FUSION
A POSSIBLE ENERGY SOURCE FOR THE FUTURE

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In a world of growing population and improving standards of living, we are facing global challenges, which inevitably will change society, economy and politics. One of those challenges is the constantly rising demand for energy. The majority of studies indicate that the electricity consumption will have increased by a factor of six by the year 2100. At the same time, energy supply must be safe, available, affordable, environmentally friendly and sustainable. Renewable energy supplies as solar and wind power appear to be the obvious pathway; it is uncertain, however, if the enormous energy demand can be covered by renewables only.

Storage technologies required for energy availability are among the greatest scientific and technological challenges in our times. If nuclear fission is considered not being a viable option for future energy supply, and if the use of fossil fuels is expected to phase out until the end of our century, nuclear fusion is the only primary energy left as an option for the future.

Fusion is the process that powers the stars in the universe, for example our sun. In the sun core matter is extremely dense and hot and the immense pressure force light atomic nuclei to fuse to heavier ones. This process of nuclear fusion releases energy according to Einstein's famous principle of the equivalence between mass and energy. On earth, we see the light and feel the warmth of the sun as a result of the fusion reaction in its core. The conditions in the core of the sun are so extreme that we cannot reproduce them on earth. But the well understood fusion mechanism itself can be used in a terrestrial power plant using the hydrogen isotopes deuterium and tritium as fusion "fuel".

In comparison to the hydrogen fusion process in the sun, the fusion process of deuterium and tritium requires way less pressure. This allows one to use an ultrathin gas mixture of deuterium and tritium, which still has to be heated to a temperature of about 100 million degrees centigrade to overcome the repellant force of the positively charged particles. Such a state of matter is known as an "ideal plasma" and can be reliably produced with suitable devices on earth. Deuterium and tritium fuse to helium and an elementary particle - the uncharged neutron - is emitted. The neutron carries the lion's share of the energy by its speed and generates heat if decelerated in a thick wall adjacent to the plasma. The efficiency of the fusion fuel is impressive: one gram of fuel generate as much heat energy as eleven tons of coal! Also the sun is in a – mostly non-ideal – plasma state and its matter is confined by its own gravity.

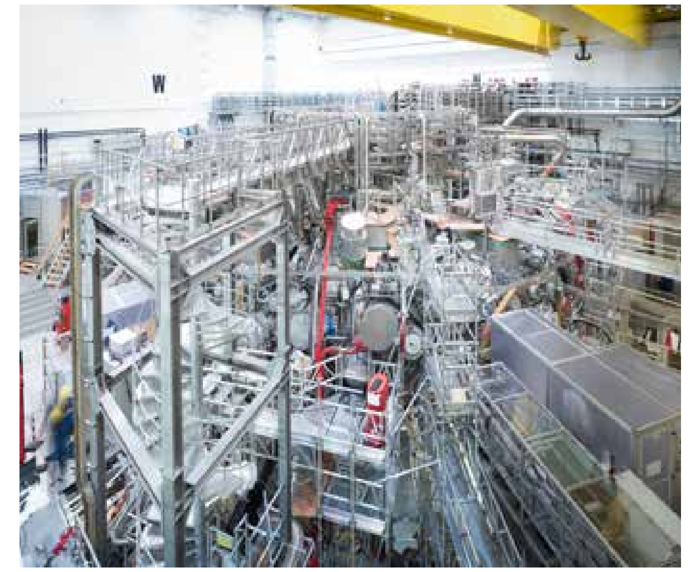
The gravitational force is, however, very weak and on earth a fusion plasma can be confined using strong magnetic fields. The magnetic field is acting on the charged particles such that the hot and thin plasma is well-insulated from the cold material walls; a significant thermal contact between the wall and the plasma would prevent reaching the required temperature.

Decades-long research has proven magnetic fields in the shape of a twisted ring - or torus - to be the most suitable. Two concepts have reached maturity: the tokamak and the stellarator. Tokamaks produce the magnetic field by combining external magnetic coils with an electric current flowing in the plasma. Stellarators create the magnetic field "cage" solely by means of specially shaped external coils.

The Max Planck Institute for Plasma Physics is the only fusion centre in the world investigating both fusion device types: ASDEX Upgrade (a tokamak in Garching, state of Bavaria) and Wendelstein 7-X (a stellarator in Greifswald, state of Mecklenburg-Vorpommern).

Named after a mountain in the Bavarian Alps, Wendelstein 7-X is the world's largest and most advanced stellarator fusion research facility. After more than 15 years of construction, first research operations started in December 2015. The goal of Wendelstein 7-X is to sustain hydrogen plasmas with fusion relevant plasma densities and temperature over 30 minutes. This would be an operational area, which has not been explored by any other fusion facility. It will provide key data on the pathway towards a stellarator-based fusion power plant.

70 superconducting coils – each about 3.5 m high - generate the magnetic field in which the plasma (indicated in pink) suspends almost contact-free inside the vacuum vessel. Graphic: IPP



Wendelstein 7-X has a diameter of 16 m and a total weight of about 1000 t. Photo: IPP, J. Hosan

The coil system consisting of 50 non-planar and 20 planar superconducting magnetic field coils is the key component of Wendelstein 7-X. During operation, they are cooled to minus 270 degrees centigrade, close to absolute zero point. The superconducting coils generate strong magnetic fields almost without any electrical losses – an important precondition for a fusion power plant. The low operation temperature requires that the coils are installed in a separate vacuum space, the so-called cryostat, which is formed between the actual plasma vessel and an outer vessel. The plasma is produced in the ring-shaped plasma vessel by heating few thousandths of a gram of hydrogen gas using strong microwaves. It is supplied, heated and finally observed through 254 openings in the vessels.

The first two operation phases of Wendelstein 7-X were extremely successful. Stellarator record values of the so-called fusion product (ion temperature, plasma density and energy confinement) were achieved. Very long-duration plasmas have been demonstrated, e.g. 100 seconds at moderate microwave heating power (2 MW) and 30 seconds at higher microwave heating power (5 MW). Power and duration have been limited only by the temperature rise of wall elements to the technical limits, not by the physics capabilities. To pave the way for 30 minutes long plasma operation at high microwave heating power (10 MW), all wall elements that come into thermal contact with the plasma must be actively cooled with water.

Working in the plasma vessel in compliance with infection protection. Photo: IPP

Prof. Thomas Klinger – scientific head of the Wendelstein 7-X project at IPP Greifswald. Photo: IPP

This is currently accomplished in a vast technical extension of Wendelstein 7-X with more than 500 pressure water cooling circuits and specially designed water-cooled components. The heating systems as well as plasma diagnostics and control and data acquisition systems are augmented as well for the planned long-duration plasmas from 2022 onwards.

The corona pandemic had also affected the assembly work at Wendelstein 7-X. Only after suitable solutions could be found for engineers and technicians to work closely distanced in the narrow space of the plasma vessel, assembly could be resumed. The works are scheduled for completion by December 2021. The third experiment phase will start in September 2022.

Fusion research is a global endeavor and scientific and technical collaboration is mandatory. During operation of Wendelstein 7-X, in addition to 150 Max Planck scientists, more than 60 researchers from the fusion laboratories organized in European fusion research consortium EUROfusion, the USA, Japan, and Australia will work on site.

There is a close exchange of experience and know-how transfer to the international fusion experiment ITER. Experience gained at Wendelstein 7-X is openly shared, particularly in the areas of engineering, assembly, quality management and commissioning. ITER is an experimental tokamak that is being built in southern France.

It will be the first fusion device to generate fusion power of 500 megawatts - ten times more than is needed to heat the plasma. The ITER Members - China, the European Union, India, Japan, Korea, Russia and the United States – schedule the first plasma for 2025. The next step on the way to a fusion power plant in the European roadmap is the demonstration power plant DEMO, which will generate electricity from nuclear fusion for the first time. This would provide the basis for the commercial use of this safe, non-carbon emitting and virtually limitless energy in the second half of the century.

ADVANTAGES OF FUSION

Fusion fuels are widely available and nearly inexhaustible. Deuterium can be distilled from all forms of water, while tritium will be produced during the fusion reaction as fusion neutrons interact with lithium. Fuel consumption is very low: 900 g of lithium (6Li) and 300 g of deuterium per day correspond to roughly 1 GWe.

Fusion power plants will not produce – except in the construction phase – greenhouse gas emissions.
Its major by-product is helium: an inert, non-toxic gas.

Nuclear fusion reactors produce no high activity, long-lived nuclear waste. Unlike nuclear fission, the nuclear fusion reaction is an inherently safe reaction - if any disturbance occurs, the plasma cools within seconds and the reaction stops.

Erstes Wasserstoffplasma 300 Foto IPP Norbert Fellechner

Foto IPP Julia Sieber