Nuclear Fusion Power

(Updated November 2017)

- **Fusion power offers the prospect of an almost inexhaustible source of energy for future generations, but it also presents so far insurmountable engineering challenges.**
- **The fundamental challenge is to achieve a rate of heat emitted by a fusion plasma that exceeds the rate of energy injected into the plasma.**
- **The main hope is centred on tokamak reactors and stellarators which confine a deuterium-tritium plasma magnetically.**

Today, many countries take part in fusion research to some extent, led by the European Union, the USA, Russia and Japan, with vigorous programs also underway in China, Brazil, Canada, and Korea. Initially, fusion research in the USA and USSR was linked to atomic weapons development, and it remained classified until the 1958 Atoms for Peace conference in Geneva. Following a breakthrough at the Soviet tokamak, fusion research became 'big science' in the 1970s. But the cost and complexity of the devices involved increased to the point where international co-operation was the only way forward.

Fusion powers the Sun and stars as hydrogen atoms fuse together to form helium, and matter is converted into energy. Hydrogen, heated to very high temperatures changes from a gas to a plasma in which the negatively-charged electrons are separated from the positively-charged atomic nuclei (ions). Normally, fusion is not possible because the strongly repulsive electrostatic forces between the positively charged nuclei prevent them from getting close enough together to collide and for fusion to occur. However, if the conditions are such that the nuclei can overcome the electrostatic forces to the extent that they can come within a very close range of each other, then the attractive nuclear force (which binds protons and neutrons together in atomic nuclei) between the nuclei will outweigh the repulsive (electrostatic) force, allowing the nuclei to fuse together. Such conditions can occur when the temperature increases, causing the ions to move faster and eventually reach speeds high enough to bring the ions close enough together. The nuclei can then fuse, causing a release of energy.

Fusion technology

In the Sun, massive gravitational forces create the right conditions for fusion, but on Earth they are much harder to achieve. Fusion fuel – different isotopes of hydrogen – must be heated to extreme temperatures of the order of 50 million degrees Celsius, and must be kept stable under intense pressure, hence dense enough and confined for long enough to allow the nuclei to fuse. The aim of the controlled fusion research program is to achieve 'ignition', which occurs when enough fusion reactions take place for the process to become self-sustaining, with fresh fuel then being added to continue it. Once ignition is achieved, there is net energy yield – about four times as much as with nuclear fission. According to the Massachusetts Institute of Technology (MIT), the amount of power produced increases with the square of the pressure, so doubling the pressure leads to a fourfold increase in energy production.

With current technology, the reaction most readily feasible is between the nuclei of the two heavy forms (isotopes) of hydrogen – deuterium (D) and tritium (T). Each D-T fusion event releases 17.6 MeV (2.8 x 10^{-12} joule, compared with 200 MeV for a U-235 fission and 3-4 MeV for D-D fusion).[a] On a mass basis, the D-T fusion reaction releases over four times as much energy as uranium fission. Deuterium occurs naturally in seawater (30 grams per cubic metre), which makes it very abundant relative to other energy resources. Tritium occurs naturally only in trace quantities (produced by cosmic rays) and is radioactive, with a half-life of around 12 years. Usable quantities can be made in a conventional nuclear reactor, or in the present context, bred in a fusion system from lithium.[b] Lithium is found in large quantities (30 parts per million) in the Earth's crust and in weaker concentrations in the sea.

In a fusion reactor, the concept is that neutrons generated from the D-T fusion reaction will be absorbed in a blanket containing lithium which surrounds the core. The lithium is then transformed into tritium (which is used to fuel the reactor) and helium. The blanket must be thick enough (about 1 metre) to slow down the high-energy (14 MeV) neutrons. The kinetic energy of the neutrons is absorbed by the blanket, causing it to heat up. The heat energy is collected by the coolant (water, helium or Li-Pb eutectic) flowing through the blanket and, in a fusion power plant, this energy will be used to generate electricity by conventional methods. If insufficient tritium is produced, some supplementary source must be employed such as using a fission reactor to irradiate heavy water or lithium with neutrons, and extraneous tritium creates difficulties with handling, storage and transport.

The difficulty has been to develop a device that can heat the D-T fuel to a high enough temperature and confine it long enough so that more energy is released through fusion reactions than is used to get the reaction going. While the D-T reaction is the main focus of attention, long-term hopes are for a D-D reaction, but this requires much higher temperatures.

In any case, the challenge is to apply the heat to human needs, primarily generating electricity. The energy density of fusion reactions in gas is very much less than for fission reactions in solid fuel, and as noted the heat yield per reaction is 70 times less. Hence thermonuclear fusion will always have a much lower power density than nuclear fission, which means that any fusion reactor needs to be larger and therefore more costly, than a fission reactor of the same power output. In addition, nuclear fission reactors use solid fuel which is denser than a thermonuclear plasma, so the energy released is more concentrated.

At present, two main experimental approaches are being studied: magnetic confinement and inertial confinement. The first method uses strong magnetic fields to contain the hot plasma. The second involves compressing a small pellet containing fusion fuel to extremely high densities using strong lasers or particle beams.

Magnetic confinement

In magnetic confinement fusion (MCF), hundreds of cubic metres of D-T plasma at a density of less than a milligram per cubic metre are confined by a magnetic field at a few atmospheres pressure and heated to fusion temperature.

Magnetic fields are ideal for confining a plasma because the electrical charges on the separated ions and electrons mean that they follow the magnetic field lines. The aim is to prevent the particles from coming into contact with the reactor walls as this will dissipate their heat and slow them down. The most effective magnetic configuration is toroidal, shaped like a doughnut, in which the magnetic field is curved around to form a closed loop. For proper confinement, this toroidal field must have superimposed upon it a perpendicular field component (a poloidal field). The result is a magnetic field with force lines following spiral (helical) paths that confine and control the plasma.

There are several types of toroidal confinement system, the most important being tokamaks, stellarators and reversed field pinch (RFP) devices.

In a tokamak, the toroidal field is created by a series of coils evenly spaced around the torus-shaped reactor, and the poloidal field is created by a system of horizontal coils outside the toroidal magnet structure. A strong electric current is induced in the plasma using a central solenoid, and this induced current also contributes to the poloidal field. In a stellarator, the helical lines of force are produced by a series of coils which may themselves be helical in shape. Unlike tokamaks, stellarators do not require a toroidal current to be induced in the plasma. RFP devices have the same toroidal and poloidal components as a tokamak, but the current flowing through the plasma is much stronger and the direction of the toroidal field within the plasma is reversed.

In tokamaks and RFP devices, the current flowing through the plasma also serves to heat it to a temperature of about 10 million degrees Celsius. Beyond that, additional heating systems are needed to achieve the temperatures necessary for fusion. In stellarators, these heating systems have to supply all the energy needed.

The tokamak (*toroidalnya kamera ee magnetnaya katushka* – torus-shaped magnetic chamber) was designed in 1951 by Soviet physicists Andrei Sakharov and Igor Tamm. Tokamaks operate within limited parameters outside which sudden losses of energy confinement (disruptions) can occur, causing major thermal and mechanical stresses to the structure and walls. Nevertheless, it is considered the most promising design, and research is continuing on various tokamaks around the world.

Research is also being carried out on several types of stellarator. Lyman Spitzer devised and began work on the first fusion device – a stellarator – at the Princeton Plasma Physics Laboratory in 1951. Due to the difficulty in confining plasmas, stellarators fell out of favour until computer modelling techniques allowed accurate geometries to be calculated. Because stellarators have no toroidal plasma current, plasma stability is increased compared with tokamaks. Since the burning plasma can be more easily controlled and monitored, stellerators have an intrinsic potential for steady-state, continuous operation. The disadvantage is that, due to their more complex shape, stellarators are much more complex than tokamaks to design and build.

RFP devices differ from tokamaks mainly in the spatial distribution of the toroidal magnetic field, which changes sign at the edge of the plasma. The RFX machine in Padua, Italy is used to study the physical problems arising from the spontaneous reorganisation of the magnetic field, which is an intrinsic feature of this configuration.

Inertial confinement

In inertial confinement fusion (ICF), which is a newer line of research, laser or ion beams are focused very precisely onto the surface of a target, which is a pellet of D-T fuel, a few millimetres in diameter. This heats the outer layer of the material, which explodes outwards generating an inward-moving compression front or implosion that compresses and heats the inner layers of material. The core of the fuel may be compressed to one thousand times its liquid density, resulting in conditions where fusion can occur. The energy released then would heat the surrounding fuel, which may also undergo fusion leading to a chain reaction (known as ignition) as the reaction spreads outwards through the fuel. The time required for these reactions to occur is limited by the inertia of the fuel (hence the name), but is less than a microsecond. So far, most inertial confinement work has involved lasers.

Recent work at Osaka University's Institue of Laser Engineering in Japan suggests that ignition may be achieved at lower temperature with a second very intense laser pulse guided through a millimetre-high gold cone into the compressed fuel, and timed to coincide with the peak compression. This technique, known as 'fast ignition', means that fuel compression is separated from hot spot generation with ignition, making the process more practical.

A completely different concept, the 'Z-pinch' (or 'zeta pinch'), uses a strong electrical current in a plasma to generate X-rays, which compress a tiny D-T fuel cylinder.

Magnetized target fusion

Magnetized target fusion (MTF), also referred to as magneto-inertial fusion (MIF), is a pulsed approach to fusion that combines the compressional heating of inertial confinement fusion with the magnetically reduced thermal transport and magnetically enhanced alpha heating of magnetic confinement fusion.

A range of MTF systems are currently being experimented with, and commonly use a magnetic field to confine a plasma with compressional heating provided by laser, electromagnetic or mechanical liner implosion. As a result of this combined approach, shorter plasma confinement times are required than for magnetic confinement (from 100 ns to 1 ms, depending on the MIF approach), reducing the requirement to stabilize the plasma for long periods. Conversely, compression can be achieved over timescales longer than those typical for inertial confinement, making it possible to achieve compression through mechanical, magnetic, chemical, or relatively low-powered laser drivers.

Several approaches are underway to examine MTF, including experiments at Los Alamos National Laboratory, Sandia National Laboratory, the University of Rochester, and private companies General Fusion and Helion Energy.

R&D challenges for MTF include whether a suitable target plasma can be formed and heated to fusion conditions while avoiding contamination from the liner, as with magnetic confinement and inertial confinement. Due to the reduced demands on confinement time and compression velocities, MTF has been pursued as a lower-cost and simpler approach to investigating these challenges than conventional fusion projects.

Hybrid fusion

Fusion can also be combined with fission in what is referred to as hybrid nuclear fusion where the blanket surrounding the core is a subcritical fission reactor. The fusion reaction acts as a source of neutrons for the surrounding blanket, where these neutrons are captured, resulting in fission reactions taking place. These fission reactions would also produce more neutrons, thereby assisting further fission reactions in the blanket.

The concept of hybrid fusion can be compared with an accelerator-driven system (ADS), where an accelerator is the source of neutrons for the blanket assembly, rather than nuclear fusion reactions (see page on Accelerator-driven Nuclear Energy). The blanket of a hybrid fusion system can therefore contain the same fuel as an ADS – for example, the abundant element thorium or the long-lived heavy isotopes present in used nuclear fuel (from a conventional reactor) could be used as fuel.

The blanket containing fission fuel in a hybrid fusion system would not require the development of new materials capable of withstanding constant neutron bombardment, whereas such materials would be needed in the blanket of a 'conventional' fusion system. A further advantage of a hybrid system is that the fusion part would not need to produce as many neutrons as a (nonhybrid) fusion reactor would in order to generate more power than is consumed – so a commercial-scale fusion reactor in a hybrid system does not need to be as large as a fusion-only reactor.

Fusion research

A long-standing quip about fusion points out that, since the 1970s, commercial deployment of fusion power has always been about 40 years away. While there is some truth in this, many breakthroughs have been made, particularly in recent years, and there are a number of major projects under development that may bring research to the point where fusion power can be commercialised.

Several **tokamaks** have been built, including the Joint European Torus (JET) and the Mega Amp Spherical Tokamak (MAST) in the UK and the tokamak fusion test reactor (TFTR) at Princeton in the USA. The ITER (International Thermonuclear Experimental Reactor) project currently under construction in Cadarache, France will be the largest tokamak when it operates in the 2020s. The Chinese Fusion Engineering Test Reactor (CFETR) is a tokamak which is reported to be larger than ITER, and due for completion in 2030. Meanwhile it is running its Experimental Advanced Superconducting Tokamak (EAST).

Much research has also been carried out on **stellarators**. A large one of these, the Large Helical Device at Japan's National Institute of Fusion Research, began operating in 1998. It is being used to study the best magnetic configuration for plasma confinement. At the Garching site of the Max Planck Institute for Plasma Physics in Germany, research carried out at the Wendelstein 7-AS between 1988 and 2002 is being progressed at the Wendelstein 7-X, which was built over 19 years at Max Planck Institute's Greifswald site and started up at the end of 2015. Another stellarator, TJII, is in operation in Madrid, Spain. In the USA, at Princeton Plasma Physics Laboratory, where the first stellarators were built in 1951, construction on the NCSX stellerator was abandoned in 2008 due to cost overruns and lack of funding[2].

There have also been significant developments in research into **inertial confinement fusion**. Construction of the $7 billion National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL), funded by the National Nuclear Security Administration, was completed in March 2009. The Laser Mégajoule (LMJ) in France’s Bordeaux region started operation in October 2014. Both are designed to deliver, in a few billionths of a second, nearly two million joules of light energy to targets measuring a few millimeters in size. The main purpose of both NIF and LMJ is for research to support both countries' respective nuclear weapons programs.

ITER

In 1985, the Soviet Union suggested building a next generation tokamak with Europe, Japan and the USA. Collaboration was established under the auspices of the International Atomic Energy Agency (IAEA). Between 1988 and 1990, the initial designs were drawn up for an International Thermonuclear Experimental Reactor (ITER, which also means 'a path' or 'journey' in Latin) with the aim of proving that fusion could produce useful energy. The four parties agreed in 1992 to collaborate further on engineering design activities for ITER. Canada and Kazakhstan are also involved through Euratom and Russia, respectively.

Six years later, the ITER Council approved the first comprehensive design of a fusion reactor based on well-established physics and technology with a price tag of $6 billion. Then the USA decided pull out of the project, forcing a 50% reduction in costs and a redesign. The result was the ITER Fusion Energy Advanced Tokomak (ITER-FEAT) – initially expected to cost $3 billion but still achieve the targets of a self-sustaining reaction and a net energy gain. The envisaged energy gain is unlikely to be enough for a power plant, but it should demonstrate feasibility.

In 2003, the USA rejoined the project and China also announced it would join. After deadlocked discussion, the six partners agreed in mid-2005 to site ITER at Cadarache, in southern France. The deal involved major concessions to Japan, which had put forward Rokkasho as a preferred site. The European Union (EU) and France would contribute half of the then estimated €12.8 billion total cost, with the other partners – Japan, China, South Korea, USA and Russia – putting in 10% each. Japan will provide a lot of the high-tech components, will host a €1 billion materials testing facility – the International Fusion Materials Irradiation Facility (IFMIF) – and will have the right to host a subsequent demonstration fusion reactor. India became the seventh member of the ITER consortium at the end of 2005. In November 2006, the seven members – China, India, Japan, Russia, South Korea, the USA and the European Union – signed the ITER implementing agreement. The total cost of the 500 MW ITER comprises about half for the ten-year construction and half for 20 years of operation.

Site preparation works at Cadarache commenced in January 2007. First concrete for the buildings was poured in December 2013. Experiments were due to begin in 2018, when hydrogen will be used to avoid activating the magnets, but this is now expected in 2025. The first D-T plasma is not expected until 2035. ITER is large because confinement time increases with the cube of machine size. The vacuum vessel will be 19 m across and 11 m high, and weigh more than 5000 tonnes.

The goal of ITER is to operate with a plasma thermal output of 500 MW (for at least 400 seconds continuously) with less than 50 MW of plasma heating power input. No electricity will be generated at ITER.

An associated CEA facility at Cadarache is WEST, formerly Tore Supra, which is designed to test prototype components and accelerate their development for ITER. It is focused on the divertor structure to remove helium, testing the durability of tungsten materials used.

A 2 GW Demonstration Power Plant, known as Demo, is expected to demonstrate large-scale production of electrical power on a continual basis. The conceptual design of Demo is expected to be completed by 2017, with construction beginning in around 2024 and the first phase of operation commencing from 2033.

JET

In 1978, the European Community (Euratom, along with Sweden and Switzerland) launched the Joint European Torus (JET) project in the UK. JET is the largest tokamak operating in the world today. A similar tokamak, JT-60, operates at the Naka Fusion Institute of Japan Atomic Energy Agency in Japan, but only JET has the facilities to use D-T fuel.

Following a legal dispute with Euratom, in December 1999 JET's international contract ended and the United Kingdom Atomic Energy Authority (UKAEA) took over the management of JET on behalf of its European partners. From that time JET's experimental programme has been co-ordinated by the European Fusion Development Agreement (EFDA) parties.[c]

JET produced its first plasma in 1983, and became the first experiment to produce controlled fusion power in November 1991, albeit with high input of electricity. Up to 16 MW of fusion power for one second and 5 MW sustained has been achieved in D-T plasmas using the device, from 24 MW of power injected into its heating system, and many experiments are conducted to study different heating schemes and other techniques. JET has been very successful in operating remote handling techniques in a radioactive environment to modify the interior of the device and has shown that the remote handling maintenance of fusion devices is realistic.

JET is a key device in preparations for ITER. It has been significantly upgraded in recent years to test ITER plasma physics and engineering systems. Further enhancements are planned at JET with a view to exceeding its fusion power record in future D-T experiments. A compact device – Mega Amp Spherical Tokamak (MAST) – is also being developed alongside JET, partly to serve the ITER project.

KSTAR

The KSTAR (Korean Superconducting Tokamak Reactor) at the National Fusion Research Institute (NFRI) in Daejeon produced its first plasma in mid-2008. It is a pilot device for ITER, and involves much international collaboration. It will be a satellite of ITER during ITER’s operational phase from the early 2020s. The tokamak with 1.8 metre major radius is the first to use Nb3Sn superconducting magnets, the same material to be used in the ITER project. Its first stage of development to 2012 was to prove baseline operation technologies and achieved plasma pulses of up to 20 seconds. For the second phase of development (2013-2017), KSTAR was upgraded to study long pulses of up to 300 seconds in H mode – the 100s target was in 2015 – and embark upon high-performance AT mode. It achieved 70 seconds in high-performance plasma operation in late 2016, a world record. In addition, KSTAR researchers also succeeded in achieving an alternative advanced plasma operation mode with the internal transport barrier (ITB). This is a steep pressure gradient in the core of the plasmas due to the enhanced core plasma confinement. NFRI said this is the first ITB operation achieved in the superconducting device at the lowest heating power. KSTAR Phase 3 (2018-2023) is to develop high performance, high efficiency AT mode technologies with long-pulse operation. Phase 4 (2023-2025) will test DEMO-related prior arts. The device does not have tritium handling capabilities, so will not use D-T fuel.

K-DEMO tokamak

In collaboration with the US Department of Energy's Princeton Plasma Physics Laboratory (PPPL) in New Jersey and South Korea’s National Fusion Research Institute (NFRI) K-DEMO is intended to be the next step toward commercial reactors from ITER, and would be the first plant to actually contribute power to an electric grid. According to the PPPL, it would generate "some 1 billion watts of power for several weeks on end", a much greater output than ITER's goal of producing 500 million watts for 500 seconds by the late 2020s. K-DEMO is expected to have a 6.65m diameter major radius tokamak, and a test blanket module as part of the DEMO breeding blanket R&D. The Ministry of Education, Science and Technology plans to invest about KRW 1 trillion (US$ 941 million) in the project. About KRW 300 billion of that spending has already been funded. The government expects the project to employ nearly 2,400 people in the first phase, which will last throughout 2016. K-DEMO is expected to have an initial operational phase from about 2037 to 2050 to develop components for the second stage, which would produce electricity.

EAST

In China the Experimental Advanced Superconducting Tokamak (EAST) at China's Institute of Physical Science in Hefei is reported to have produced hydrogen plasma at 50 million degrees centigrade and held it for 102 seconds.

TFTR

In the USA, the Tokamak Fusion Test Reactor (TFTR) operated at the Princeton Plasma Physics Laboratory (PPPL) from 1982 to 1997.[d] In December 1993, TFTR became the first magnetic fusion device to perform extensive experiments with plasmas composed of D-T. The following year TFTR produced 10.7 MW of controlled fusion power – a record at that time. TFTR set other records, including the achievement of a plasma temperature of 510 million degrees centigrade in 1995. However, it did not achieve its goal of break-even fusion energy (where the energy input required is no greater than the amount of fusion energy produced), but achieved all of its hardware design goals, thus making substantial contributions to the development of ITER.

ALCATOR

At the Massachusetts Institute of Technology (MIT) since the 1970s a succession of small ALCATOR (Alto Campus Torus) high magnetic field torus reactors have operated on the principle of achieving high plasma pressure as the route to long plasma confinement. Alcator C-Mod is claimed to have the highest magnetic field and highest plasma pressure of any fusion reactor, and is the largest university-based fusion reactor in the world. It operated 1993-2016. In September 2016 it achieved a plasma pressure of 2.05 atmospheres at a temperature of 35 million degrees Celsius. The plasma produced 300 trillion fusion reactions per second and had a central magnetic field strength of 5.7 tesla. It carried 1.4 million amps of electrical current and was heated with over 4 MW of power. The reaction occurred in a volume of approximately 1 cubic metre and the plasma lasted for two seconds. Having achieved this record performance for a fusion reactor, government funding ceased.

A scaled-up version planned to be built at Triotsk near Moscow in collaboration with the Kurchatov Institute is Ignitor, with 1.3 m diameter torus.

Large Helical Device – stellarator

The Large Helical Device (LHD) at Japan's National Institute for Fusion Science in Toki, in the Gifu Prefecture, was the world's largest stellarator. LHD produced its first plasma in 1998 and has demonstrated plasma confinement properties comparable to other large fusion devices. It has achieved an ion temperature of 13.5 keV (about 160 million degrees) and plasma stored energy of 1.44 million joules (MJ).

Wendelstein 7-X stellarator

Following a year of tests, this started up at the end of 2015, and helium plasma briefly reached about one million degrees centigrade. In 2016 it progressed to using hydrogen, and using 2 MW it achieved plasma of 80 million degrees centigrade for a quarter of a second. W7-X is the world's largest stellarator and it is planned to operate continuously for up to 30 minutes. It cost €1 billion ($1.1 billion).
Some good diagrams are in a Business Insider Australia article on the Wendelstein 7-X.

Heliac-1 stellarator

At the Australian Plasma Fusion Research Facility at the Australian National University the H-1 stellarator has run for some years and in 2014 was upgraded significantly. H-1 is capable of accessing a wide range of plasma configurations and allows exploration of ideas for improved magnetic design of the fusion power stations that will follow ITER.

National Ignition Facility – laser

The world's most powerful laser fusion facility, the $4 billion National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), was completed in March 2009. Using its 192 laser beams, NIF is able to deliver more than 60 times the energy of any previous laser system to its target[e]. LLNL announced in July 2012 that in "an historic record-breaking laser shot, the NIF laser system of 192 beams delivered more than 500 TW of peak power and 1.85 megajoules (MJ) of ultraviolet laser light to its (2mm diameter) target" for a few trillionths of a second. It was reported that in September 2013 at NIF for the first time the amount of energy released through the fusion reaction exceeded the amount of energy being absorbed by the fuel, but not the amount supplied by the giant lasers. Publication of this in 2014 said 17 kJ was released.

An earlier high-power laser at LLNL, Nova, was built in 1984 for the purpose of achieving ignition. Nova failed to do this and was closed in 1999, but provided essential data that led to the design of NIF. Nova also generated considerable amounts of data on high-density matter physics, which is useful both in fusion power and nuclear weapons research.

In connection with NIF, LLNL is developing the Laser Inertial Fusion Engine (LIFE), a hybrid fusion system where neutrons resulting from laser fusion would drive a subcritical nuclear fission blanket to generate electricity. The blanket would contain either depleted uranium; used nuclear fuel; natural uranium or thorium; or plutonium-239, minor actinides and fission products from reprocessed used nuclear fuel[4].

Laser Mégajoule

Meanwhile, the French Atomic Energy Commission (Commissariat à l'énergie atomique, CEA) has operated a similar size laser – the Laser Mégajoule (LMJ) – near Bordeaux since 2014. Its 240 laser beams are able to generate 1.8 MJ pulses for a few billionths of a second, concentrated on a small deuterium and tritium target. A prototype laser, the Ligne d'Integration Laser (LIL), commenced operation in 2003.

SG-II

China's National Laboratory of High-Power Laser and Physics, associated with the China Academy of Science, has a laser inertial confinement experiment in Shanghai – the Shenguang-II eight-beam laser facility (SG-II), similar to the National Ignition Facility in the USA and Laser Mégajoule in France. It is the only high power neodymium-glass solid laser facility with an active probe light in China. In 2005 a ninth beam was added, advancing the capacity for fusion research. The SG-II facility is China's high-power laser technology international demonstration base.

PETAL and HiPER lasers

The Petawatt Aquitaine Laser (PETAL) laser facility is a high energy multi-petawatt laser (3.5 kJ energy with a duration of 0.5 to 5 ps) under construction near Bordeaux, on the same site as LIL. PETAL will be coupled with LIL to demonstrate the physics and laser technology of fast ignition. First experiments are expected in 2012.

The High Power Laser Energy Research Facility (HiPER) is being designed to build on the research planned at the PETAL project. HiPER will use a long pulse laser (currently estimated at 200kJ) combined with a 70kJ short pulse laser. A three-year preparatory phase that commenced in 2008 has direct funding or in-kind commitments amounting to around €70 million from several countries. The detailed engineering phase is projected to begin in 2011, with a six-year construction phase possibly commencing by 2014.

Z machine

Operated by Sandia National Laboratories, the Z machine is the largest X-ray generator in the world. As with NIF, the facility was built as part of the country's Stockpile Stewardship Program, which aims to maintain the stockpile of nuclear weapons without the need for full-scale testing.

Conditions for fusion are achieved by passing a powerful electrical pulse[f] (lasting less than 100 nanoseconds) through a set of fine tungsten wires inside a metal hohlraum[g]. The wires turn into a plasma and experience a compression ('Z-pinch'), forcing the vapourized particles to collide with each other, thereby producing intense X-ray radiation. A tiny cylinder containing fusion fuel placed inside the hohlraum would therefore be compressed by the X-rays, allowing fusion to occur.

In 2006, Z machine had achieved temperatures of over 2 billion degrees,[6] considerably higher than what is needed for fusion, and in theory high enough to allow nuclear fusion of hydrogen with heavier elements such as lithium or boron.

Other fusion projects

There is a considerable amount of research into many other fusion projects at various stages of development.

Lockheed CFR. Lockheed Martin at its so-called 'skunk works' is developing a Compact Fusion Reactor (CFR) which uses conventional D-T plasma in evacuated containment but confines it differently. Instead of constraining the plasma within tubular rings, a series of superconducting coils will generate a new magnetic-field geometry in which the plasma is held within the broader confines of the entire reaction chamber. The energy is supplied by radiofrequency heating. Superconducting magnets within the coils will generate a magnetic field around the outer border of the chamber. The aim is to go to plasma pressure being as great as confining pressure at high enough temperature for ignition and net energy yield. Heat exchangers in the reactor wall would convey energy to a gas turbine. It has progressed to a magentised ion confinement experiment, but has some way to go before any prototype, which they claim will be very much smaller than conventional designs such as the ITER tokamak.

Italy's National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) is developing a small tokamak reactor by the name of **Ignitor**. Under an Italian-Russian agreement signed in May 2010, a reactor will be assembled in Italy and installed at the Kurchatov Institute's Troitsk Institute for Innovation and Fusion Research (TRINITI) near Moscow[7].

An alternative to using powerful lasers for inertial fusion is '**heavy ion fusion**', where high-energy particles from an accelerator are focused using magnetic fields onto the fusion target[h]. Heavy ion fusion experiments are planned for the NDCX-II (Neutralized Drift Compression Experiment II) accelerator, which is under construction (due to be completed in early 2012) at Lawrence Berkeley National Laboratory[8].

The **Polywell** ('polyhedron' combined with 'potential well') device consists of magnetic coils arranged in a polyhedral configuration. The magnetic fields confine a cloud of electrons in the middle of the device so as to be able to accelerate and confine the positive ions to be fused. This concept differs from traditional magnetic confinement because the fields do not need to confine ions – only electrons. As with other fusion methods, sufficient funding is difficult to obtain due to the bulk of fusion research being focused on a few large-scale projects, most notably ITER.

Another line of fusion research using lasers involves fusing hydrogen and boron-11 (**HB11**) to produce helium nuclei, which continue the chain reaction from boron. One laser generates a powerful magnetic confinement field in a coil to trap the fusion reaction in a small area for a nanosecond, while a second more powerful laser triggers the nuclear fusion process. Early HB11 fusion trials at the Prague Asterix Laser System, using high-energy iodine lasers, have generated more energy than needed to trigger the fusion process.

General Fusion is one of a number of private efforts to develop a commercial fusion power plant. The company's magnetized target fusion (MTF) approach generates a compact toroid plasma in an injector, containing and compressing it using a magnetic field before injecting it into a spherical compression chamber. The chamber holds a liquid lead-lithium liner which is pumped to create a vortex, into which the plasma target is injected. A synchronized array of pistons firing simultaneously creates a spherical compression wave in the liquid metal, compressing the plasma target and heating it to fusion conditions. General Fusion, founded in Canada in 2002, is funded by a syndicate of private investors, energy venture capital companies, sovereign wealth funds and the Canadian government's Sustainable Development Technology Canada (SDTC) fund. The company has demonstrated milestones including successfully creating 200-300 eV magnetized spheromak plasmas and confining them for over 500 µs.

Much of current work underway on MTF is derived from programs at the Soviet Kurchatov Institute of Atomic Energy, under E. P. Velikhov, circa 1970. This inspired the LINUS project at the Naval Research Laboratory in the USA, and later the fast-liner project at Los Alamos.

Tokamak Energy in the UK is a private company developing a spherical tokamak, and hopes to commercialize this by 2030. The company grew out of Culham laboratory, home to JET, and its technology revolves around high temperature superconducting (HTS) magnets, which allow for relatively low-power and small-size devices, but high performance and potentially widespread commercial deployment. Its first tokamak with exclusively HTS magnets – the ST25 HTS, Tokamak Energy's second reactor – demonstrated 29 hours' continuous plasma during the Royal Society Summer Science Exhibition in London in 2015, a world record. The next reactor is the ST40 at Milton Park in Oxfordshire, which achieved first plasma in April 2017. It is expected to produce plasma temperatures of 15 million degrees Celsius – hotter than the centre of the Sun in 2017 after the commissioning of further magnetic coils. "The ST40 is designed to achieve 100 million degrees C and get within a factor of ten of energy break-even conditions. To get even closer to break-even point, the plasma density, temperature and confinement time then need to be fine-tuned." The company is working with Princeton Plasma Physics Laboratory on spherical tokamaks, and with the Plasma Science and Fusion Centre at MIT on HTS magnets. It aims to achieve commercial scale fusion power by 2030.

Cold fusion

In March 1989, spectacular claims were made for another approach, when two researchers, in the USA (Stanley Pons) and the UK (Martin Fleischmann), claimed to have achieved fusion in a simple tabletop apparatus working at room temperature. 'N-Fusion', or 'cold fusion', involves the electrolysis of heavy water using palladium electrodes on which deuterium nuclei are said to concentrate at very high densities. The researchers claimed that heat – which could only be explained in terms of nuclear processes – was produced, as well as fusion byproducts, including helium, tritium and neutrons. Other experimenters failed to replicate this, however, and most of the scientific community no longer considers it a real phenomenon.

Low-energy nuclear reactions (LENR)

Initiated by claims for ‘cold fusion’, research at the nanotechnology level is continuing on low-energy nuclear reactions (LENR) which apparently use weak nuclear interactions (rather than strong force as in nuclear fission or fusion) to create low-energy neutrons, followed by neutron capture processes resulting in isotopic change or transmutation, without the emission of strong prompt radiation. LENR experiments involve hydrogen or deuterium permeation through a catalytic layer and reaction with a metal. Researchers report that energy is released. The main practical example is hydrogen plus nickel powder evidently giving more heat than can be explained on any chemical basis.

The Japanese government is sponsoring LENR research – notably a nano-metal hydrogen energy project (MHE) – through its New Energy and Industrial Technology Development Organization (NEDO), and Mitsubishi is also active in research.

Assessing fusion power

The use of fusion power plants could substantially reduce the environmental impacts of increasing world electricity demands since, like nuclear fission power, they would not contribute to acid rain or the greenhouse effect. Fusion power could easily satisfy the energy needs associated with continued economic growth, given the ready availability of fuels. There would be no danger of a runaway fusion reaction as this is intrinsically impossible and any malfunction would result in a rapid shutdown of the plant.

However, although fusion does not generate long-lived radioactive products and the unburned gases can be treated on site, there would a short- to medium-term radioactive waste problem due to activation of the structural materials. Some component materials will become radioactive during the lifetime of a reactor, due to bombardment with high-energy neutrons, and will eventually become radioactive waste. The volume of such waste would be similar to the corresponding volumes from fission reactors. However, the long-term radiotoxicity of the fusion wastes would be considerably lower than that from actinides in used fission fuel, and the activation product wastes would be handled in much the same way as those from fission reactors with some years of operation.[9].

There are also other concerns, principally regarding the possible release of tritium into the environment. It is radioactive and very difficult to contain since it can penetrate concrete, rubber and some grades of steel. As an isotope of hydrogen, it is easily incorporated into water, making the water itself weakly radioactive. With a half-life of about 12.3 years, the presence of tritium remains a threat to health for about 125 years after it is created, as a gas or in water, if at high levels. It can be inhaled, absorbed through the skin or ingested. Inhaled tritium spreads throughout the soft tissues and tritiated water mixes quickly with all the water in the body. Although there is only a small inventory of tritium in a fusion reactor – a few grams – each could conceivably release significant quantities of tritium during operation through routine leaks, assuming the best containment systems. An accident could release even more. This is one reason why long-term hopes are for the deuterium-deuterium fusion process, dispensing with tritium.

While fusion power clearly has much to offer when the technology is eventually developed, the problems associated with it also need to be addressed if it is to become a widely used future energy source.

Notes & References

Notes

a. The nucleus of deuterium (D) consists of one proton and one neutron, whereas hydrogen only has one proton. Tritium (T) has one proton and two neutrons. When the nuclei of D and T fuse, helium-4 (two protons and two neutrons) is formed, along with a free neutron. The 17.6 MeV of energy released in the fusion reaction takes the form of kinetic energy, the helium having 3.5 MeV and the neutron 14.1 MeV. The products of the fusion reaction have a total mass that is slightly lower than the starting materials (D and T), this decrease in mass having been converted to energy according to $E=mc^2$. [Back]

b. Tritium can be produced by bombardment of lithium-6 with neutrons of any energy. When lithium-6 (three protons, three neutrons) absorbs a neutron it splits into helium (two protons, two neutrons) and tritium (one proton, two neutrons), along with the release of 4.8 MeV of energy. Tritium can also be produced from the more-abundant lithium-7 from high-energy neutrons. Hence, natural lithium can be used for tritium generation in a fusion reactor. According to the European Commission[1]: "A 1 GW (electric) fusion plant will need about 100 kg deuterium and 3 tons of natural lithium to operate for a whole year, generating about 7 billion kWh." [Back]

c. The European Fusion Development Agreement (EFDA, see www.jet.efda.org) was established to provide a framework for magnetic confinement fusion research within the European Union and Switzerland. [Back]

d. The Princeton Plasma Physics Laboratory has a webpage on TFTR at www.pppl.gov/projects/pages/tftr.html [Back]

e. The first inertial confinement fusion experiments at NIF (see https://lasers.llnl.gov) will use the 'indirect drive' method, which differs from the 'direct drive' method described in the main text. In the indirect drive method, the lasers are focused on a gold cavity (known as a *hohlraum*) containing the fuel pellet. The lasers rapidly heat the inside surface of the hohlraum, generating X-rays that cause a blowoff of the capsule surface, in turn causing the fuel capsule to implode in the same way as if it had been hit with the lasers directly. It is hoped that NIF will be the first laser in which the energy released from the fusion fuel will exceed the laser energy used to produce the fusion reaction. [Back]

f. Z machine was designed to supply X-ray pulses of 50 terawatts, but improvements allowed pulses of 290 terawatts. Following a major refurbishment in 2007, Z machine's electrical pulse was increased from 18 million amps to 26 million amps delivered over a few nanoseconds. [Back]

g. A *hohlraum* is a metal cavity used in 'indirect drive' methods for inertial confinement fusion – see Note e above. [Back]

h. See Tutorial on Heavy-Ion Fusion Energy on the website of the Virtual National Laboratory for Heavy-Ion Fusion (http://hif.lbl.gov) for more information on heavy ion fusion. [Back]

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