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In a Nutshell!

Is Nuclear Fusion an Energy Source of the Future?

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In a Nutshell!

In nuclear fusion, **light atomic nuclei merge, releasing energy**. The aim of fusion research is to harness this process to **produce electricity**. Research is focused on two basic approaches: **magnetic confinement fusion and inertial confinement fusion**, which also includes laser fusion, among others.

A high-tech concept: Very high temperatures and in some cases high pressures are needed to achieve nuclear fusion. This poses special challenges for the materials used in high-tech fusion devices.

A technology still in the early stages of development: Much of the work on both magnetic and inertial confinement fusion is still at the basic research stage. However, some individual process steps and components have now reached the applied research stage

First power plant possible in 20 to 25 years' time: Various research facilities currently exist around the world. However, a working power plant prototype has yet to be built. Many experts estimate that it will be at least 20 to 25 years before the first power plant starts supplying electricity to the grid.

A climate-friendly technology: If a commercially viable power plant can be built, nuclear fusion could contribute to a climate-friendly energy supply in the longer term, since the nuclear fusion reaction doesn't emit greenhouse gases. Researchers are also investigating the production of at least some of the necessary fuel on-site in the fusion power plant itself.

Contents

What is nuclear fusion?

In nuclear fusion[1], **atomic nuclei merge together**. The fusion reaction produces a new atom with a higher number of particles (protons and neutrons) in its nucleus (see Figure 1) – in other words, a new chemical element. The mass of an atomic nucleus is lower than the sum of the masses of the individual particles within it. This “mass defect” is converted into energy as described by Albert Einstein’s formula “$E = m \cdot c^2$”. The size of the mass defect, and thus the amount of energy released, depends on the elements and particles involved. The energy is often released in the form of neutron **kinetic energy**.

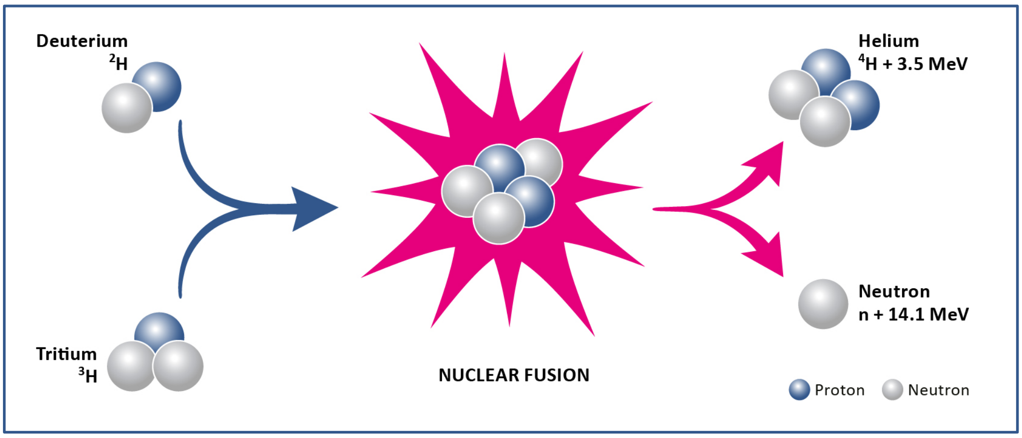

Figure 1: Principle of nuclear fusion as illustrated by the formation of helium (^{4}He) from the hydrogen isotopes deuterium (^{2}H) and tritium (^{3}H). A neutron (n) with a characteristic kinetic energy of 14.1 MeV (megaelectron volts) is released. The alpha particle (helium) with a kinetic energy of 3.5 MeV heats the plasma further, accelerating the fusion processes. Source: authors’ own illustration.

An example of atomic nuclei fusing together occurs in the Sun’s core, where hydrogen atoms are constantly merging to form helium atoms at a temperature of 15 million degrees Celsius and a pressure of 100 billion bars. Huge amounts of energy are released through this process [1]. The aim of fusion research is to develop a technology that replicates this principle on Earth so that it can be harnessed to produce energy.

The first challenge is that in order to achieve a successful nuclear fusion reaction, it is necessary to overcome the repulsive forces between the atomic nuclei (known as the Coulomb barrier) that occur because the nuclei are all positively charged. This means that energy is needed to start a nuclear fusion reaction. Because the high pressures in the Sun’s core cannot be replicated here on Earth, higher temperatures of **between about 100 and 150 million degrees Celsius** are needed instead. Under these conditions, a “plasma” forms. In a plasma, the atoms are ionised and their electrons can move freely. The plasma state is often described as the fourth state of matter, alongside the solid, liquid and gaseous states. In this extremely hot plasma, the atomic nuclei reach such high speeds that they can overcome the repulsive forces between their positively charged protons. Once they cross the Coulomb barrier, they attract each other and fuse to form a new chemical element. [2; 3; 4]

For a nuclear fusion reaction to be self-sustaining, the amount of energy produced must be equal to or greater than the energy used to heat the plasma in order to start the fusion

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[1] Some members of the research community prefer to use the terms “fusion” or “fusion energy” instead of “nuclear fusion”. Among other things, this is intended to distinguish it from nuclear fission, the technology used in nuclear power plants. However, “nuclear fusion” is used in this paper because the technology is based on physical interactions in atomic nuclei and because “nuclear fusion” is more commonly used in the general public debate. In the interests of legibility, the abbreviated form “fusion” is normally used in compounds.

reaction. To achieve this, the product of plasma temperature, plasma density and a characteristic confinement time[2] must exceed a certain threshold known as the Lawson criterion. The confinement time influences the probability of the helium nuclei produced by the fusion reaction colliding with each other. The longer the confinement time achieved at a constant temperature and pressure, the likelier it is that the helium nuclei will collide and transfer their energy to the plasma, thereby heating it so that it can maintain itself. The attainment of the Lawson criterion is referred to as “plasma ignition”. [5; 6; 7; 1]

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[2] The confinement time is the time it takes for the plasma’s energy to dissipate into its surroundings. In inertial confinement fusion, the much higher plasma density in the fusion reaction (approx. 10^{25} particles/cm^3) means that the required energy confinement time (10^{-9} seconds) is much shorter than for magnetic confinement fusion, where a confinement time of at least 1 second is required for a plasma density of 10^{14} particles/cm^3. [5]

What’s the difference between nuclear fusion and nuclear fission?

Both nuclear fusion and nuclear fission release the energy bound in atomic nuclei. However, there is one key difference. In **nuclear fusion**, energy is released when atomic nuclei with a low number of protons (light elements) merge with each other to **form elements with a higher number of protons** in their nucleus. In **nuclear fission**, on the other hand, energy is released by splitting atomic nuclei with a high number of protons (heavy elements). Fission produces elements **with a lower number of protons** in the atomic nucleus.

In most types of nuclear fission power plant, special measures must be taken to prevent an unwelcome chain reaction from occurring. This is not an issue with nuclear fusion, where the nuclear reaction only occurs if the required product of plasma pressure, plasma temperature and confinement time is maintained. It is technically challenging to achieve this. If the pressure changes due to a leak, for example, the reaction quickly stops of its own accord. In contrast to nuclear fission power plants, in which the reactor chamber contains fuel quantities for longer operation, in fusion power plants the fuel would be continuously fed into the plasma chamber from outside. Without additional fuel and due to the rapid termination of the nuclear fusion reaction, the formation of radioactive nuclei ceases very quickly. In addition, decay heat hardly ever occurs in fusion reactions. Continuous cooling of the reactor core to dissipate this heat is therefore not necessary - unlike in nuclear fission power plants where decay heat is generated by short-lived fission products. In other words, if a fusion power plant is damaged, it enters a safe state more or less automatically.

	Nuclear fusion	Nuclear fission
Process	• merging of atomic nuclei	• splitting of atomic nuclei
Fuels	• light elements and their isotopes, mainly the hydrogen isotopes deuterium (^{2}H) and tritium* (^{3}H)	• heavy elements, often uranium* (^{235}U) or plutonium* (^{239}Pu)
Reaction products	• depends on fuel • Example: deuterium and tritium react to form helium (^{4}He) plus a neutron	• depends on fuel • Example: uranium* (^{235}U) is split into various radioactive materials (e.g. strontium* (^{90}Sr), caesium* (^{137}Cs), barium* (^{145}Ba)), neutrons, electrons and stable elements
Temperature/energy production	• initially, extremely high, externally generated temperatures needed to start the reaction (approximately 100 - 150 million degrees Celsius) • nuclear fusion generates kinetic energy and thus heat that is used to produce energy	• approximately 290 - 1,000 degrees Celsius in the primary circuit[3] [8; 9]; the fission process generates kinetic energy/heat that is used to produce energy
Safety	• no uncontrollable chain reaction, but can produce tritium* • radioactive waste may be generated, depending on the fusion method used and the reactor materials and/or fuels • radioactive waste is generally low-level to intermediate-level and must be stored for approximately 100 years until it decays [7; 4; 10]	• risk of accidents resulting in uncontrollable chain reactions and release of (highly) radioactive materials • high levels of radiation with long half-lives, especially from spent fuel • radioactive waste ranges from low-level to high-level; if high-level, final disposal in Germany planned for up to 1 million years[4]

Table 1: The differences between nuclear fusion and nuclear fission

*radioactive

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[3] Boiling water reactors: approximately 290 degrees Celsius at 70 bars; pressurised water reactors (commonest reactor type worldwide): approximately 320 degrees Celsius at 160 bars; ranging to high-temperature reactors with temperatures of > 1,000 degrees Celsius [8; 9].

[4] Repository Site Selection Act, Article 1.2

What are the current concepts for nuclear fusion power plants?

Research into the potential use of nuclear fusion to produce electricity and in some cases also heat is focused on **two fundamental principles**: magnetic confinement fusion and inertial confinement fusion. If successful, both approaches would be implemented as **thermal power plants**. The particles released in the nuclear fusion reaction, mostly neutrons, are trapped and decelerated by the plasma chamber's first wall or the reactor vessel, converting their kinetic energy into heat. The heat is routed through a heat exchanger respectively circuit which produces hot steam. The steam drives turbines which in turn power generators that generate the desired electricity. [4; 11; 12; 7]

Magnetic confinement fusion

In **magnetic confinement fusion**, the ionised gas containing the fuel for the nuclear fusion reaction is confined within the reactor by means of strong magnetic fields. An external heating system heats the fuel mix to over 100 million degrees Celsius, causing it to enter the plasma state and enabling ignition of the nuclear fusion reaction. To achieve plasma ignition, the heating system supplies between 50 and 100 megawatts of power for a few seconds [13]. Once the atomic nuclei fuse and the heat generated is sufficient for the **plasma** to become **self-sustaining**, the heating system can be switched off. [1; 11; 12; 13] Due to the longer confinement time at roughly the same temperature, the plasma does not need to be heavily compressed like it does in inertial confinement fusion – a pressure of 3-7 bars is enough. To achieve optimal energy transport in the plasma, magnetic confinement fusion reactors will need to be large devices with a plasma chamber volume of about 1,000 cubic metres. [4]

Magnetic confinement of the plasma ensures that the particles in the plasma collide often enough to be able to fuse together. It also prevents the plasma from touching the plasma chamber's first wall and dissipating its energy. If this happened, it would lose its plasma state and the nuclear fusion reaction would end. Moreover, contact with the plasma chamber's wall could scour off particles that would contaminate the plasma. [1; 11; 12]

The two most important **types** of magnetic confinement fusion **reactor** are the tokamak and the stellarator. Both use magnets to confine the plasma in a ring-shaped plasma vessel. However, they differ with regard to the geometry of the magnetic fields inside the plasma chamber (see Figure 2).

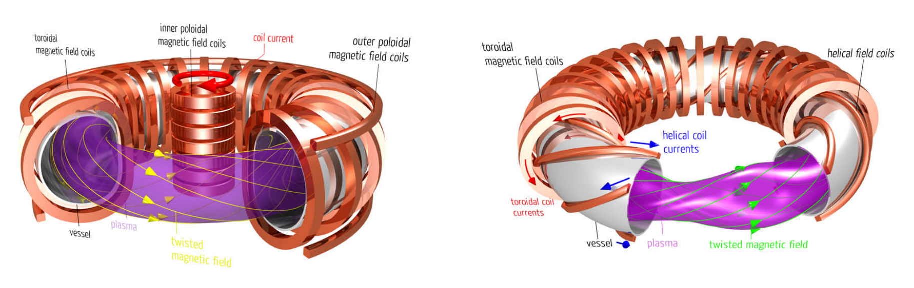

Figure 2: Comparison of the design of a tokamak (left) and a stellarator (right). Source: © Wengenmayr, R. | MPI für Plasmaphysik / CC BY-NC-ND 4.0 [14]

In a **tokamak**, the plasma is confined by three superposed magnetic fields. The doughnut-shaped torus is surrounded by coils that create a ring-shaped magnetic field (see Figure 2). A second magnetic field that introduces a twist in the particles' movement is required to stop the plasma getting too close to the plasma chamber wall and to enable uniform energy distribution in the plasma. It is created by running an electric current through the plasma that is induced by a transformer coil inside the tokamak. The third magnetic field, which is generated by vertical coils, confines the plasma current from above and below. The drawback of this relatively simple design is that, in current tokamaks, after a while the transformer coil that induces the internal electric current must be switched off and on again. This is referred to as pulsed operation. [11; 15] However, research ideas have been proposed that could potentially enable steady-state operation.

By contrast, the **stellarator** is capable of steady-state operation. While a tokamak uses an electric current to achieve the extra twist of the particles in the plasma chamber, in a stellarator the twist is generated by the specific arrangement and shape of the magnetic coils. There is thus no need to run an electric current through the plasma. However, the arrangement of the coils is so complex that it could not be realised until the 1980s, when mainframe computers became powerful enough to run the necessary simulations. [11; 16]

Inertial confinement fusion

Unlike magnetic confinement fusion, in **inertial confinement fusion** the conditions required for fusion are only achieved for a very short time, usually just a few nanoseconds. **High-power lasers or ion beams** are fired at a "target". The targets are capsules or pellets of a few millimetres in diameter containing the fuels that will fuse together.

It is called "inertial confinement fusion" because **inertia** is critical to achieving plasma ignition (see Figure 3). During the very short, intense burst of energy, the fuel under the target's outer layer is compressed enough to achieve the conditions needed to ignite the plasma: a temperature of over 100 million degrees Celsius, a pressure of hundreds of gigabars and a density greater than 1,000 times solid density. Once the plasma ignites, the energy from the nuclear fusion reaction is released outwards. [4; 17]

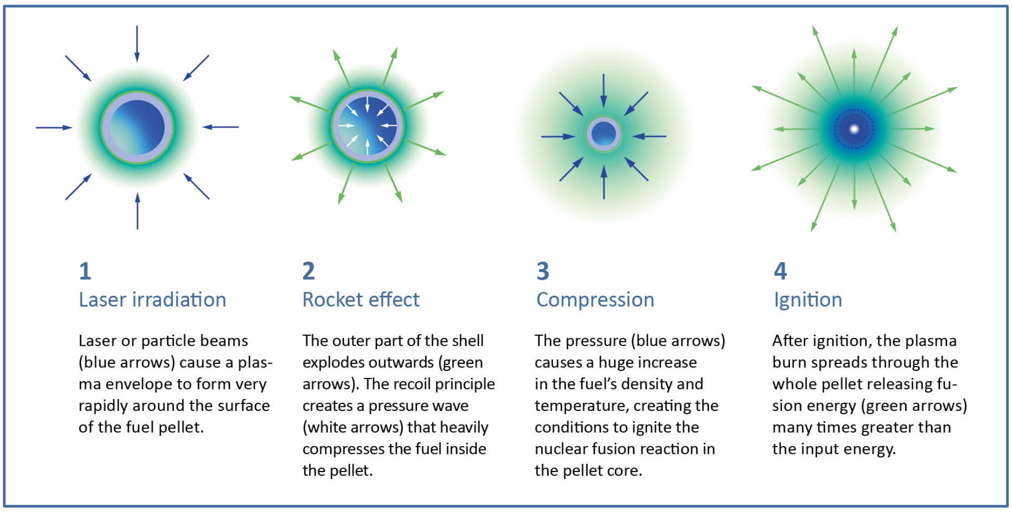

Figure 3: The inertial confinement fusion (ICF) process. Source: Illustration from FOCUSED ENERGY [18] with adapted text.

Current research in the field of inertial confinement fusion is focused on **a number of different basic concepts**. The indirect drive process is the most advanced, followed by direct drive, fast ignition and shock ignition. [4; 1; 19]:

- In the **indirect drive** approach, the target is inside a cylindrical shell. The laser beams enter the shell through openings in its walls, generating X-rays (referred to as “blackbody radiation”) when they hit its inner wall. This radiation hits the target in the centre of the cylinder from all sides, uniformly compressing it until a nuclear fusion reaction is ignited.

- In the **direct drive** approach, the high-power laser beams are focused directly on the fuel pellet from all sides. Firing the beams directly at the target ensures that the energy is delivered to it more efficiently than in the indirect drive approach. However, the laser or ion beams must hit the fuel pellet extremely symmetrically from all sides or the uniform compression of the target required to ignite the plasma will not be achieved.

- Unlike the direct and indirect drive approaches, in the **fast ignition** approach the compression stage induced by laser or energy pulses is not continued until the fusion reaction is ignited. Ignition is initiated by a short additional laser or ion beam pulse that is delivered inside the pre-compressed target through a hole or “cone”. With this approach, less energy is needed to achieve ignition.

- The **shock ignition** approach also decouples the compression and ignition stages. Following the laser-induced compression stage, ignition is initiated by a second, short, very high-energy laser pulse, creating a shock wave that hits the target. Unlike in fast ignition, however, it is not delivered directly inside the target. In both of these approaches, the indirect or direct drive methods can be used for the target compression stage.

Which fuels are used in nuclear fusion?

Since the same chemical elements fuse together in both magnetic and inertial confinement fusion, both approaches can in principle use the same fuels. The higher the number of protons in the nuclei of the elements to be fused together, the higher the amount of energy required to overcome the repulsive forces between the nuclei. The most reactive and easiest to achieve nuclear fusion reaction is between the two hydrogen isotopes[5] **deuterium** and **tritium**, since hydrogen atoms only have one proton in their nucleus. [20] Nuclear fusion can be achieved at a lower temperature with these fuels than with any other fuel combination. This reaction also has the highest theoretical fusion return, i.e. the highest ratio of energy output to energy input into the plasma. Consequently, deuterium and tritium are the most widely used fuels in nuclear fusion experiments, and are currently regarded as the likeliest candidates for use in fusion power plants. [4; 21; 22]

However, this fuel combination is not without its drawbacks. Tritium is radioactive (it is a beta emitter with a half-life of 12 years) and would need to be specially produced, since only tiny amounts occur naturally. Moreover, the neutrons emitted from nuclear fusion reactions activate the materials that the reactor core components are made from, usually turning them into sources of low- to intermediate-level radiation. For these and other reasons, researchers are also investigating fusion reactions that use other chemical elements as fuel. These include the reaction between two **deuterium atoms**, between two **helium atoms**, between **deuterium and helium** and between simple hydrogen and boron. The latter is also known as the **proton-boron reaction**. Some of these reactions produce comparatively few neutrons, reducing the level of radiation from activated reactor materials. However, much more energy is required to form the plasma in these reactions due to the higher number of particles in the nuclei of the chemical elements being fused together. Furthermore, the higher temperatures or pressures needed for these reactions place even greater demands on the materials used in the reactor. [4; 21; 22]

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[5] A simple hydrogen atom (^{1}H) has just one proton in its nucleus. The nucleus of deuterium (^{2}H/D), also known as heavy hydrogen, contains one proton and one neutron. Tritium (^{3}H/T), or “super-heavy hydrogen”, has a second neutron in its nucleus. Some 99.99 percent of the naturally-occurring hydrogen on Earth is simple hydrogen. Just 0.015 percent of naturally-occurring hydrogen is deuterium, while the figure for tritium is far lower still (10^{-15} percent). [20]

The history of nuclear fusion

People have contemplated using nuclear fusion to produce energy for over 100 years. The British astrophysicist Arthur Eddington set out this vision in his 1920 paper "The Internal Constitution of the Stars" [23]. The American physicist and chemist Irving Langmuir's investigations of ionised gases led him to coin the term "plasma" in 1928 [24]. In 1934, Mark Oliphant, Paul Hareck and Ernest Rutherford achieved the first human-caused nuclear fusion reaction. Helium was produced when a particle accelerator fired deuterium nuclei at a metallic foil. They also discovered the hydrogen isotope tritium in a subsequent experiment. [25; 26; 27]

The first concepts for the civilian use of nuclear fusion to produce energy were based on the magnetic confinement fusion approach. The tokamak reactor concept was developed by the Soviet researchers Andrei Sakharov and Igor Tamm in 1950 [28]. Just one year later, the American astronomer and physicist Lyman Spitzer produced a design for the second main magnetic confinement fusion concept, the stellarator [29].

However, it was military purposes, not the goal of producing energy, that was the main driver of systematic nuclear fusion research in the 1950s. The potential of nuclear fusion for military nuclear weapons research had become apparent in the 1940s [30], ultimately leading to the development of the hydrogen bomb in both the USA and the Soviet Union.[6] [31; 32; 33] Due to the onset of the Cold War, even most non-military, energy-related research was thus kept secret in both countries [34].

The 1958 "Atoms for Peace" conference in Geneva marked a turning point. In view of the numerous challenges facing nuclear fusion and plasma research, the US military declassified its magnetic confinement fusion concepts so that, together with models for potential reactors and power plants, they could be presented to and discussed with researchers around the world. This move marked the start of targeted international cooperation in civilian nuclear fusion research. [35; 34; 36]

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[6] The USA detonated the first hydrogen bomb at ground level in 1952. In 1953, the Soviet Union successfully tested a nuclear fission bomb where 20 percent of the energy came from a nuclear fusion reaction. This was followed by the first "proper" air-dropped Soviet hydrogen bomb in 1955. [31; 32; 33]

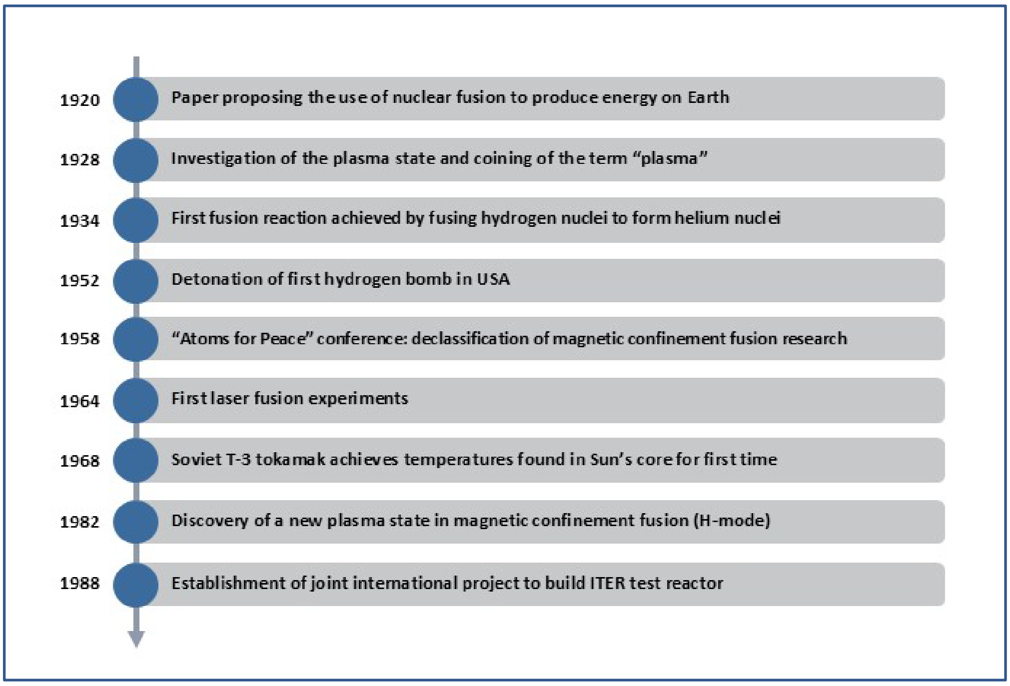

Figure 4: Selected historical milestones in the development of nuclear fusion. Source: authors' own illustration.

In the early 1960s, researchers discovered that instabilities can develop in plasmas, leading to the rapid loss of thermal and magnetic energy. This remains a challenge for the tokamak concept to this day [36]. Nevertheless, a breakthrough came in 1968, when a group of Soviet scientists led by Andrei Sakharov and Igor Tamm became the first to achieve temperatures similar to those in the Sun's core with their T-3 tokamak. The T-3's performance was ten times higher than any other fusion machine at the time. As a result of this success, the tokamak became the leading design concept for nuclear fusion reactors for many years. [27; 37; 36]

The discovery of lasers in the 1960s expanded the range of technological approaches to nuclear fusion. Magnetic confinement fusion research was now joined by research into inertial confinement/laser fusion. [38] The idea of using pulsed laser energy to start a nuclear fusion reaction occurred to both Soviet and American scientists. In 1964, Nikolai Basov and Oleg Krokhin started experimenting with this concept in the Soviet Union. [39] However, the first developments in this field were once again classified as military secrets. The publication of a paper on laser compression [40] in 1972 led to a surge of interest in inertial confinement fusion among researchers, which contributed to its eventual declassification. [41; 42]

International cooperation on the use of nuclear fusion to produce energy intensified in the 1970s. In 1978, Euratom[7], along with Sweden and Switzerland, reached an agreement to build the JET (Joint European Torus) tokamak in the UK. Once completed, this would remain the largest reactor of its kind for many years. [43; 44; 45] Prompted by the oil crisis, several alternative confinement concepts were pursued in parallel and supported through targeted public funding. This led to significant advances in basic and concomitant research. [27]

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[7] At the time, the European Atomic Energy Community (Euratom) was an organisation of the European Community (EC), the predecessor of the European Union (EU). The treaty that established it in 1957 was one of the first treaties to institute cooperation between the countries of Europe in a specific area. Its mission is to promote, coordinate and strengthen research into and the development of civilian uses of nuclear power among the member states. Accordingly, nuclear fusion research forms part of its remit, and Euratom was/is involved in the initiatives to build the JET (tokamak/UK/no longer operational) and ITER (tokamak/France/under construction) research reactors. [43; 44; 45]

Meanwhile, the IAEA (International Atomic Energy Agency) coordinated research into associated aspects such as the potential environmental impacts and safety issues. [36] The development of supercomputers in the 1980s was a key milestone for the stellarator concept, since for the first time it was now possible to calculate configurations for the complex interplay between its coils. [34; 46]

As Cold War tensions eased, in autumn 1985 the Soviet and American leaders Mikhail Gorbachev and Ronald Reagan proposed a collaborative project on the use of nuclear fusion for peaceful purposes. This led to the establishment of the international joint venture ITER (International Thermonuclear Experimental Reactor) three years later. As well as the Soviet Union and the USA, ITER's other founding members included Japan and the European Community (EC).[8] The aim of this tokamak demonstration reactor, which is currently under construction in Cadarache, France, is to confirm the fundamental technological feasibility of industrial-scale fusion energy. However, the energy produced by the test reactor will not be greater than the energy needed to operate the entire device, and it will also not supply electricity to the grid. The intention is for these steps to be achieved by ITER's successor, the DEMO prototype power plant, which is currently scheduled to commence operation around 2050. [47; 48; 49]

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[8] The current members of the ITER consortium are China, Euratom (including the UK), India, Japan, South Korea, Russia and the USA.

What recent advances have there been in nuclear fusion research?

For many years now, nuclear fusion research has raised hopes of a new, climate-friendly energy source. The current surge in public interest in nuclear fusion is partly driven by the **research successes** achieved in this field in recent months and years, some of which have also attracted public attention:

- The current record for maintaining a stable plasma is around seventeen-and-a-half minutes. The record was set in December **2021** in a magnetic confinement fusion experiment with China's Experimental Advanced Superconducting Tokamak (EAST). [50]
- In December **2022**, a laser fusion experiment at the National Ignition Facility (NIF) in the USA achieved the first nuclear fusion reaction in the lab where **the amount of energy produced exceeded** the amount of energy input into the plasma chamber to start the fusion reaction. However, a positive energy balance was not achieved for the entire device, since the amount of energy required to operate the lasers, diagnostics technology, control systems, etc. was still several times greater than the energy produced. [51; 21]
- In February **2023**, Germany's Wendelstein 7-X test reactor set a new record for the plasma discharge time in a stellarator. The magnetic confinement fusion experiment managed to maintain the plasma for approximately eight minutes. [52]
- Europe's now defunct JET tokamak research reactor set a new energy record for a nuclear fusion experiment. On 3 October **2023**, 69 megajoules of energy were released during a 5.2 second plasma discharge. However, the energy input to ignite the plasma in this magnetic confinement fusion experiment was still greater than the energy produced by the reaction. [53]

In addition to these research successes, nuclear fusion has received a substantial boost from the significant recent rise in the number of startups around the world devoted to its commercial realisation. Some of these enterprises are pursuing technology concepts that are no longer being specifically pursued by established research institutions or are still in the very early stages of development. As well as expanding the range of technological solutions that could potentially be deployed, these startups are also raising substantial additional research and development funding for the realisation of nuclear fusion from private investors. [54; 55]

Can nuclear fusion help to meet the climate targets?

Bearing in mind the advances that have been achieved to date and the remaining challenges outlined above, many experts estimate that it will be at least 20 to 25 years before the first prototype or commercial power plant is built, assuming that there are no surprise disruptive breakthroughs in the meantime. Consequently, if nuclear fusion makes any contribution at all to meeting the energy transition targets of ending fossil fuel use by 2045 in Germany and 2050 in the EU, it will come towards the end of this period and will be correspondingly small. [56]

Systematic advances in nuclear fusion research have been achieved over the past few years. However, there is still **a long way to go before a fully operational power plant can be built**. A commercially viable fusion power plant will require a severalfold improvement in the energy balance, i.e. the total net energy yield calculated as the difference between the power plant's total energy consumption and losses and the amount of energy it produces. **None of the nuclear fusion concepts** currently has a power plant-scale **prototype**. In other words, both the technological feasibility and eventual commercial viability of a power plant have yet to be demonstrated. Based on current knowledge, the main areas where **further technological advances** are required include the design of the reactor core components, the development of materials robust enough to withstand neutron bombardment and extreme temperatures, the production of tritium fuel and fuel pellets (targets), and the power and shot rate of the lasers. [56]

If commercial nuclear fusion can be successfully realised within the abovementioned timeframe, its low CO_2 emissions mean that it could make a meaningful contribution to a climate-friendly energy supply from the second half of the century. In this scenario, however, it would encounter a profoundly transformed energy system in Germany and much of Europe. By this time, many solutions will be electrically powered and the energy system will have a more decentralised structure and be largely based on renewable energy. Fusion power plants are currently expected to be in the 1 gigawatt electrical output (1 GW_{el}) range, comparable to today's coal-fired and nuclear power plants. The high investment costs for their construction and relatively low operating costs mean that, like today's base load power plants, they would need to produce electricity more or less continuously.

Nuclear fusion power plants falling into the large power plant category could be integrated with the future energy system, provided that the system is flexible enough. A key way of achieving this flexibility could be through integration with the new hydrogen system, which will need to be built anyway to integrate the large number of renewable energy installations into the energy system. However, it is not currently possible to predict with any confidence whether nuclear fusion can become commercially viable. This will largely be determined by the cost of the electricity supplied by fusion power plants. [57; 56]

The fact that nuclear fusion is still in the early stages of development and a lot of further research is required means that, for the time being, it is hard to say what role it will play in the future energy system. If successfully realised, it has the potential to contribute to a climate-friendly energy supply, probably from the second half of the century. However, it is not yet known when, if at all, fusion power plants will be able to supply electricity to the grid and how much this energy will cost. Consequently, the energy sector must continue to focus on achieving a secure, net-zero energy supply by the middle of the century, with or without fusion power plants. If nuclear fusion can provide an additional future source of climate-friendly energy, it will be a valuable asset for helping humanity to significantly limit global warming in years to come.

More on this topic

What is the current state of nuclear fusion research? Which challenges have yet to be overcome? What role could fusion power plants play in the future energy system and when might the first fusion power plant start supplying electricity to the grid? These additional questions are addressed by the ESYS Discussion Paper:

Wurbs, Sven/ Dehlwes, Sonja et al. "Can Nuclear Fusion Contribute to a Net-Zero Energy Supply? Opportunities, Challenges and Timeframes" (Discussion Paper), "Energy Systems of the Future" (ESYS) series, 2024, https://doi.org/10.48669/esys_2024-12.

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