Magnetic Controlled Fusion - a review

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Abstract

In the quest for sustainable energy sources to meet global demand while mitigating environmental impacts, nuclear fusion stands out as a promising solution. This comprehensive review delves into the potential of Magnetic Controlled Fusion (MCF) as a practical and sustainable energy source. Starting with an overview of fusion research history, including the tokamak design and the construction of key reactors like the Tokamak Fusion Test Reactor and Joint European Torus, the document explores the challenges facing practical fusion reactors. Emphasis is placed on addressing issues such as the behavior of alpha particles in deuterium-tritium reactions. Researchers are actively employing advanced confinement techniques, such as high magnetic fields and plasma shaping, alongside innovative fueling and heating methods to overcome these challenges. The review also acknowledges potential risks, including accidents and nuclear material proliferation, associated with pursuing nuclear fusion as a major energy source.

Despite these challenges, the document concludes optimistically, asserting that Magnetic Controlled Fusion holds tremendous promise as a clean and efficient energy source for the future. It underscores the necessity for continued research and development in this field to responsibly meet the world's energy needs in a sustainable manner.

The combined information highlights key aspects of fusion power, tokamak design, and major projects like ITER, emphasizing the collaborative efforts towards proving the feasibility of fusion as a large-scale, carbon-free energy source. The need for increased fusion performance and the potential role of Demo as a prototype commercial reactor are underscored, along with insights into the behavior of alpha particles and design requirements for tokamaks. Together, these elements paint a comprehensive picture of the current state and future potential of magnetic controlled fusion for student readers.

Introduction

The world faces a pressing need for sustainable energy sources that can meet the growing global demand while mitigating the environmental impacts of conventional energy production. Nuclear fusion, the process that powers the sun and stars, offers a promising solution. In this process, two or more light atomic nuclei combine to form a heavier nucleus, releasing a tremendous amount of energy. This energy release is far greater than that of chemical reactions, making nuclear fusion an attractive alternative to fossil fuels and other energy sources. In the present, nuclear fusion reactors use fusion of hydrogen isotopes to create fusion energy. Under terrestrial conditions, the two hydrogen isotopes, Deutritium (D) and Tritium (T), fuse the most easily. They create a helium nucleus, a neutron, and energy in the process.

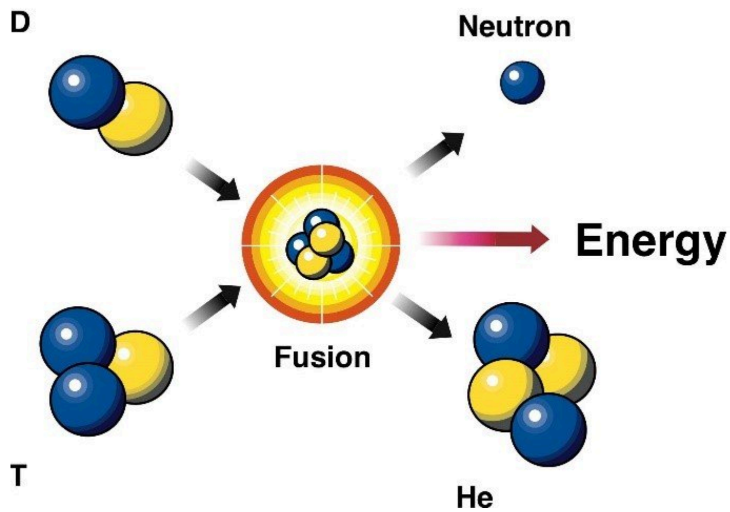


Figure 1. Fusion of deuterium and tritium

Nuclear fusion stands out for its exceptional energy density, exceeding that of any other known energy source. To put this into perspective, one gram of fusion fuel,A single gram of fusion fuel could generate 90000kW.hrs of energy, 4 times more efficient than fission and equivalent to 11,000,000 grams of coal. Moreover, nuclear fusion is a remarkably clean process, with many advantages over other methods of energy production -

- **No carbon emissions.** The sole byproduct of fusion processes is trace amounts of inert gas called helium, which may be released into the atmosphere without posing any environmental risks.
- **Abundant fuels.** Tritium will be created inside the power plant from lithium, an element that is abundant in the earth's crust and ocean, while deuterium may be collected from water. These fuel reserves would continue for many thousands of years, even with widespread use of fusion power plants.
- **Energy efficiency.** The energy content of one kilogramme of fusion fuel is equivalent to ten million kilogrammes of fossil fuel. Less than one tonne of fuel will be required for a one gigawatt fusion power plant to run for a whole year.
- **Less radioactive waste than fission.** The fusion reaction does not produce any radioactive waste as a byproduct. The only parts of the reactor that become radioactive are the structural materials; the activity level varies accordingly. Studies on appropriate materials are being conducted in an effort to reduce degradation times as much as feasible.
- **Safety.** In a fusion reactor, a significant nuclear accident is not conceivable. Fusion machines require relatively little amounts of fuel—roughly the weight of a postage stamp at any given moment. Furthermore, there is no chance of a runaway reaction that could result in a meltdown because the fusion process is challenging to initiate and maintain.
- **Reliable power.** Fusion power plants are expected to generate substantial amounts of electricity on a constant basis. Costs are anticipated to be largely comparable to those of other energy sources once they are established in the market.

“A crucial metric in evaluating the feasibility of nuclear fusion is the plasma amplification factor, denoted by 'Q'. This factor represents the ratio of energy released from fusion reactions to the energy injected into the plasma to sustain the fusion process. A Q value greater than one indicates that the fusion process is generating more energy than it consumes, a prerequisite for practical fusion power plants.”

The pursuit of controlled nuclear fusion has led to the development of various experimental devices, each with its unique approach to confining and heating the plasma fuel. Prominent examples include tokamaks, stellarators, and inertial confinement fusion (ICF) devices. Tokamaks employ a donut-shaped vacuum chamber and powerful magnetic fields to confine the plasma. Stellarators, on the other hand, utilize a more twisted, three-dimensional configuration to achieve confinement. ICF devices, such as laser-driven inertial fusion facilities, rely on intense laser pulses or particle beams to compress and heat the plasma to fusion temperatures. In the later sections, we will talk about Tokamaks and Stellarator design reactors.
Magnetism plays a pivotal role in magnetic confinement fusion (MCF) devices, the most widely pursued approach to controlled fusion. Strong magnetic fields are employed to confine the hot plasma fuel, preventing it from contacting the reactor walls and cooling down. This confinement is essential for achieving the high temperatures and densities required for fusion reactions to occur. The magnetic fields not only confine the plasma but also contribute to its heating and stability.
As the quest for controlled nuclear fusion continues, the role of magnetism is likely to expand and evolve. Researchers are actively exploring novel magnetic configurations, investigating advanced materials for superconducting magnets, and developing sophisticated plasma control techniques to further enhance the efficiency and performance of MCF devices. Ultimately, the harnessing of magnetic forces holds the key to unlocking the vast potential of nuclear fusion, paving the way for a clean, abundant, and sustainable energy future.

Ignition Condition : Lawson Breakeven criterion

Fusion fires do not start on their own, much like wood fires do. Specific ignition conditions must be met for fusion to occur. A significant number of particles must collide with one another often enough to create an ignited plasma. Thus, a number of particles whose thermal energy must not be transported to the plasma container too quickly must be contained by the magnetic field. This places constraints on the plasma's density, temperature, and thermal insulation. These are:

1. An absolute plasma temperature of at least: T = 273+°C = 100 x 106 K.
2. An energy confinement time of: $r \geq 2$ seconds.

   This measure for the thermal insulation gives the time that elapses till the thermal energy pumped into the plasma by heating equipment such as neutral beams, transformer action, or microwaves is again lost to the outside.
3. A plasma density of about n=1014 [particles/cm^3]

This is 250,000 times less in density than the Earth's atmosphere. This extremely low density means that, despite its high temperature, a burning fusion plasma involves a power density scarcely larger than an ordinary light bulb.

4. Energy breakeven $n*T*t_E > 10^{21}$ (keV m^{-3} s) with T between 10 to 20 keV

   The energy received from a plasma must be greater than the energy input necessary to ignite it as well as the plasma's radiation losses.

Linear Fusion Mirror Concept

Linear fusion mirrors are a type of magnetic confinement fusion device that uses a series of magnetic fields to confine a plasma in a linear geometry. The magnetic fields are arranged in a way that creates "mirror traps" that reflect the charged particles in the plasma back and forth, preventing them from escaping. This confinement is essential for achieving the high temperatures and densities required for fusion reactions to occur.

A linear fusion mirror typically consists of a long, cylindrical vacuum chamber that contains a series of magnetic coils. The magnetic coils are arranged in a way that generates a magnetic field that is strong at the ends of the chamber and weak in the middle. This creates a series of mirror traps that reflect the charged particles in the plasma back and forth. The plasma is heated to fusion temperatures using a variety of methods, such as radio waves or neutral beams.

One of the main challenges with linear fusion mirrors is that they are susceptible to axial plasma loss. This is because the magnetic fields at the ends of the chamber are not strong enough to completely confine the plasma particles. As a result, some of the particles escape from the ends of the chamber, which reduces the overall confinement efficiency.

There are two ways to decrease the plasma losses -

- Increasing the mirror ratio

$$\text{Mirror ratio} = R_{mirror} = \frac{B_{mirror}}{B_{linear}}$$

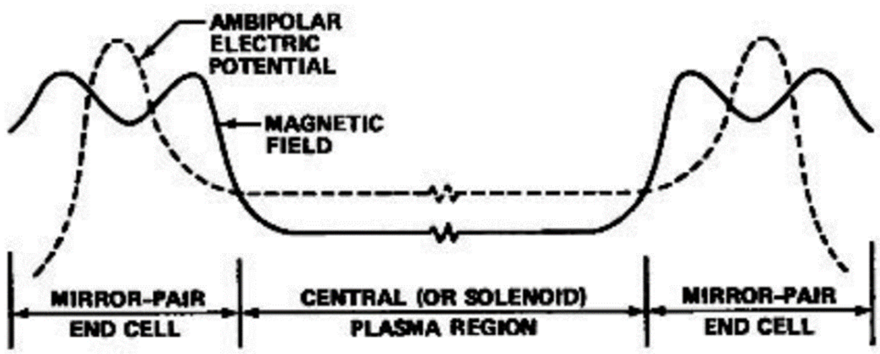
- Increasing the particle energy or temperature

Tandem Mirror

A tandem mirror is a type of magnetic confinement fusion reactor that uses a combination of magnetic fields and electric fields to confine a plasma in a linear geometry. The tandem mirror consists of a central solenoidal region, where the plasma is heated and confined, and two mirror cells at each end, which reflect the charged particles in the plasma back and forth. The electric fields are used to create potential wells that trap the ions in the plasma, while the magnetic fields are used to confine the electrons.

The electric fields are used to create potential wells that trap the ions in the plasma.Electrons in plasma travel faster than ions because they have a lower mass for the same energy or temperature. As a result, they escape via a linear mirror faster than the ions. This eventually results in partial charge separation. A positive potential or space charge is developed between the

mirrors, this holds the plasma together, and tends to equalize the rate of escape of electrons or ions.
The combination of magnetic and electric fields allows the tandem mirror to confine a plasma at high temperatures and densities. This is essential for achieving fusion reactions, which require that the plasma be heated to temperatures of millions of degrees Celsius. The power generated in the solenoid region is proportional to the volume of the plasma. A typical value of the plasma amplification factor of Q=5 can be expected, with a large enough volume. Since the end cells can serve as plugs of any plasma volume, the central cell can be made as large as desired without being affected by the size and design of the end cells.



Tokamak Design

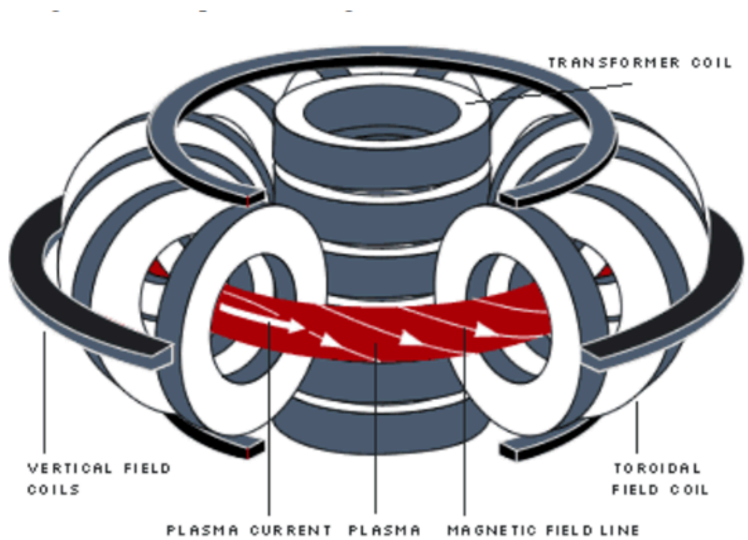
Tokamaks, a type of magnetic confinement fusion reactor, have emerged as a frontrunner in the quest for harnessing the immense energy of nuclear fusion. These doughnut-shaped devices employ powerful magnetic fields to confine a superhot plasma, the fuel for fusion reactions, within a donut-shaped vacuum chamber known as a torus. By achieving and maintaining the extreme temperatures and densities required for fusion, tokamaks hold immense potential as a clean and abundant source of energy. In 1958, Russia launched T-1, the world's first tokamak, into service. The Tokamak Fusion Test Reactor at Princeton Plasma Physics Laboratory and Joint European Torus in England were built as a result of further developments, and in the 1990s, both facilities produced record fusion power.

The tokamak design was introduced by russian scientist “Basov”. To construct a magnetic field in tokamak requires generation of 3 superimposed magnetic fields.

1. The toroidal field (Bt) - A plane external magnet first creates a toroidal field.
2. The Poloidal Field (Bp) – Plasma current Ip, which flows in the plasma itself, generates the poloidal field. A helical field is formed by combining toroidal and poloidal fields.
3. The Vertical Field (Bv) –A third, vertical field holds the plasma current in place. Furthermore, it prevents plasma drift caused by field differences.

After poloidal – This causes the basket weave twisting of field lines and the formation of magnetic surfaces, both of which are required for confining the plasma.

“Magnetic surfaces are a fundamental concept in magnetic confinement fusion. They are defined as the regions of space where the magnetic field lines are closed and nested. This means that particles traveling along a magnetic field line will eventually return to their starting point.”

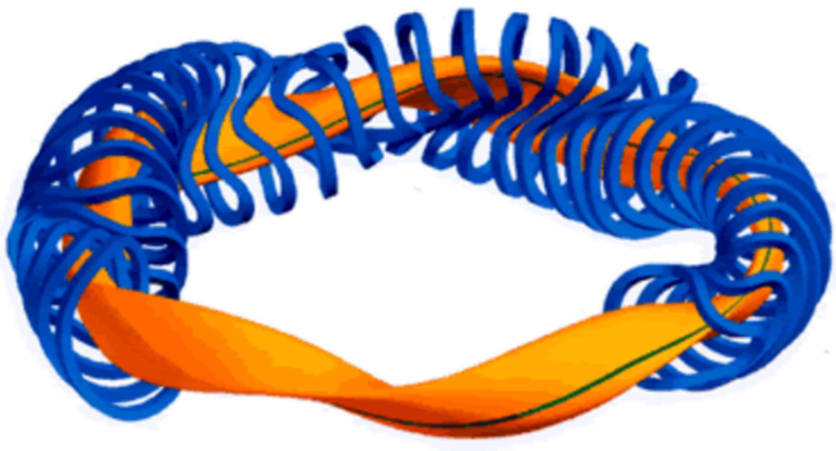


Stellarator Toroidal Design

Stellarators, like their close cousins, tokamaks, stand as promising candidates in the quest to achieve controlled nuclear fusion. These intricate devices, with their twisted, three-dimensional geometry, employ a unique configuration of magnetic fields to confine and heat the plasma, the fuel for fusion reactions. While tokamaks rely on a combination of toroidal and poloidal magnetic fields, stellarators utilize a more intricate arrangement of helical coils, generating magnetic fields that wrap around the torus in a spiral fashion.

"Lyman Spitzer" discovered the stellarator design. Stellarators are three-dimensional toroidal plasma confinement devices that rely on a numerically determined plasma surface shape for optimal plasma confinement, stability, and steady-state operation. The magnetic bottle in a stellarator is produced by a single coil system, with no longitudinal net current in the plasma. As a result, stellarators are suitable for continuous operation, whereas tokamaks typically operate in a pulsed mode. Because helical twisting of magnetic lines is only accomplished by external coils, the latter must be twisted accordingly. As a result, the magnetic field and plasma take on a complex shape. To eliminate toroidal plasma current, axial symmetry in tokamaks must be abandoned. This allows for more flexibility in shaping the magnetic field and optimizing its properties.

Stellarators could provide a technically simpler solution for a fusion power plant than tokamaks. In a power reactor situation, the lack of transformer coils in the center allows for radiation shielding of the coils.



Magnetic Coils

Stellarators use more flexible copper strands embedded in winding forms rather than rigid copper rails. The superconducting coils are made of niobium-titanium and can generate magnetic fields up to 6 Tesla on the coils and 3 Tesla on the magnetic field axis. The superconducting material is embedded in copper wire braided to form a cable as thin strands. For superconducting coils, cryogenic cooling with liquid helium to 4K is required. The cable is encased in a helium-tight aluminum sheath for this purpose.

Plasma Vessel

Although the magnetic field confines plasma, it must be produced in a vacuum vessel. A hoover prevents both fuel and air from escaping. Even minor amounts of incoming air would extinguish the plasma. The vessel must be vacuum tight and capable of withstanding pressures of 10-8 millibar. As a result, high-quality steel is used in the construction of vessels.

Plasma Boundary and Diverters

In Stellarator, unlike a Tokamak, no additional magnet system is required to divert the plasma boundary. This makes density and impurity control much easier. The plasma boundary, like the divertor plasma in a Tokamak, splits in accordance with the symmetry of the magnetic field into individual offshoots through which energy and particles move to limited areas of the vessel wall. Special collector plates, typically ten in number along the plasma column, protect these areas of the wall. The incident particles, as well as the undesirable impurities from the plasma, can be neutralized and pumped away here. The ash from the thermonuclear fusion process, helium, will also be removed in this manner in a future fusion power plant.

Plasma Heating

Three popular techniques used to heat up the plasma to fusion temperatures are -

1. Ohmic Heating
2. Microwave or High Frequency Heating

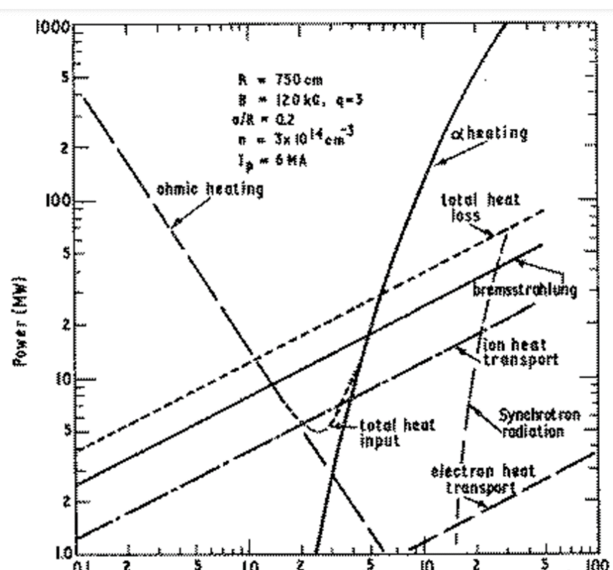
3. Neutral Particle Injection

Plasma Refueling

Diverter-limited plasmas continue to lose plasma particles, which are removed along with impurities by diverter pumps. There are several refueling methods, including gas puffing from the vessel's edge, neutral particle injection, and pellet injection. Pellet injection involves cooling deuterium and tritium gas until it freezes, allowing pellets a few millimeters in diameter to form. After being accelerated in a gas gun or a centrifuge, they are injected at a rate of 20 pellets per second into the hot plasma, where they evaporate and the individual atoms are ionized.

Fusion Powerplant Layout and Function

Till ignition, a start-up heating system provides the plasma with power of 50-100 MW for a few seconds. The resulting fast helium nuclei are trapped in the magnetic field as charged particles and transfer their energy to plasma via collisions. Coolants, heat exchangers, and turbo generators are used to convert thermal energy to electric energy. To avoid extinguishing the fusion fire, the divertor removes helium ash from the plasma. The electrically neutral neutrons can easily exit the magnetic field. They collide with the blanket that surrounds the plasma vessel, where they produce tritium fuel from lithium. This fuel is collected and injected back into the plasma along with deuterium. A 1000 MWe fusion power plant will require approximately 20 g of tritium and 13 g of deuterium per hour. During fusion reactions, we observe bremsstrahlung and synchrotron radiation losses due to acceleration of particles in electric and magnetic fields respectively.



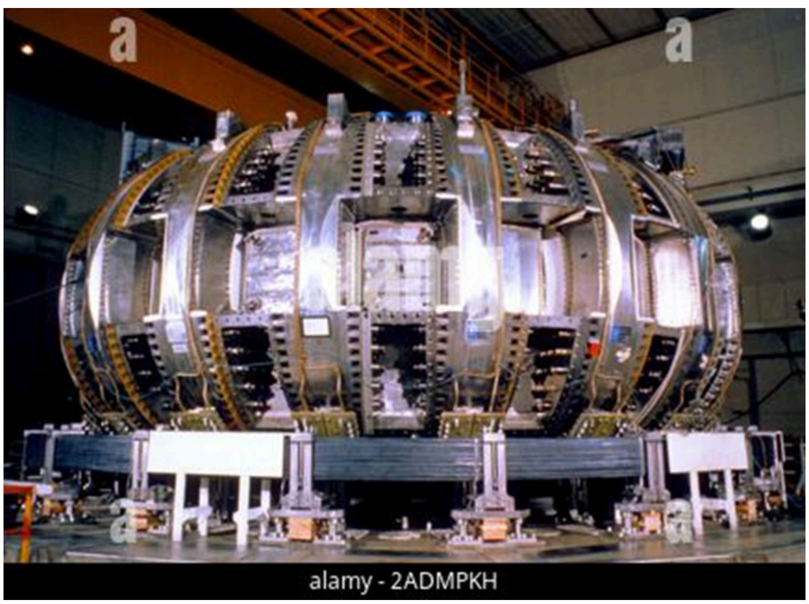
Popular Experiments and Current Status of Fusion Power

Tokamak Fusion Reactor Test (TFTR)

The Tokamak Fusion Test Reactor (TFTR), a pioneering experimental tokamak built at the Princeton Plasma Physics Laboratory (PPPL), played a pivotal role in advancing the field of nuclear fusion research. From its inception in 1982 to its decommissioning in 1997, TFTR set a series of world records in plasma temperature, fusion power output, and total fusion energy production.

TFTR Made several international records, including the highest plasma temperature ever produced in a laboratory (510 million degrees Celsius). TFTR became the world's first magnetic fusion device to conduct extensive experiments with plasmas composed of 50/50 deuterium/tritium, the fuel mix required for practical fusion power production, in December 1993. As a result, in 1994, TFTR produced a world-record 10.7 million watts of controlled fusion power, enough to power over 3,000 homes. These experiments also focused on the behavior of alpha particles generated by deuterium-tritium reactions. The extent to which the alpha particles transfer their energy to the plasma is critical to achieving sustained fusion.

Tokamak fulfilled all its hardware goals, thus making significant contributions in nuclear fusion technology development.



International Thermonuclear Experimental Test Reactor

ITER ("The Way" in Latin) is one of the world's most ambitious energy projects. 35 nations are working together in southern France to construct the world's largest tokamak, a magnetic fusion device designed to demonstrate the feasibility of fusion as a large-scale, carbon-free source of energy. Since the concept of an international joint fusion experiment was first proposed in 1985, thousands of engineers and scientists have contributed to the design of ITER. China, the European Union, India, Japan, Korea, Russia, and the United States are now engaged in a

decades-long collaboration to build and operate the ITER experimental device, bringing fusion to the point where a demonstration fusion reactor can be designed.
The ITER's niobium titanium superconductor generates a magnetic field of 13 tesla on the coil and 5.7 tesla on the magnetic axis. The superconducting strands are embedded in copper wires that are surrounded by a high-grade steel blanket. Liquid helium flows inside the blanket, cooling the coil to 4.5K, or near absolute zero.

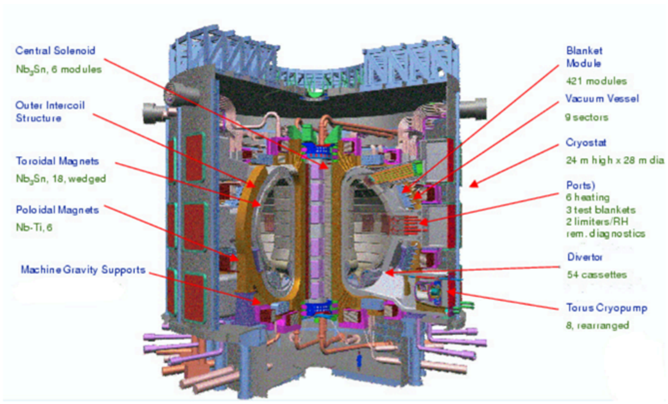


Figure 23. ITER facility at Cadarache, France. Source: ITER Organization.

The Demo Reactor

The fusion level will be increased by a factor of four if Demo, a successor to ITER, is of comparable physical size. The electrical power potential provided to the network will be around 500MW, which is standard of a modern power station, and the total amount of heat refluxes through the structure's walls will be four times that of the ITER. Plasma Performance must be improved to achieve this fourfold increase. Calculations show that increasing ITERs linear dimensions by 15% and plasma density by 30% will result in this performance. If the systems on Demo operate flawlessly, Demo can be utilized to develop a commercial reactor prototype.

Present

Fusion scientists claimed a breakthrough last December. The National Ignition Facility (NIF) in California reported that it extracted more energy from a controlled nuclear fusion reaction than it had used to start it. It represented the world's first and an important leap forward for fusion, but fusion as an energy source is still a long way off. The high-profile statement elicited an established pattern of responses to fusion studies: praise from supporters of the technology and contempt from detractors, who grumble that scientists continually promise that fusion will be available in 20 years (or 30 or 50, depending on the perspective).
The following are four developments that have yielded positive results:

1. Japan's Superconductor - Located at the National Institute of Fusion Research in Toki, Japan, the Large Helical Device is the largest superconducting plasma confinement

device in the world. Fuel is combined with charged and heated plasma to create massive amounts of energy through nuclear fusion. A fusion reaction needs areas where plasma can be contained. In the 2020 fiscal year, the device-powered plasma reached a temperature of 100 million degrees. In the past, lower electron temperatures were associated with ions at this or greater temperatures. But this institute's research produced a lot of heat for electrons and ions, two crucial constituents of the plasma used in nuclear fusion.

2. MIT's Magnetic Field - Scientists at the Massachusetts Institute of Technology (MIT) are conducting fusion experiments since the 1970s. In 2021, the Institute's Plasma Science and Fusion Centre (PSFC) will collaborate with Commonwealth Fusion Systems to create one of the most powerful magnetic field of this sort ever created on Earth, a superconducting magnet with a field strength of 20 teslas. Engineers and scientists can now at last facilitate the fusion process in labs, which previously had made limited progress.
3. Europe's Commercially Viable Tokamak - The Joint European Torus (JET) is the largest operational tokamak in the world. Similar to those in previous programmes, the plasmas in JET are the hottest in the solar system. JET is well-equipped to advance towards the general application of nuclear fusion in power grids that so many labs are striving for because it was created specifically to study fusion processes for use in power plants.
4. California's powerful laser system - The National Ignition Facility is the world's strongest laser fusion facility, situated in Livermore, California. The facility's 192 beams are capable of delivering 60 times more energy to its target. The output of a fusion reaction at the laser site in 2013 exceeded the amount of energy consumed by the fuel, but not the energy used to power the laser beams. However, by the end of the year of 2022, the facility had ultimately demonstrated a net energy output, earning it the title of the latest nuclear fusion "breakthrough" in the press. Lawrence Livermore National Laboratory's National Ignition Facility now houses two historical nuclear fusion reactions that drove the industry closer to commercialization of energy development.

Challenges and future

Physicists have been studying fusion power since the 1950s, but the process of converting it into a practical energy source has proven incredibly difficult. The majority of experts concur that it is improbable that humanity will be able to produce nuclear fusion energy on a big scale before approximately 2050 (the more pessimistic may add another ten years). Fusion cannot be a salvation, as the rise in global temperature during the current century may be substantially decided by what we do—or fail to do—about carbon emissions prior to that time. (This is a point that Observatory columnist Naomi Oreskes also raises.) "I do think fusion looks a lot more plausible now than it did 10 years ago as a future energy source," says Omar Hurricane, a program leader at Lawrence Livermore National Laboratory, where the NIF is housed. "But it's not going to be viable in the next 10 to 20 years, so we need other solutions."

Nuclear fusion was identified as a potential energy source almost as soon as fission was. During the debriefing conference held by the Manhattan Project in late 1945, Italian physicist Enrico Fermi, the man who oversaw the effort to build the first fission reactor in Chicago during WWII, proposed the idea of fusion reactors for power production. Scientists discovered a way to release fusion energy a few years later, but only through the wildly explosive detonation of hydrogen bombs.

- One of the most significant barriers to magnetic-confinement fusion is the need for materials that can withstand the harsh treatment from the fusing plasma. Deuterium-tritium fusion, in particular, produces an intense flux of high-energy neutrons that collide with the nuclei of atoms in the metal walls and cladding, causing tiny spots of melting. The metal then recrystallizes, but it is weakened because the atoms have been shifted from their initial positions. Each atom in the cladding of a typical fusion reactor may be displaced 100 times during the reactor's lifetime.
- Another significant challenge is the production of fusion fuel. Deuterium is abundant in the world: it makes up 0.016 percent of natural hydrogen, so the seas are literally awash in it. However, tritium is only found in trace amounts in nature, and it decays radioactively with a half-life of only 12 years, so it is constantly depleted and must be replenished.

Conclusion

In conclusion, this comprehensive review provides a thorough examination of Magnetic Controlled Fusion (MCF) as a promising solution to the global demand for sustainable energy. The document begins by tracing the historical development of fusion research, highlighting key milestones such as the tokamak design and the construction of influential reactors like the Tokamak Fusion Test Reactor and Joint European Torus. Throughout, the challenges confronting practical fusion reactors, particularly the behavior of alpha particles in deuterium-tritium reactions, are scrutinized.

The review underscores the proactive measures researchers are taking to overcome these challenges, delving into advanced confinement techniques, high magnetic fields, plasma shaping, and innovative fueling and heating methods. Potential risks associated with nuclear fusion, including accidents and nuclear material proliferation, are acknowledged. Despite these challenges, the document concludes optimistically, asserting that Magnetic Controlled Fusion holds significant promise as a clean and efficient energy source for the future.

Key aspects such as the need for increased fusion performance, the potential role of Demo as a prototype commercial reactor, and insights into the behavior of alpha particles and design requirements for tokamaks contribute to a subtle understanding of the subject matter. Additionally, the review incorporates information on popular experiments and the current global status of fusion power, citing breakthroughs from notable projects worldwide.

However, the cautious tone remains prevalent, with acknowledgment that while recent breakthroughs demonstrate progress, practical large-scale energy generation from nuclear fusion is not anticipated before 2050. The document aligns with the sentiment expressed by experts, such as Omar Hurricane from Lawrence Livermore National Laboratory, who emphasizes the need for alternative energy solutions in the next 10 to 20 years to address pressing environmental concerns.

Magnetic Controlled Fusion presents a compelling avenue for sustainable energy, with ongoing research, collaboration, and innovation being crucial for realizing its potential. The review urges a diversified approach, recognizing both the promise and challenges associated with fusion power, while emphasizing the importance of parallel efforts to meet immediate energy needs and environmental goals.

References

DOE Explains...Nuclear Fusion Reactions | Department of Energy
Fusion in brief - Culham Centre for Fusion Energy
linear magnetic mirror: Topics by WorldWideScience.org
DOE Explains...Tokamaks | Department of Energy.
DOE Explains...Stellarators | Department of Energy
Tokamak Fusion Test Reactor | Princeton Plasma Physics Laboratory
What is ITER?
What Is the Future of Fusion Energy? | Scientific American
Five Signs of Nuclear Fusion Progress Around the World
MAGNETIC CONFINEMENT FUSION
W. J. Emrich, Jr., "Field-Reversed Magnetic Mirrors for Confinement of Plasmas," NASA Tech Briefs, March 2001.
S. Glasstone, "Fusion Energy," U. S. Department of Energy, Technical Information Center, 1980.
Magdi Ragheb, "Thorium Fuel Cycle using Electrostatic and Electrodynamic Neutrons Generators," Thorium Energy Alliance Conference, TEAC4, Chicago, Illinois, USA, http://www.thoriumenergyalliance.com/ThoriumSite/TEAC4.ht
M. Ragheb, "Gamma Rays Interactions with Matter," Lecture Notes, GAMMA RAYS INTERACTION WITH MATTER