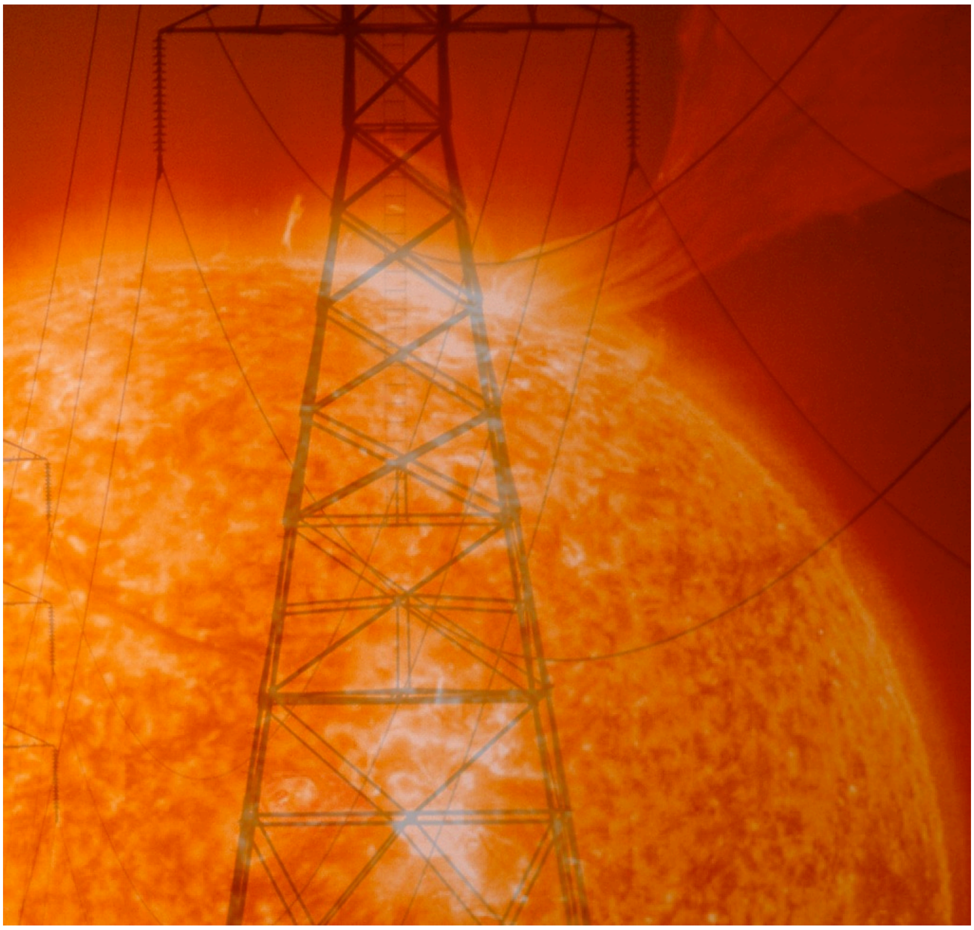
Fusion



Harnessing the power of the Sun: fusion reactors

Renewable, clean, unlimited energy – how can it be achieved? ***Christine Rüth*** *from EFDA introduces the tokamak, the most advanced fusion device.*

The Sun produces vast amounts of energy by fusing light atomic nuclei into heavier particles. If scientists could make this process work sustainably on Earth, we would have a nearly inexhaustible and climate-friendly energy source. A 1 gigawatt fusion power plant would consume only 250 kilograms of fuel per year and produce electricity without emitting carbon dioxide. A coal-powered plant with the same capacity burns 2.7 megatonnes of coal each year.

And unlike fission, fusion is not a chain reaction, which makes it inherently and reassuringly safe: to halt the reaction, it is necessary only to stop the supply of fuel. Furthermore, although some components of a fusion reactor will become radioactive during operation, this radioactivity is short-lived: the materials can be safely disposed of after about 100 years, as opposed to the many thousands of years required for a fission reactor (for more details, see Warrick, 2006).

Scientists at Europe’s largest fusion experiment, the Joint European Torus (JET) in Culham, UK, have been making significant progress towards fusion energy for more than 30 years. Nonetheless, the JET experiment still requires more power than it generates – which is not good for a power plant. The next step will be the international experiment ITER, due to be switched on in 2019. ITER is expected to be the first to produce a net power surplus – 500 megawatts from a 50 megawatts input (see Warrick, 2006). This would prove that fusion power plants are viable.

So how does fusion work?

Figure 1: A fusion power plant will fuse tritium (two neutrons, blue, one proton, red) and deuterium (one neutron, one proton) nuclei, generating a helium-4 nucleus and a highly energetic neutron

To achieve fusion on Earth, scientists picked the most efficient reaction that takes place in the Sun – the fusion of two isotopes of hydrogen: deuterium and tritium. This reaction yields a helium-4 nucleus and a neutron, which carries 80% of the fusion energy (Figure 1). These fast neutrons are captured in the steel wall of the fusion reactor, which transfers the heat to cooling fluids within the wall, which in turn drive a turbine to produce electricity.

The fusion device

Currently, the most advanced type of fusion device is the tokamak. At the heart of a tokamak is the reactor, a ring-shaped steel vessel with numerous openings for heating, measurement and other systems, and an inner wall lined with removable heat-resistant tiles (Figure 2). To start the fusion process, the vessel is subjected to high vacuum – at JET, this value is around 0.00000001 millibar – and a few grams of deuterium and tritium gas are injected. The gas is heated to above 10 000 °C, at which point the electrons escape from their nuclei. This ionised gas is called plasma, or the fourth state of matter; it is the basis for producing fusion power.

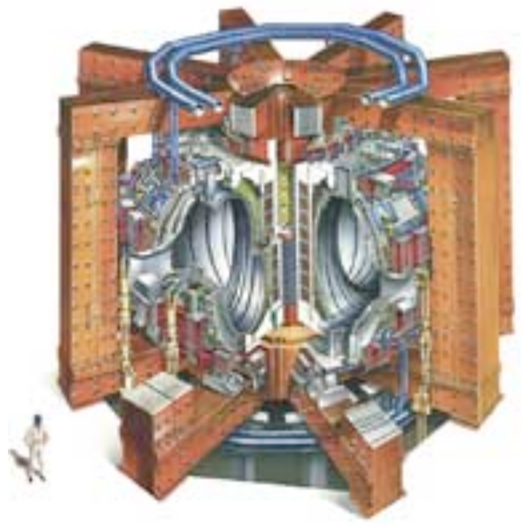


Figure 2: Cutaway diagram of the tokamak JET showing the steel vessel surrounded by eight large copper coils, which produce the magnetic fields. Note the person on the left to give an indication of size
Image courtesy of EFDA

Conditions for fusion

Getting nuclei to fuse is no easy feat: they are positively charged and repel each other, so they must collide at extremely high speeds to fuse[w1]. Because particle speed corresponds to temperature, the plasma has to be millions of degrees Celsius before the fusion process will start. Although the plasma loses heat at its edges, it can keep itself hot by absorbing energy carried by the helium nuclei produced in the reaction, and this self-sustained fusion process can continue as long as new fuel is injected. However, the challenge is to reach that state and ignite the plasma. To ignite, the plasma must be hot enough, dense enough (to ensure a sufficient fusion reaction rate) and keep its energy for long enough – this last condition is called the confinement time.

The Sun, as imaged by the Extreme Ultraviolet Imaging Telescope aboard the Solar and Heliospheric Observatory (SOHO), stationed 1.5 million kilometres from Earth
Image courtesy of ESA, NASA, SOHO / EIT team

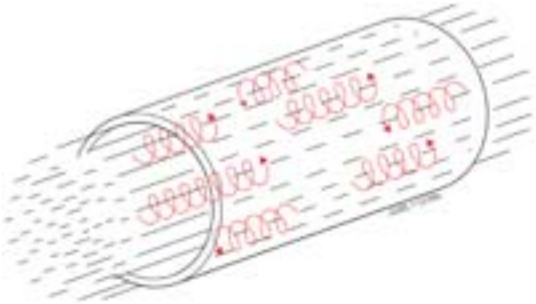
The product of the three parameters – temperature, density and confinement time – is the *triple product*,a central parameter in fusion science. Typically, for the fusion reaction to start, the plasma has to be 100-200 million °C, with a density of about 10^{20} particles per cubic metre, (approximately 1 mg/m^3, one millionth of the density of air) and this state must be confined for around 3-6 secondsw2. Such a high temperature sounds challenging, but heating is not the problem (see below). Instead, it is the confinement time that is hard to achieve – maintaining that temperature (and density) – because the plasma rapidly loses energy as well as particles (which also carry energy).

How does a tokamak work?

1) Keeping the plasma together: magnetic fields

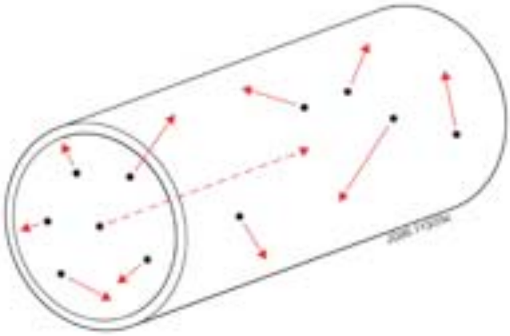
To maintain the high temperature and protect the reactor walls (which would otherwise erode quickly), the plasma needs to be kept away from the reactor walls. To do this, fusion scientists exploit the *Lorentz force* experienced by a moving charged particle when a magnetic field is applied. This force is perpendicular to both the particle's direction of travel and the magnetic field, and therefore causes the particle to rotate around the magnetic field line. As a result, the particle spirals around the field line – with electrons and nuclei moving in opposite directions (Figure 3).

Figure 3: A magnetic field *B* imparts a force on moving charged particles. The entire electromagnetic force on a charged particle with charge *q* and velocity *v* is called the Lorentz force and is given by
$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$
The first term (*qE*) is contributed by the electric field. The second term (*qv x B*) is the magnetic force and has a direction perpendicular to both the velocity *v* and the magnetic field *B*. The magnetic force is proportional to q and to the magnitude of *v* × *B*. In terms of the angle ϕ between *v* and *B*, the magnitude of the force equals *qvB* sin ϕ.
(Source: Encyclopædia Britannica Online (magnetic force: moving charges). Accessed 23 January 2012. www.britannica.com/EBchecked/media/1319/Magnetic-force-on-moving-charges)



A: Moving charged particles in a magnetic field are subject to the Lorentz force and spiral around the field lines. Positively and negatively charged particles spiral in opposite directions.

B: The particles' movement without a magnetic field



The most advanced magnetic confinement design is the tokamak, a ring-shaped vacuum chamber surrounded by coils. An electric current flowing through one set of coils (the toroidal field coils, Figure 4) generates a ring-shaped magnetic field. The strength of this toroidal (doughnut-shaped) field is not uniform across the ring, because the coils are closer together on the inside of the torus (doughnut). Therefore the particles experience a stronger Lorentz force on the inner side of the field line around which they are rotating. As a result, they gradually drift away from their field line towards the plasma edge.

To reduce this effect, a second magnetic field, the *poloidal field*, is generated. The resulting helical magnetic field winds in spirals around the plasma and confines it very effectively. The easiest way to generate a poloidal field is with a plasma current.

That in turn is generated when the plasma particles travel along the ring around the toroidal field lines – electrons and ions moving in opposite directions. Like a wire, this current creates a ring-shaped magnetic field around itself. It is induced by a transformer in which the plasma itself acts as a secondary coil around a large primary coil (the inner poloidal field coils). Because the plasma tends to drift vertically, an additional magnetic field created by the outer poloidal field coils is used to control its position and shape.

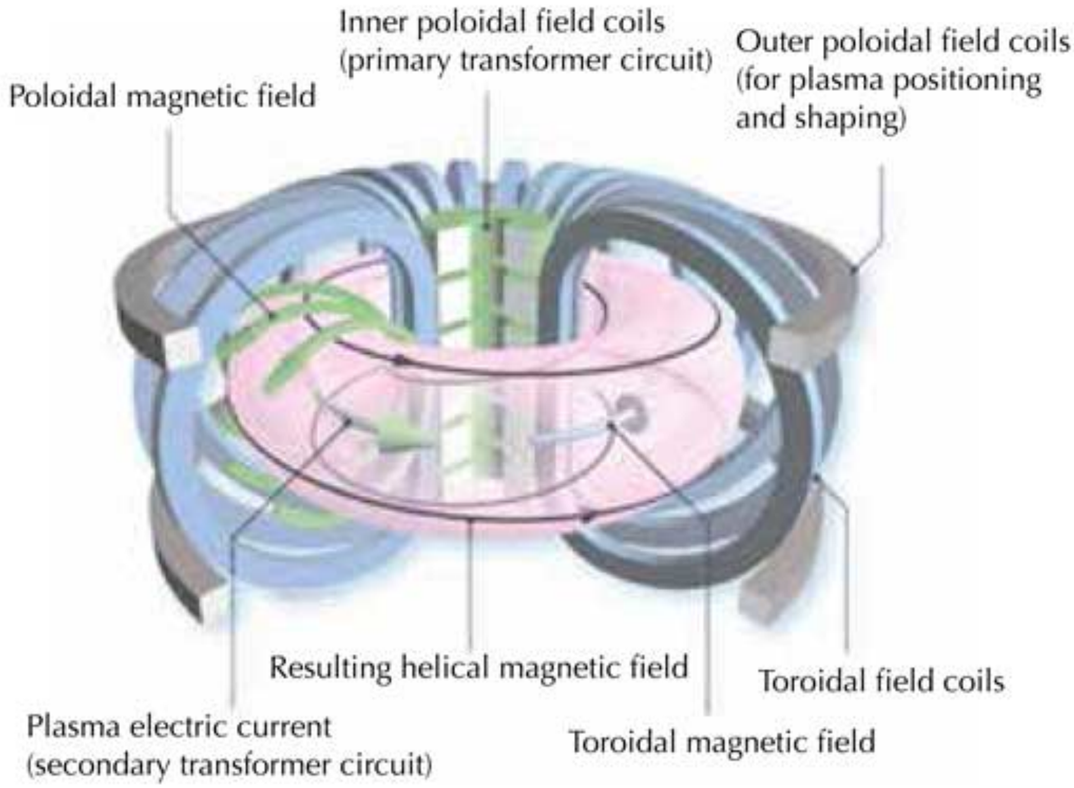


Figure 4: Several sets of coils, together with a plasma current, create the helical magnetic field that confines the plasma. The inner poloidal field coils in the central solenoid induce the plasma current. Click on image to enlarge
Image courtesy of EFDA

2) Heating

To heat the plasma to 100-200 million °C, fusion scientists use three complementary systems (Figure 5).

a) The plasma current produces heat (ohmic heating) itself – just as a wire warms up when an electric current flows through it.

b) Beams of high-energy particles, usually hydrogen atoms, are injected into the plasma, where they transfer their energy to the plasma particles via collisions (think of a fast billiard ball hitting a slower ball, which then speeds up). The particle beam is generated by accelerating ions with high voltage. Because charged particles cannot penetrate the magnetic field around the plasma, they are turned into neutral atoms before injection.In practice, this is no easy task. To give the particles the necessary velocity, a particle accelerator relies on the attractive force that a high voltage exerts on a charged particle (or ion). However, only uncharged (neutral) particles can penetrate the magnetic field around the plasma, so the (uncharged) hydrogen atoms must first be stripped of their electrons, accelerated and then neutralised again before injection[w3].

c) Antennae in the vessel wall are used to propagate electromagnetic waves of certain frequencies into the plasma. These cause the spiralling plasma particles to resonate and absorb the wave energy.

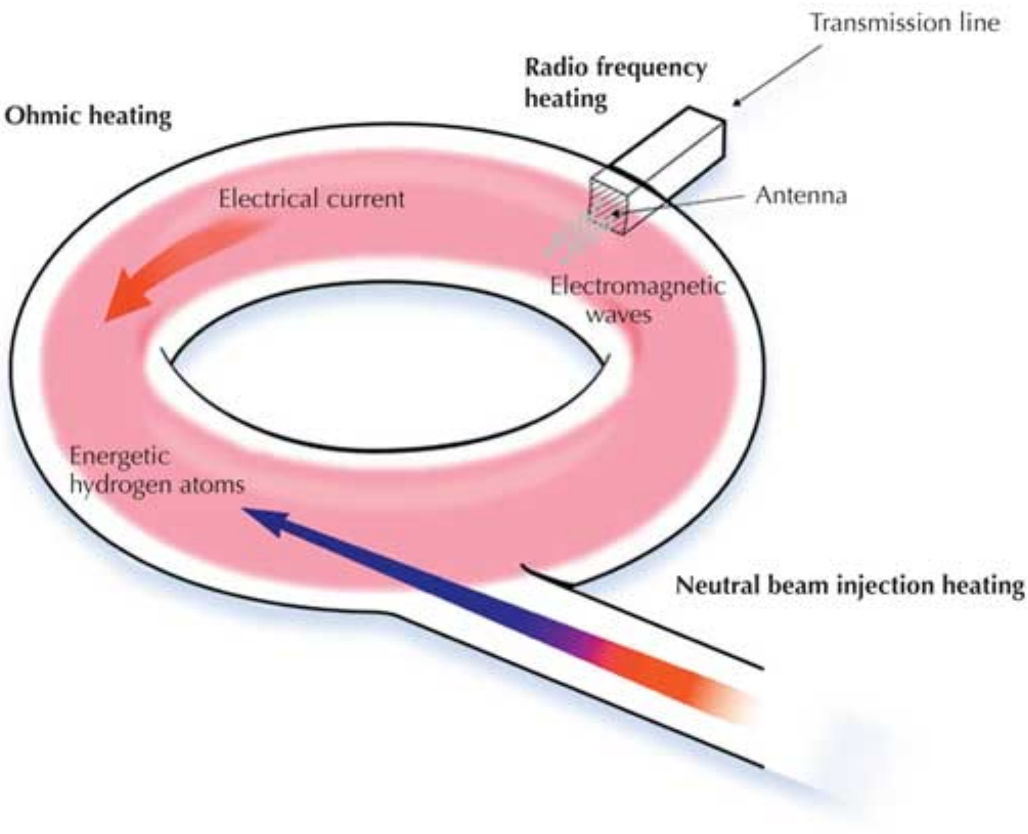


Figure 5: To achieve a plasma of 100-200 million °C, three complementary heating systems are used: ohmic heating, neutral beam injection and radio frequency heating. Click on image to enlarge
Image courtesy of EFDA

Why is fusion power taking so long?

In the 1970s, scientists believed that once they could heat the plasma sufficiently and create large enough magnetic fields, they would have reached the goal of fusion energy. But the plasma has turned out to be highly unstable and loses much more energy than they expected. Since then, scientists have been investigating the physics behind these phenomena and developing methods to control these instabilities. If, as expected, ITER finally generates a net surplus of fusion power, these issues can be considered to be solved and the first fusion power plant could be in operation by 2050.

Will future power stations be powered by fusion?
Image courtesy of Khánh Hmoong; image source: Flickr

Fusion energy

The fusion of one tritium (T) and one deuterium (D) nucleus releases 17.6 MeV of energy, 80% of which – 14.1 MeV – is carried by the neutron and can be used to produce electricity. Fusing 1 kg D with 1.5 kg T (the mass of T is 1.5 times that of D) yields $14.1/(2*1.67262*10^{-27}) = 4.2*10^{27}$ MeV, taking into account that one D nucleus comprises one proton and one neutron, each weighing $1.67262 \cdot 10^{-27}$ kg.

One kilogram of D contains $3 \cdot 10^{26}$ nuclei (one D nucleus comprises one neutron and one proton, each weighing $1.6 \cdot 10^{-27}$ kg). Fusing 1 kg of D (with 1.5 kg of T, as the mass of T is 1.5 times that of D) therefore results in $3 \cdot 10^{26}$ fusion reactions and yields $14.1 \times 3 \cdot 10^{26} = 4.2 \times 10^{27}$ MeV of energy.
A fusion power plant with an efficiency of 40% could generate 70 GWh of electricity (with 1 eV = $1.6*10^{-19}$ J or Ws) from 1 kg D, enough to supply 20 average households in an industrial country.

Deuterium can be extracted from seawater, which contains 35 grams per cubic metre. Tritium is not found in large quantities in nature but can be obtained from the light metal lithium, with the aid of some of the neutrons produced in the fusion reaction:

$^{6}Li + n \Rightarrow {}^{4}He + {}^{3}H + energy$

or in a similar reaction with ^{7}Li. Most of Earth's minerals contain lithium, 2.3 kg of which yields 1 kg tritium. A fusion power plant producing 1 GW electricity (a capacity similar to those of nuclear fission plants) will use 150 kg T and 100 kg D per year.

Reference

Warrick C (2006) Fusion – ace in the energy pack? *Science in School* **1**: 52-55. www.scienceinschool.org/2006/issue1/fusion

Web references

w1 – At the 2007 Science on Stage international teaching festival, Zoltán Köllö won a prize for his simple demonstration of nuclear fusion and the Coulomb barrier using a couple of drops of water and the base of a drinks can. To learn how to do it, see: www.esa.int/SPECIALS/Science_on_Stage/SEMRE58OY2F_0.html

To find out more about Science on Stage, the network of European science teachers, see: www.scienceonstage.eu

w2 – To learn more about fusion, fusion reactors and EFDA-JET, see: www.efda.org

In particular, for the full story of JET, its design and results, see: http://tinyurl.com/scienceofjet

To watch a video of a plasma pulse in JET, see the multimedia section of the EFDA website (www.efda.org/multimedia; 'Video Gallery' then 'JET Experiment') or use the direct link http://tinyurl.com/plasmapulse

w3 – For more details of how the high-energy particle beams are produced, see the EFDA website (www.efda.org) or use the direct link: http://tinyurl.com/neutralbeam

w4 – To find out more about EIROforum, see: www.eiroforum.org

Resources

To learn more about fusion in the Sun, see:

Westra MT (2006) Fusion in the Universe: the power of the Sun. *Science in School* **3**: 60-62. www.scienceinschool.org/2006/issue3/fusion

For a comprehensive overview of fusion research in Europe, including background information on plasma physics and reactor types, as well as wonderful animations and videos, see: www.efda.org

To find out how scientists accidentally created plasma in their microwave, and how they used it for their research, see:

Stanley H (2009) Plasma balls: creating the 4th state of matter with microwaves. *Science in School* **12**: 24-29. www.scienceinschool.org/2009/issue12/fireballs

If you enjoyed reading this article, why not take a look at the full collection of articles on fusion published in *Science in School*? See: www.scienceinschool.org/fusion

Dr Christine Rüth is the editor of the EFDA newsletter Fusion in Europe. She did her physics PhD in the field of climate research and finds it interesting to be involved now in climate-friendly energy solutions. After working as a physicist in industry, she gained a master's degree in science communication and has worked since then as a science and technology communicator

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http://www.scienceinschool.org/2012/issue22/fusion

Problem 1:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

Calculated in MeV, the energy released by the fusion of a deuterium nucleus with a tritium nucleus according to the reaction. knowing that the masses of nuclei are atomic mass unit u: (unified atomic mass unit):

$^{2}_{1}H = 2{,}0135$ $^{4}_{2}He = 4{,}0015$

$^{3}_{1}H = 3{,}0155$ $n = 1{,}0087$

Problem 2:

What is the minimum mass of tritium consumed per day in a future fusion power plant of 1500 MW?