a fusion power plant to heat the plasma. (Graphic: MPI for Plasma Physics)

ignition temperature of 100 million degrees. Due to the high temperature, the plasma cannot be confined directly in material vessels. The hot gas would cool down immediately whenever it touches the wall. Instead, magnetic fields are used to confine the plasma and keep it away from the vessel walls.

Releasing energy with a deuterium-tritium plasma according to this principle was first achieved in 1991 at the joint European facility JET (Joint European Torus) in Culham/Great Britain, the largest magnetic fusion experiment in the world until 2023. JET set a world record for fusion energy at the end of 2023: The plant generated 69 megajoules during a five-second plasma discharge with deuterium-tritium fuel. However, the JET plasma, with its 80 cubic meters of volume, is too small for a net gain in energy. This is the task of the international experimental reactor ITER (Latin for the „way“). In its plasma volume of approx. 840 cubic meters, a fusion power of 500 megawatts is to be generated – ten times more than the power used to heat the plasma. ITER is for research purposes only and will not supply electricity.

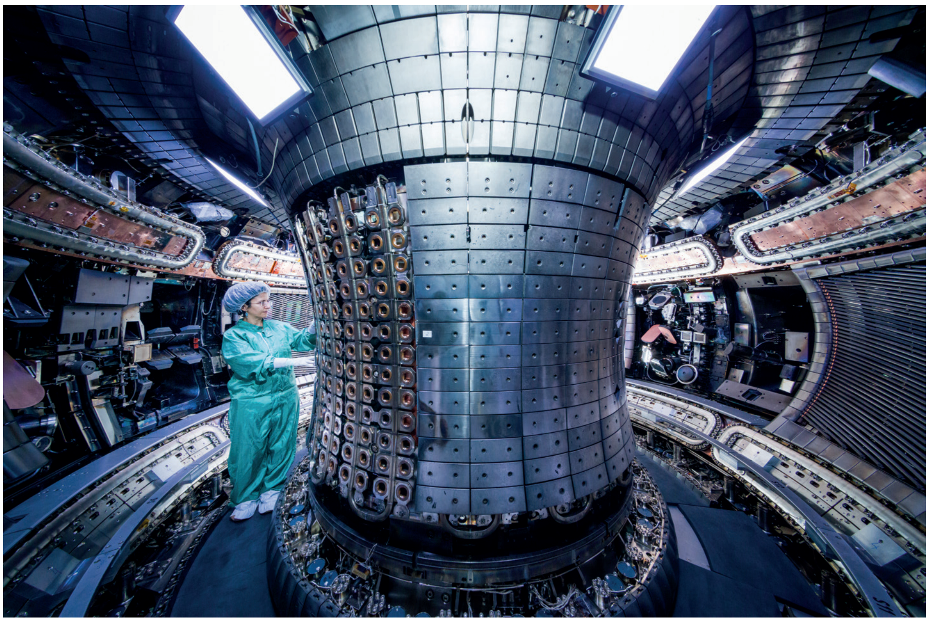
The international fusion test facility ITER

ITER was initiated in 1985 as a joint project to overcome the cold war in talks between the then Soviet Secretary General Gorbachev and the presidents of France and the USA, Mitterrand and Reagan. In the spring of 1988, the planning work for ITER began at the Max Planck Institute for Plasma Physics in Garching. Interrupted by lengthy political decision-making breaks between the start-up of the project, the design and the detailed planning as well as lengthy negotiations on the location, the international ITER organisation was founded in 2007. The construction of the plant in Cadarache in the south of France could then begin. Contributions from the seven ITER partners are mainly made available in the form of finished components manufactured in the respective countries and delivered to Cadarache. The assembly of ITER components officially started at the end of July 2020.

Most commonly used: Tokamak devices

JET and ITER are magnetic fusion devices of the “tokamak” type, at present the most widely operated and best understood concept in the world. Tokamaks generate their magnetic field cage partly through external magnetic coils wrapped around the plasma vessel. The other part of the magnetic field cage is generated by an electric current flowing in the plasma, which is induced there in pulses by a transformer. As a result, tokamaks can only be operated in pulsed mode.

In the European fusion program EUROfusion, research is being carried out using several tokamak experiments with different specialisations: The large JET plant investigated the plasma behaviour near the ignition until its end of operation in December 2023. More specialised questions are addressed by the smaller national facilities – ASDEX Upgrade in Garching near Munich, MAST in the UK, TCV in Switzerland (these two countries are associate members) and WEST in Cadarache, which uses superconducting magnetic coils: For example, ASDEX Upgrade is dedicated to topics that are important for a demonstration power plant and for ITER. This includes the search for optimised modes of operation, i.e. the investigation of plasma states with improved thermal insulation, effective heat extraction and extended pulse duration. Consequently, the knowledge gained with ASDEX Upgrade, which has already been significantly incorporated into ITER planning, will also influence the scientific operation of the plant. At the end of 2023, the JT-60SA tokamak in Japan also produced its first plasma.



View into the ASDEX Upgrade plasma vessel in Garching near Munich, a tokamak fusion plant (Photo: MPI for Plasma Physics, Jan Hosan)

The Japanese-European joint project is larger than JET, but smaller than ITER. Similar to the latter, it is equipped with superconducting magnetic coils and is intended to support ITER operation as well as to prepare a future demonstration power plant.

The alternative: stellarators

In contrast to tokamaks, magnetic fusion systems of the „stellarator“ type can work in continuous operation from the outset: They are operated without plasma current and with a field generated exclusively by external coils. However, they require magnetic coils of much more complex shape than in tokamaks.

At the Max Planck Institute for Plasma Physics in Greifswald, Wendelstein 7-X went into operation in 2015, the world‘s largest experiment of the stellarator type, but it is significantly smaller than ITER with its plasma volume of 30 cubic meters. Wendelstein 7-X is intended to demonstrate the power plant suitability of this alternative concept. The goal is to raise the quality of plasma equilibrium and confinement to the level of tokamaks. For this purpose, the generated magnetic field and the required shape of the magnet coils were calculated with supercomputers, making this stellarator superior to its predecessors. With discharges of up to 30 minutes duration, Wendelstein 7-X is intended to demonstrate the essential stellarator characteristic: continuous operation. The device, however, is not intended to generate energy. To do this, Wendelstein 7-X would have to be as large as ITER. However, essential properties of energy-providing plasmas can be transferred from tokamaks to stellarators.

Fusion power plants from the middle of the century

The ITER tokamak is to show that an energy-yielding fusion fire is possible. On the technological side, there are further challenges, especially in the field of materials research and qualification: In parallel with ITER, researchers must develop heat- and erosion-resistant materials for the plasma vessel by means of for example a neutron source. Fusion neutrons should damage and activate these materials as little as possible. ITER is to be followed by a demonstration reactor (DEMO) that shows all the functions of a power plant. If Wendelstein 7-X can experimentally confirm its calculated good properties, then a future demonstration power plant could also be a stellarator.

The entire research programme is designed in such a way that a fusion power plant could provide economically viable energy by the middle of the century. This future power plant is to be built up in layers like an onion: The ring-shaped plasma in the centre is surrounded by a „first wall“. This is followed by the blanket covering the vacuum vessel and finally the magnetic field coils wrapped along it. Due to the superconducting magnets working at low temperature, the entire core is enclosed by a cryostat.

The fuel – deuterium and tritium – is injected deep into the plasma in the form of frozen pellets. A power plant with 1000 megawatts of electrical output consumes approximately 50 grams of this per hour. Up to the ignition of the fusion plasma, start-up heating supplies power of approximately 100 megawatts for some minutes. The fast helium nuclei, which are formed during the fusion reactions that are now starting, are trapped in the magnetic field as charged particles and transfer their energy to the plasma through collisions. As a result, the external heating system can be largely switched off; the plasma continues to burn independently and maintains the high fusion temperature by self-heating.

The neutrons generated in the fusion reactions leave the plasma unhindered and are slowed down in the blanket, the inner shell of the vessel wall. There, they release all their kinetic energy in the form of heat. In the blanket, the neutrons also generate from lithium the fuel component tritium, which is removed with the help of a purge gas and returned to the fuel cycle.

The „ash“ of the fusion reaction,

Stellarator Wendelstein 7-X: The graphics show from top to bottom the plasma shape, the superconducting stellarator magnet coils, the planar magnet coils, wiring, cooling lines and inner support structure, parts of the outer vessel and the entire outer vessel.
(Graphic: MPI for Plasma Physics)

helium, is removed by the divertor. The divertor consists of cooled plates, to which the ionised waste products of the fusion reactions are directed in a controlled manner along magnetic field lines onto the plates. The heat deposited in the blanket and divertor is transported by a coolant – helium or water – to a steam generator. The hot steam serves for generating electricity that is fed into the grid. The conventional parts of a fusion power plant – steam generator, turbine and generator – hardly differ from similar components in today‘s coal or nuclear power plants.

Safety and environmental characteristics

Considerations about the safety of fusion power plants apply to the radioactive fuel component tritium and the energy-rich fusion neutrons, which activate the walls of the plasma vessel, i.e. generate radioactivity there.

An uncontrolled chain reaction is basically excluded due to physical reasons in a fusion power plant. The plasma extinguishes immediately if its parameters move outside the desired range. Unlike in a nuclear fission reactor, which contains the entire fuel supply from the beginning, there are only a few grams of fuel in the vacuum vessel in a fusion power plant at any time. Climate-damaging gases such as carbon dioxide are not emitted by such a power plant.

The walls of the plasma vessel must be temporarily stored after the end of operation. This waste quantity is initially larger than that from nuclear fission plants. However, these are mainly low- and medium-level radioactive materials that pose a much lower risk to the environment and human health than high-level radioactive materials from fission power plants. The radiation from this fusion waste decreases significantly faster than that of high-level radioactive waste from fission power plants. Scientists are researching materials for wall components that allow for further reduction of activation.

They are also developing recycling technologies through which all activated components of a fusion reactor can be released after some time or reused in new power plants. Currently, it can be assumed that recycling by remote handling could be started as early as one year after switching off a fusion power plant. Unlike nuclear fission reactors, the long term storage should not be required.

Outlook

With its favourable properties and its large fuel reservoir, fusion could become one of the pillars of a sustainable energy supply: With about one gigawatt of electrical power, fusion power plants would primarily serve the base load and could be integrated into the interconnected power supply system like today‘s large power plants. Also in an energy industry strongly dominated by renewable energies, fusion power plants would find their place as a buffer for wind and solar power plants dependent on the weather. They could also be used for hydrogen production and for the provision of heat for households and industry.

Studies predict a global increase in energy demand for the coming decades. Fusion is one of the few options to continuously provide large amounts of energy without CO2 emissions in the second half of this century.

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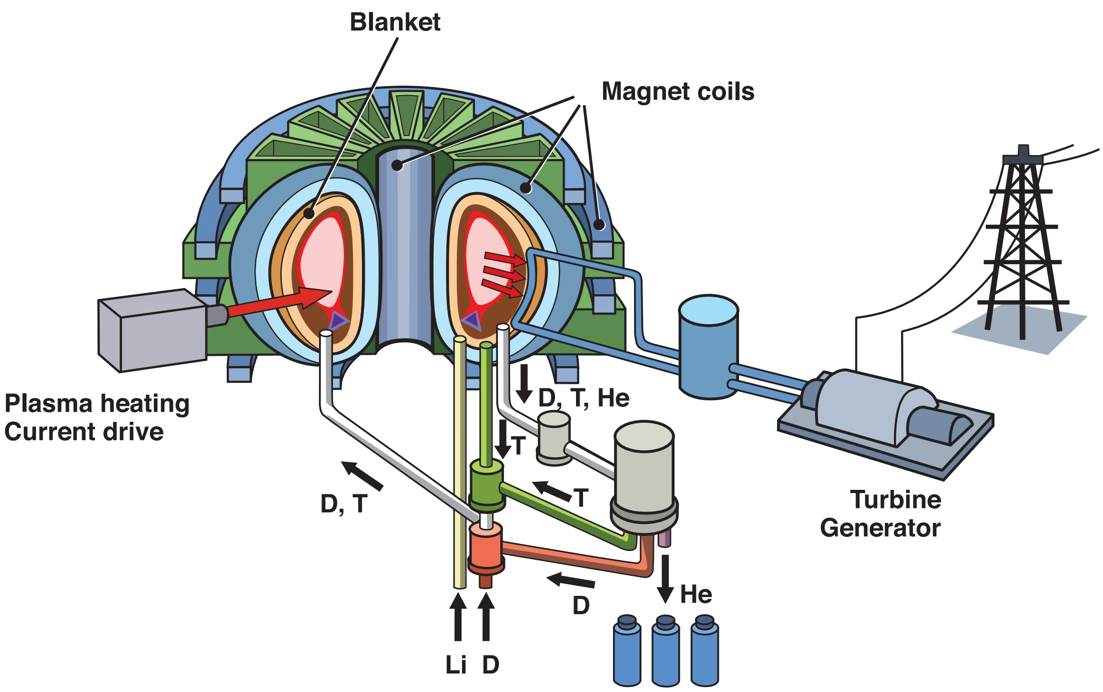

Construction of a tokamak-type fusion power plant (Graphic: MPI for Plasma Physic, Karin Hirl)

Imprint Max Planck Institute for Plasma Physics (IPP), Boltzmannstraße 2, 85748 Garching near Munich
Contact: press@ipp.mpg.de, Frank Fleschner (V.i.S.d.P., press officer), www.ipp.mpg.de