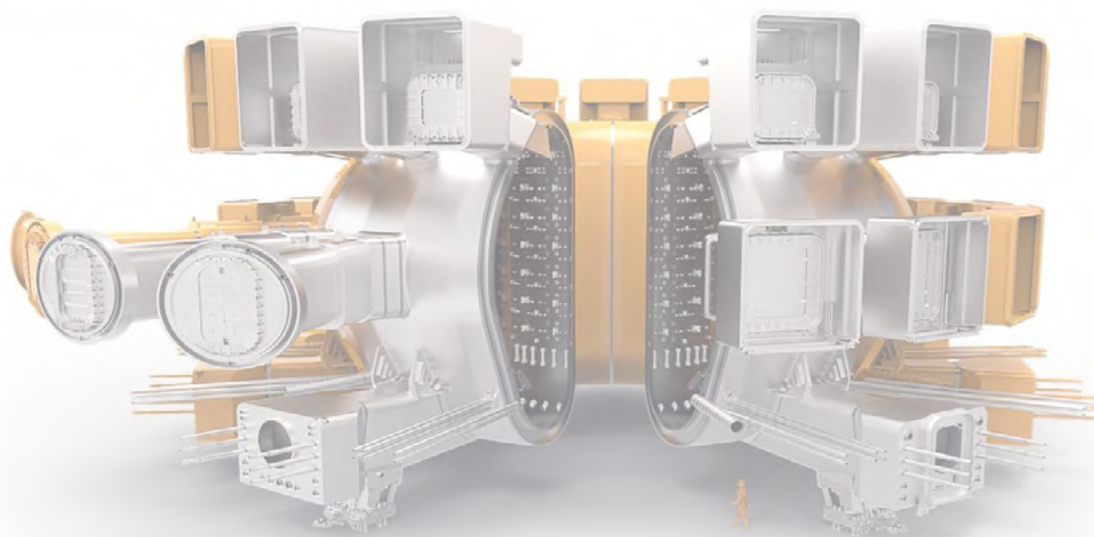


Nuclear Fusion: An Energy Source for the Future

Unlike fission power, which involves splitting very heavy atoms to release energy, i.e. the reaction that takes place in all nuclear power stations currently in operation around the world, **fusion releases energy as a result of two light atoms binding together.**

The fuel for fusion reactors consists of two isotopes of hydrogen gas: deuterium and tritium. Thus, a fusion power plant will utilize a fuel that is available in nearly unlimited amounts on Earth and will not give off greenhouse gases or give rise to long-lived radioactive waste.



Fusion could provide a large-scale, sustainable and continuous energy supply

The current goal of nuclear fusion research reactors such as that of the ITER project — which we will discuss below — is **to use nuclear fusion as it takes place in the Sun or the stars as a power source here on Earth.** Inside the Sun, hydrogen atoms collide and combine with each other at incredibly high temperatures — close to 15M degrees Celsius — and are subjected to huge gravitational pressures: every

second 600 million tonnes of hydrogen fuse and form helium.

However, here on Earth fusion will necessarily take place at a much modest scale, so the temperatures that need to be achieved inside fusion reactors must be much higher — in the order of 100M degrees Celsius — so as to be able to have a technically viable power source.

Technological requirements

Harnessing fusion power requires developing technological systems that meet two basic requirements:

- **Heating hydrogen to temperatures of millions of degrees Celsius** to produce an overheated gas or plasma in which electrons leave their orbitals and nuclei can be contro-

lled in order to fuse them into heavier ones.

- **Confining matter** to keep it in an ionized gas or plasma state by enclosing it inside the reactor cavity long enough for it to react.

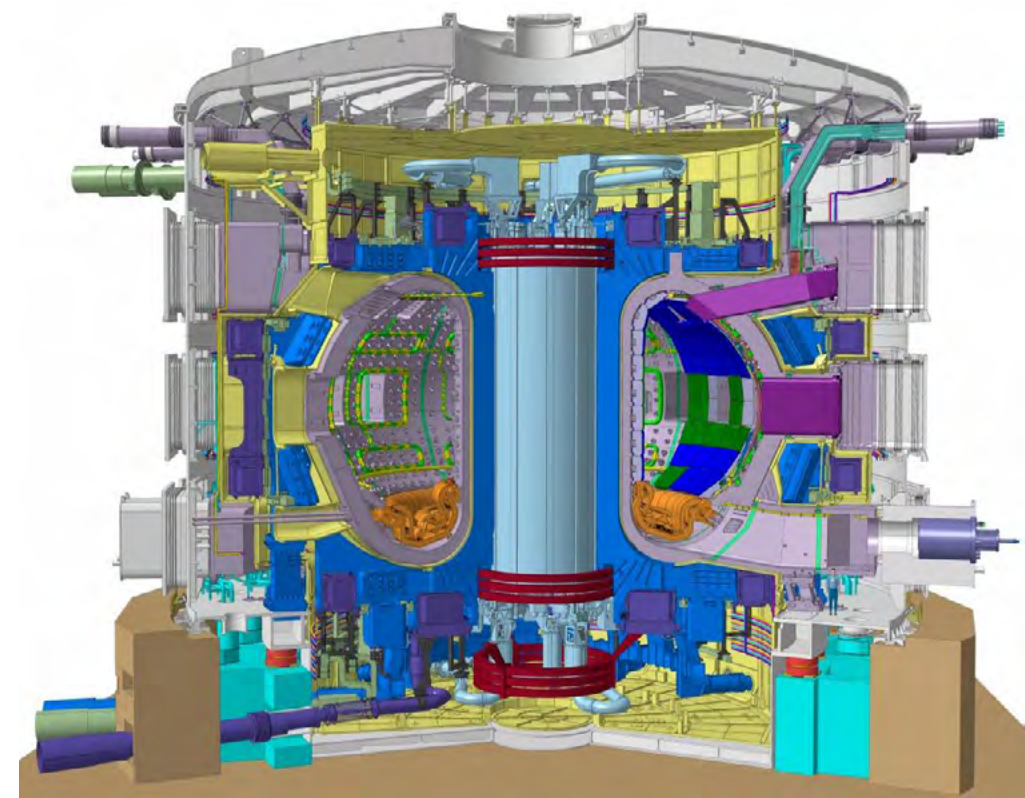
Heating matter to millions of degrees Celsius and confining it are two of the technological requirements for achieving nuclear fusion

Main lines of development

There are two main lines of development of fusion technology:

- **Magnetic confinement fusion.** The electrically charged particles in the plasma are trapped inside a space delimited by a magnetic field and forced to move along helical paths determined by the latter's lines of force. The most developed device at the moment is toroidal-shaped and known as tokamak — the technology used in the ITER project.
- **Inertial confinement fusion.** It consists in creating a medium so

dense that particles hardly have a chance to escape without reacting with each other. After being suddenly hit by powerful laser-created light beams, a small sphere of a solid deuterium-and-lithium compound implodes due to the effect of the shock wave. Thus, it becomes hundreds of times denser than in its normal solid state and explodes as a result of the fusion reaction.



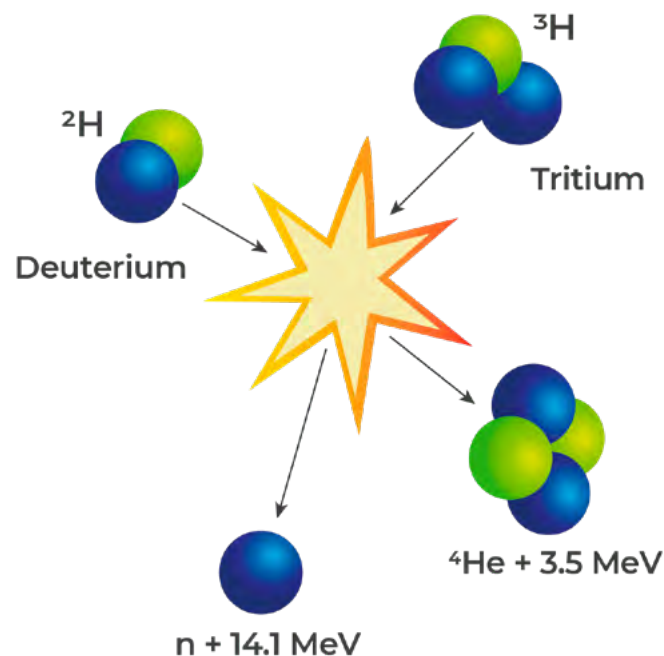
Source: ITER

Technical considerations

The different possible reactors for carrying out nuclear fusion require reaching different temperature and density values to achieve optimal efficiency. Current studies focus mostly on the reaction of two isotopes of hydrogen — deuterium and tritium — because it is one of the easiest to create and its components the easiest to obtain: Deuterium directly from water, and tritium inside the reactor itself by neutron bombardment of a layer of lithium, which is also very abundant

in nature. Even for this reaction, the required temperatures are incredibly high as they exceed 100M degrees Celsius.

Fusion with deuterium and tritium consists in the merging of their nuclei — according to a process similar to the one that happens inside the Sun — to produce an alpha particle with a nucleus of helium (He^4) consisting of two neutrons and two protons, as shown in the picture below:



$$E = m \cdot c^2$$

If we apply Einstein's equation ($E = m \cdot c^2$) to the mass difference, we can see that there is a large amount of energy potentially available per reaction (17.6 MeV) — even after subtracting the necessary energy for nuclear fusion to be self-sustaining. The net difference is still big and is one of the main appeals of fusion.

The two light nuclei that undergo fusion are positively charged and hence repel each other. In order to overcome this repulsion force so that the strong nuclear force — which is always a short-range attraction force — can act, the nu-

clei must move at sufficiently high speeds, something which requires a very high temperature.

At very high temperatures, matter is in a state known as plasma in which electrons cease to be bound to their atomic nuclei. Furthermore, in order for a sufficiently large number of fusion reactions to occur, there must be a lot, i.e. a high density, of atomic nuclei, which must remain in this situation long enough for the reactions among them to occur. Under these conditions, the plasma is said to be "confined."

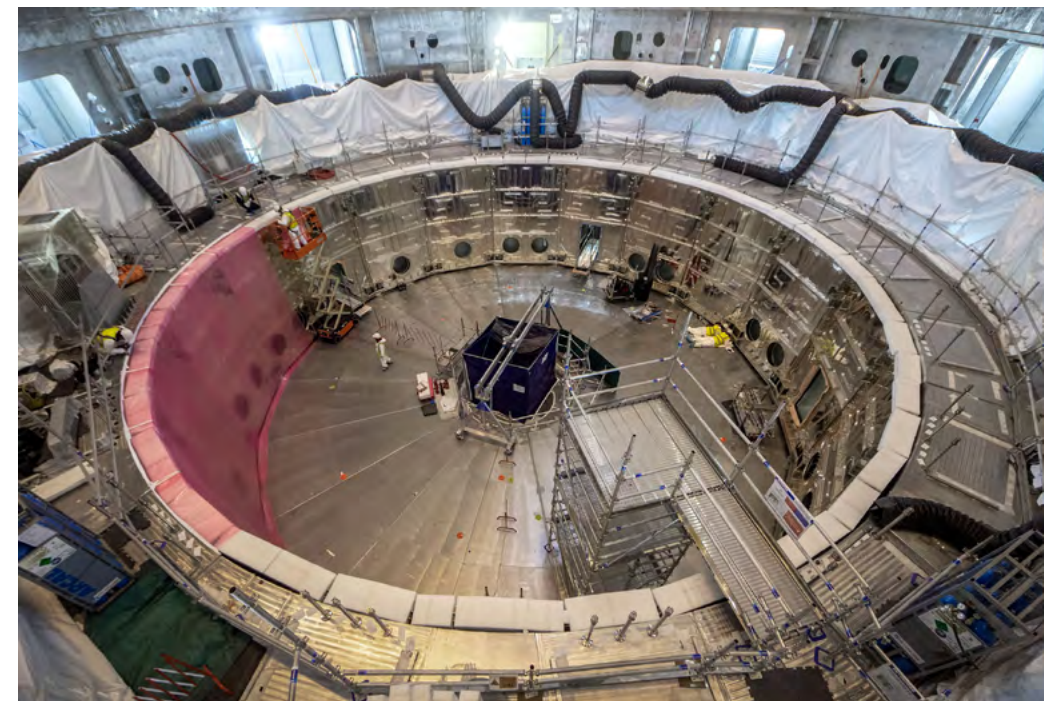
Advantages & challenges

Nuclear fusion might become a large-scale energy resource in the second half of this century and has big advantages compared to other power sources:

- **Safety.** Since the fusion reaction is not a chain reaction, control thereof cannot be lost. The reaction can be stopped at any time by simply cutting off the fuel supply.
- **Abundant cheap fuel.** It is uniformly geographically distributed, and there is enough of it in the water of all the oceans and lakes for millions of years based on current energy consumption levels.
- **Clean energy.** The resulting gases from the reaction do not contribute to the greenhouse effect. The radioactivity of the reactor's structure — caused by the neutrons released during the fusion reactions — can be minimized by carefully choosing low activation materials. Therefore, the elements of the reactor do not need to be stored for more than 50 years.

Nuclear fusion, however, also poses some challenges:

- **It is still a long way away from commercial availability.** The biggest project — the ITER experimental fusion reactor — aims to prove that a large-scale, self-sustaining fusion reaction is possible. Once success is achieved, an electricity producing demonstration reactor will have to be built, which pushes the project's horizon to the end of this century. This timespan may be shortened if the SPARC (*Scalable Processor AR-Chitecture*) project — discussed below — is successful.
- **High costs.** The high costs of fusion technology put it out of reach of private initiatives. At this time, development is taking place at the scale of agreements among the governments of several nations. This difficulty could be reduced if the projected advancements in high temperature superconductors finally take place.



Source: ITER

The first demonstration reactor for producing electricity by fusion could be a reality by the end of this century



THE ITER PROJECT

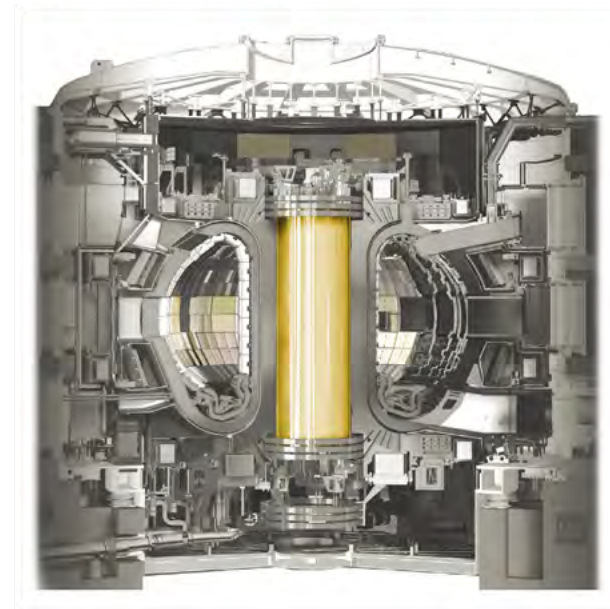
The purpose of the ITER (International Thermonuclear Experimental Reactor) is to determine the technological and financial viability of magnetic confinement nuclear fusion as a large-scale, CO₂-free power source — albeit without generating electrical power yet.

The ITER will be the first fusion facility capable of producing net energy and maintaining the fusion process over long periods of time as well as of testing all necessary technology and materials, thus representing a preliminary stage to the construction of a commercial demonstration facility.

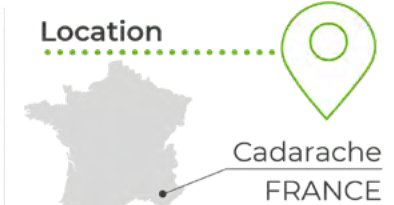
The purpose of the ITER is to determine the technological and financial viability of magnetic confinement nuclear fusion as a large-scale, CO₂-free power source

ITER: Energy of the future

ITER is an **experimental fusion reactor** with the purpose of determining the technological and economic viability of magnetic confinement nuclear fusion for the generation of electricity



Location



Participants



European Union
India
Japan
Russia
United States
South Korea
China

Data

100,000 km
of superconducting wires

23,000 t
of total weight of the completed reactor

830 m³
of volume for the Tokamak's plasma

150 million °C
of plasma temperature

60 m height
for the main building

5,000 people
working in its construction

500 MW as a goal
of energy power

42 ha of site ground

Sources: ITER and Foro Nuclear

The ITER is currently being built in Cadarache, Southern France, and is a collaboration among 35 countries integrated in 7 main blocs: China, the EU (through Euratom), India, Japan, South Korea, Russia, and the U.S. The first reactor tests will take

place, and the first plasma will be achieved, in 2025, once construction is completed in 2024. This will be the phase prior to operation, whose planned duration is 20 years.



Source: ITER

35 countries participate in the ITER Fusion Project under construction in France, including Spain through the European Union

When the agreement for its development was signed in 2006, the countries taking part in the project undertook to share all building, operating and dismantling costs as well as the experimental results and any resulting intellectual property.

The total cost of construction currently stands at around €23,500M. The European Union is responsible for 45.6% of the funding (more than €10,700M), a commitment it meets via funds managed by Fusion for Energy (F4E), a EU body headquartered in Barcelona. France, as the host country, provides approximately 20% of this sum. 90 percent of all contributions are in kind. The project's other six members contribute equally to the rest of the budget.

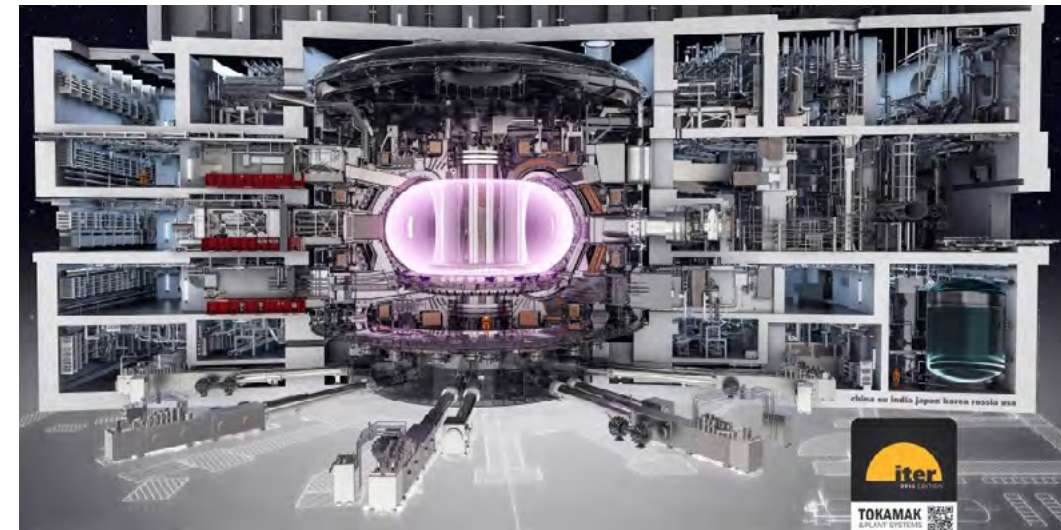


Source: ITER

The principal piece of equipment is a tokamak-shaped reactor, inside of which the fusion energy will be absorbed through the vessel's walls as heat. This heat will then be used to generate steam and, with the latter, electricity in turbo-alternators.

The heart of the tokamak is its toroidal vacuum chamber in which deuterium and tritium will completely become ionized — the electrons becoming separated from the nuclei — under the influence of extreme temperatures and pressures, thereby creating the chance for nuclear fusion to occur in

the plasma thus generated. The plasma's electrically charged particles will conform to the shape of the powerful magnetic field created by the coils situated around the vessel — which are kept at cryogenic temperatures near absolute zero ($-273\text{ }^{\circ}\text{C}$) — and remain confined in it without touching the walls of the latter, which cannot withstand their high temperature.



Tokamak-shaped reactor
Source: ITER

The Spanish nuclear industry participates in the ITER Project exporting products, technology and services to achieve nuclear fusion

Main characteristics of the ITER

The amount of energy a tokamak reactor can produce is the direct result of the number of fusion reactions that take place in its core. The larger the vessel that contains the plasma, the bigger the volume of plasma it can hold and, hence, the higher the potential of the fusion energy.

The ITER tokamak reactor has a plas-

ma volume that is ten times greater than that of the largest device currently in operation. It will be a unique experimental tool capable of:

- Generating a power of 500 MW with a 50 MW input, that is, of achieving an energy gain equal to ten.
- Demonstrating the integrated operation of technologies for a fusion

power plant, whereby aspects such as heating, control, diagnostics, cryogenics and remote maintenance can be tested.

- Obtaining a deuterium-tritium plasma where the fusion reaction can be extended by internal heating.
- Conducting tests for tritium production inside the vacuum vessel by

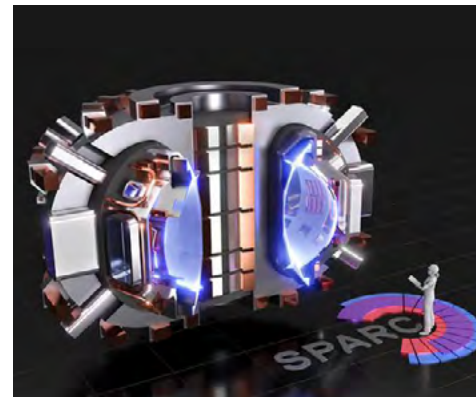
means of the neutron bombardment of lithium, which is plentiful in nature.

- Demonstrating the safety of a fusion device's features. The first big step was the obtaining of a license as a nuclear operator in France after undergoing a thorough examination of its safety procedures.

THE SPARC PROJECT

The Massachusetts Institute of Technology's (MIT) Plasma Science & Fusion Center is developing, in collaboration with the private company Commonwealth Fusion Systems, a conceptual design for a **compact experimental fusion machine — the Scalable Processor ARChitecture (SPARC)** — with an energy gain greater than 2, i.e. it should be able to produce 50-100 MW with an input equivalent to half of said power.

SPARC's high intensity magnetic fields — which will be generated thanks to a new technology that would render the ITER's huge superconducting coil magnets kept at cryogenic temperatures unnecessary — **have sparked a lot of interest in this reactor, which will have the size of an average-size fusion machine.** For the sake of comparison, the ITER's magnets will have to be kept at a temperature of around 4 K — approximately 269 °C below zero —, whereas SPARC's magnets would operate at approximately 90 K, which is still a very low — but easier to manage — temperature.



Conceptual design of the SPARC project
Fuente: PSFC-MIT

The first thing that needs to be done to achieve this is finishing developing new high flux, high temperature superconducting magnets. The next stage would be building a model having a torus field with a major radius of 1.65 m and a minor radius of 0.5 m that is capable of generating a 12-T field. Please note that the Earth's magnetic field ranges from 25 to 65 μ T.

As a result of the above, the SPARC machine would be smaller than **the ITER, which would allow it to be put into service by 2025 at a significantly lower cost.**

OTHER PROJECTS

The previous magnetic confinement fusion energy record in Europe was set by the UK's JET tokamak (Joint European Torus), which managed to yield 16 MW of fusion energy in 1997. Some important developments have been made since then. Among them are the artificial suns of South Korea and China.

The first one, known as KSTAR (Korea Superconducting Tokamak Advanced Research), is the result of the collaboration between the

Korea Institute of Fusion Energy and the University of Seoul. It has permitted extending the previous time record of 8 s of controlled fusion to 20 s with a plasma temperature of 100M degrees Celsius obtained thanks to new technology and in particular to the development of more powerful superconducting coils. This achievement was also made possible by the development of an internal transport barrier that allows the plasma to be stabilized around its periphery.



The KSTAR reactor
Source: National Research Council of Science and Technology of South Korea

China's HL-2M tokamak is another of the reactors currently under development. It stands out for reaching temperatures of 150M degrees Celsius — ten times higher

than the Sun's. This has allowed China to increase its scientific and technological contribution to the ITER project.

Along with the ITER Project there are other fusion advances in China, South Korea, United States and the United Kingdom