Magnetic Fusion – an Option for Base-Load Electricity

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Energy can be gained through nuclear reactions either by splitting heavy nuclei, or by fusing light ones. The former is used in today's nuclear power stations. It works in the form of a chain reaction in which neutrons, liberated in the breaking-up of a nucleus split further ones. Active control measures are needed to ensure that the number of fission reactions remains constant in time and thus no unwanted power excursions occur. The new nuclei produced are radioactive. Those nuclei that decay fast produce a strong afterheat that needs active cooling even after the reactor has been shut down. Neutrons capture also produces nuclei heavier than U238. Some of the long-lasting nuclei have half-times of over 10,000 years, calling for geological storage of the radioactive waste generated.

Nuclear fusion offers a different path to the usage of nuclear energy. In the foreseeable future only one reaction type is likely to be exploited on a terrestrial scale. Two hydrogen isotopes – deuterium (2H) and tritium (3H) – combine to form a He-atom and set free a neutron, releasing energy in this process (Figure 1). Thus, the reaction product of a fusion reactor is helium, an inert gas, which is not radioactive and does not produce any afterheat. The fusion reaction is not a chain reaction, and there is no possibility of loss of control due to insufficient safety provisions in the design, or of re-criticality in case of a melt-down as occurred in Fukushima.

Nuclear fusion requires high energy on the part of both partners. This reaction is analogue to combustion, but the burn temperature is in the 100 million °C rather than the several 100 °C range, and the energy set free in a single reaction is correspondingly several million times larger. However, as with combustion we face the need to first obtain a sufficient temperature and to keep the reactants from cooling too much from contact with their cold surroundings.

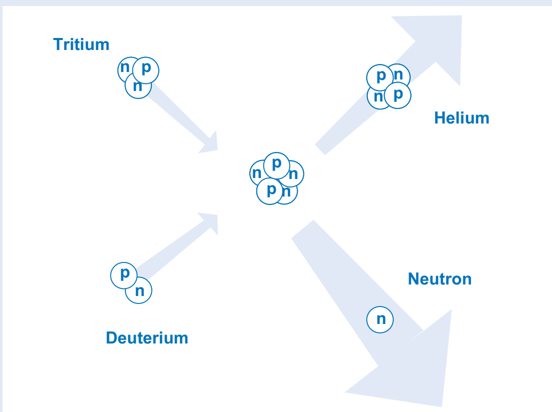
In principle there are two ways that a fusion reactor can operate: via so-called inertial fusion and via magnetic fusion. For inertial fusion a small pellet with frozen deuterium and tritium is heated up very fast so that a sufficient number of fusion reactions can occur before the pellet explodes. Research into inertial fusion energy will not be reported here as it is mainly performed outside Europe and – in the USA – driven to a large extent by military interests.

50 years of fusion research – what has been achieved?

Research into the field of magnetic fusion started as early as the 1960s. The long time-scale needed to develop fusion as an energy source is caused by the enormous challenges to be tackled on the way to creating a fusion reactor. One challenge is the high temperature: as discussed above, in the center of a fusion reactor it has to be 100 million °C, i.e., temperatures about ten times higher than in the solar core have to be reached.

Figure 1

Fusion Reaction



Fusion reaction: The two hydrogen isotopes – deuterium (2H) and tritium (3H) – fuse to a He-nucleus and set free a neutron, releasing in this process 17.6 MeV of energy. In a future power plant the energetic helium nuclei heat the plasma. The energetic neutrons heat up the walls and breed tritium out of lithium.

Source: Max Planck Institute for Plasma Physics.

* Max Planck Institute for Plasma Physics.

As a stationary fusion power plant is a system with inherently low power density – only about one hundredth of that of a fission plant – the heat insulation has to be very good (about 50 times better than polysterene). Fortunately, at these temperatures, a gas is fully ionised, and the motion of the particles of this so-called plasma can be influenced by electromagnetic fields. Only a strong and properly shaped magnetic field in combination with a very low plasma density can provide this exceptional insulation, but even then a large volume is required for self-sustaining burn.

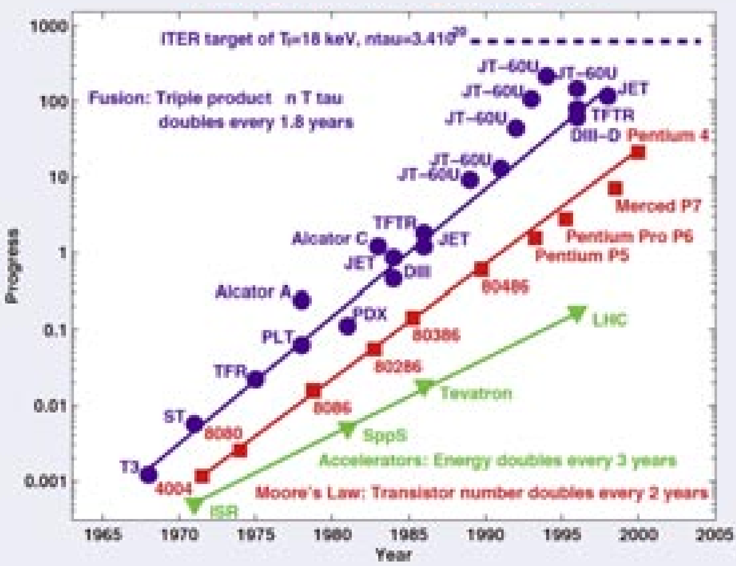
The two magnetic configurations that have proven successful are called tokamak and stellarator. The tokamak is by far the most advanced configuration. For confinement it requires the continuous flow of an electric current in a donut-shaped plasma. In present devices this plasma current forms the secondary loop of a transformer, and can therefore be maintained only over a certain time, which – in a reactor – could, however, amount to several hours. Then the discharge would have to be stopped, and the transformer recharged. Thermal storage would provide for continuity of the electric power production during this short interval (on the scale of several minutes). An alternative to the tokamak is the stellarator. Both have in common their basic topology of a toroidal plasma, but the stellarator has a considerably more complex magnetic configuration. It is, however, intrinsically stationary.

Since its beginning, the progress of fusion research has been remarkable. Before the end of the last century temperatures of up to 400 Mio °C had been achieved in tokamaks. For stellarators sufficiently high temperatures can only be achieved if the complex magnetic geometry is carefully optimised to confine the energetic particles. Such an optimization was not possible before high-performance computers became available. Therefore, the stellarator is at least one machine generation behind the tokamak.

The universally accepted measure of progress in fusion is the product of pressure and the energy confinement time – the latter expressing the quality of thermal insulation. This quantity has been increased by about a factor of 100,000 since the beginning of tokamak research. This progress is impressive even if compared to the development in the performance of computers where the number of transistors on a chip roughly doubles within two years. From 1965 until 2000 progress in fusion was just as fast. It has only slowed down during the last ten years, as a machine of ITER-size (see below) is needed to improve heat insulation sufficiently to gain more energy from fusion reactions than is needed to heat the plasma (Figure 2). This remarkable progress in fusion research is unfortunately not reflected in public opinion. For fusion to become an energy source, a certain threshold in the above mentioned parameter has to be overcome. Unless this threshold is reached, the power needed to heat up the plasma to sufficiently high temperatures exceeds the power released by fusion reactions.

Figure 2

RAPID PROGRESS IN DIFFERENT HIGH TECHNOLOGY FIELDS



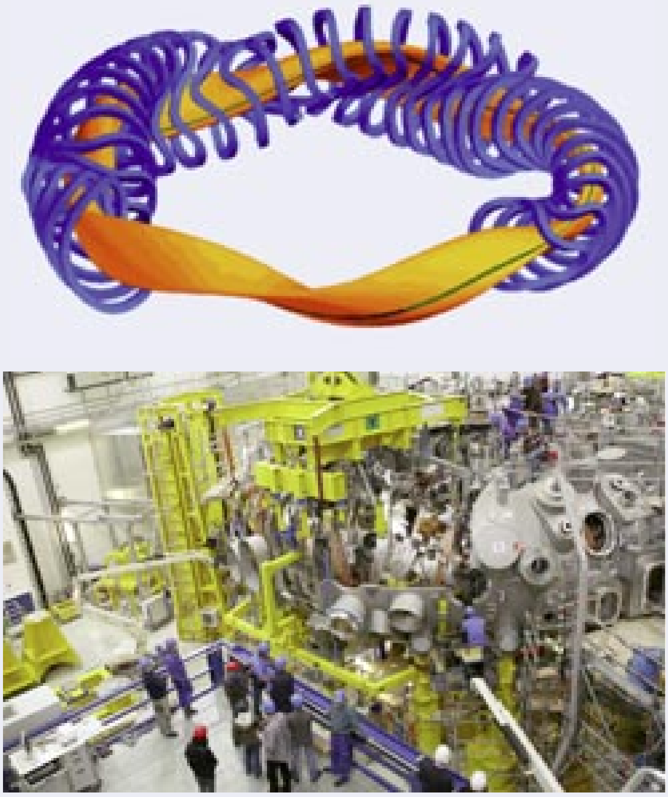
Source: Lister and Weisen (2005).

ITER – ten times more fusion power than power needed to heat up the plasma

All of today's existing devices are too small to achieve the required heat insulation. Therefore, more power than produced by fusion reactions is needed to heat up the plasma. The world record for fusion power has been established at the largest tokamak presently existing, JET (Culham, UK), where 16 MW of fusion power have been produced, corresponding to 60 percent of the heating power injected to the plasma. In order to demonstrate a positive power balance, the international experimental reactor ITER – a tokamak – is currently being built in Cadarache, France. ITER will be the first device to demonstrate power production exceeding the heat input to the plasma by an order of magnitude. ITER is a joint enterprise launched by seven partners: the EU, Japan, Russia, USA, China, the Korean Republic and India.

Figure 3

THE COIL SYSTEM OF THE STELLARATOR W7-X, UNDER CONSTRUCTION IN GREIFSWALD, GERMANY



Note: All superconducting coils are already manufactured and assembled. The device will go into operation in 2014.

Source: Max Planck Institute for Plasma Physics.

ITER will be larger in linear dimensions by about a factor of two compared to the largest presently existing tokamak – JET. Besides JET, several present-day tokamaks, among them the best-suited European tokamak ASDEX Upgrade in Garching, Germany, are already now preparing for ITER operation. They can provide a "step-ladder" approach to developing efficient ITER operational scenarios in a similar way to wind tunnel experiments. The flexibility of the smaller devices makes it possible to test novel ideas more rapidly and at a moderate cost. Subsequently those ideas can be tested on JET and afterwards extrapolated to ITER. In addition, these smaller tokamaks offer the opportunity to train the generation of physicists and engineers that will later operate ITER.

The stellarator Wendelstein 7-X

The stellarator Wendelstein 7-X, currently being built in Greifswald, Germany, will start operation in 2014. Just like ITER, it is a super-conducting device. The geometry of the magnetic field coils is given in Figure 3 together with a photograph taken during assembly. As the first optimised stellarator of sufficient size, W7-X shall provide the proof that such stellarators can achieve sufficiently high temperatures and heat insulation comparable to that of tokamaks. After commissioning, the first operational period (2015–2017) will allow for pulsed operation only. The completion phase (2017–2019) will enable the device for steady-state operation. Although the geometry of tokamaks and stellarators is quite different, the results of ITER will also be important for stellarators.

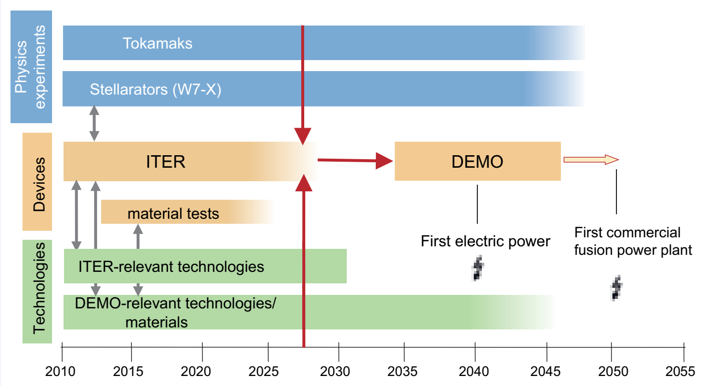
The way to a fusion reactor

Assuming that the ITER experiment is successful, there will be one final step to take on the road to setting up a commercial fusion power plant, namely building a demonstration reactor (DEMO). DEMO is expected to demonstrate all required technologies needed for a commercial power plant. It will provide electricity to the grid, but it is not expected to be economically competitive initially. Figure 4 presents a possible roadmap to a fusion power plant. In a fusion reactor the neutron fluences to the walls will be much larger than in ITER. Therefore, parallel to

ITER, a dedicated programme in materials research is needed. Such a material development programme is already part of the European fusion programme. It has resulted, for example, in the successful development of low activation steels like Eurofer. However, the fusion-generated neutrons have a different energy spectrum than those in fission reactors. Therefore, to allow for ultimate testing of the developed materials, a dedicated neutron source is needed that can generate a sufficient flux of neutrons with an energy spectrum similar to that of fusion.

Figure 4

THE WAY TO A FUSION POWER PLANT



Source: Max Planck Institute for Plasma Physics.

If the aim is to build the first demonstration reactor (DEMO) immediately following successful ITER results, the stellarator will not be ready in time. In that case DEMO would have to be a tokamak. According to the European roadmap to fusion energy, the first electricity to the grid is expected to be available around the year 2050. As the crucial ITER experiments are planned for 2027, one does not expect to start building DEMO before 2035. With a usual construction time of about ten years, DEMO could be ready by 2045. Some countries, however, have much more ambitious plans. China, for example, plans to start building a kind of a DEMO reactor in the near future (around 2016). This reactor would be ready prior to 2030 and could thus demonstrate provision of fusion power to the grid as early as then. China plans to replace part of its nuclear power stations with fusion power plants during this century with the aim of producing 100 GW of fusion-powered electricity by 2100.

In a future fusion reactor, the heating of the plasma will almost entirely be provided by fusion energy. The fusion-generated He-ions remain trapped in the magnetic field and keep the plasma hot, whereas the neutrons leave the vessel and are absorbed in a blanket. There they deposit their energy – which is subsequently further used for electricity generation in a steam or gas turbine – and react with lithium nuclei to produce tritium, which does not occur naturally. A Gigawatt power plant would only need a couple of hundred kgs of lithium and deuterium (which occurs naturally in water) per year, and on this scale the availability of the raw materials is not a constraint: they would be available worldwide and for several thousands of years, extending to millions of years, if we tapped the lithium in sea water.

No final storage of radioactive waste needed

Although no radioactive products result from the fusion reaction, radioactive isotopes are produced due to the neutron bombardment of components in the reactor core. The amount of radioactive elements and their half-time depend heavily on the choice of materials used. For example, steels (Eurofer) have been developed which could be fully recycled within a period of a hundred years. After this time, the radioactivity of such steels is comparable to that of coal ash produced in a coal power plant during its life-time. Further materials research is underway to reduce the half-time of the radioactive waste of a fusion power plant even further. It is thus to be expected that the radioactive waste of a fusion reactor will be recycled so that no final storage of any waste will be required.

Inherent safety of fusion reactors

Compared to a fission reactor the safety of a fusion reactor is not only a consequence of provisions taken in its construction and operation, but is simply due to the inherent absence of certain risk factors:

- In contrast to fission, fusion does not involve a chain reaction. The number of fusion reactions remains constant in time. Hence, there is no need for an active control to avoid unwanted power increases.

- In fission reactors, the amount of radioactive fuel required for over a year is stored (a few hundred tons). In contrast, in fusion reactors, the only volatile, radioactive element is tritium, which is both produced and consumed in the reactor itself and the inventory required will therefore be kept very low (about 1 g in the plasma).
- The products of fission reactions are radioactive. They decay even after the shutdown of the reactor, which is accompanied by significant heat production. This afterheat needs to be controlled by cooling. If cooling completely breaks down, a meltdown as occurred in Fukushima is possible. The reaction products of fusion are not radioactive. A small afterheat only occurs due to the activation of the walls by the fusion neutrons. This afterheat, however, is about a hundred times smaller than in fission reactors. Therefore, even in case of a complete loss of cooling, the decay heat cannot lead to gross melting of structures.
- With fusion the energy per volume in the reactor core is about a hundred times smaller than it is in a fission reactor. Thus, no accidents driven by in-plant energies, not even the most severe accidents that can be conceived, could result in confinement failure.

The inherent safety properties, the crisis-proof availability of the fuel and the promise of small environmental impact make fusion an attractive alternative for CO_2-free electricity production, which is particularly well-suited to covering base-line loads. Given the remaining physics questions to be addressed and the need to further develop and characterize materials, fusion can only make a significant contribution to the electric energy supply in the second half of this century. However, even after 2050, electricity needs are still expected to rise (by a further factor of about three by 2100) and some of the shorter-term solutions to the CO_2-problem, like the enhanced usages of gas, nuclear fission and CO_2-sequestration, might face a shortage of suitable repositories by that time. A further growth of renewables will compete for space and fertilizers with other needs, and some of its associated technologies – like energy storage – still carry in themselves significant development risks. Fusion, which is available continuously and independently of location, promises to offer a significant complement to renewables.

Reference

Lister J. and H. Weisen (2005) “What we learn from ITER”, *Europhysics News* 36(2), 47-51.