Nuclear fusion by magnetic confinement: advances, challenges and prospects

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Mastering fusion energy would offer a low-carbon energy resource of major interest. With ITER, the experimental reactor under construction at Cadarache, research will enter a decisive phase.
This article describes the principles of nuclear fusion by magnetic confinement, the steps taken up to the ITER project, and its objectives. The future of fusion depends on other research currently underway, in particular the choice of the optimum magnetic configuration. The implementation of breakthrough technologies, particularly in the field of materials, could also prove decisive for the future of fusion.

Mastering fusion energy, the only source of nuclear energy with virtually unlimited resources and low environmental impact, would offer a major opportunity for a low-carbon energy supply. With the construction of the ITER experimental reactor making rapid progress at the Cadarache site, research will be able to enter a decisive phase, with the possibility of studying conditions where the plasma is dominated by the power of fusion reactions.

After a brief review of the principles of fusion by magnetic confinement and the steps taken up to the ITER project, we will summarise the challenges and issues at stake in this last indispensable phase before the first power reactor. The results of the planned experimental programme will indeed be decisive, but the future of fusion will also depend on other ongoing research. These include, in particular, the choice of the optimum magnetic configuration for the commercial reactor. alongside *tokamak-type* configurations, such as ITER [1], *stellarator-type* configurations have not yet had their last word. We will take a look at the advances and projects in this field, illustrated in particular by the Wendelstein 7-X (W7-X) machine in operation at Greifswald (Germany) since 2015.

Whatever the final magnetic configuration, there are many challenges to be met, particularly in the field of materials. But decisive technological breakthroughs could be achieved through innovative projets recently launched around the world by a number of *start-ups*.

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The ITER experimental reactor. Aerial view of the site, 17 March 2023.

Thermonuclear fusion by magnetic confinement

Nuclear fusion

While the fusion reactions of light nuclei, particularly hydrogen, are the mechanism at the root of the nucleosynthesis process and the source of the energy radiated by the Sun, mastering these reactions for energy supply purposes represents an enormous challenge. The Lawson[a] criterion [1], which defines the maintenance thresholds for these reactions, provides a measure of the scale of this challenge. The threshold to be crossed, called "ignition", corresponds to an amplification factor Q, where $Q = P_{fus}/P_{ext}$, which expresses the ratio between the power produced by the fusion reactions and the heating power supplied from the outside, must be equal to or greater than unity. Roughly speaking, it can be expressed as a minimum to be obtained for the product of the pressure of the deuterium-tritium[b] mixture (a mixture of isotopes of hydrogen isotopes for which the conditions are most favourable for fusion reactors) by the energy confinement time in this medium[c]. This threshold, which corresponds in order of magnitude to one bar x second, applies to the following two extreme cases: (i) the so-called inertial confinement method [3], in which, when subjected to a pressure of several hundred gigabars, the medium reaches a density of the order of ten thousand times that of the liquid for an extremely short confinement time of the order of 10^{-12} s; (ii) the magnetic confinement method, for which the threshold conditions correspond to a pressure of around two bars (with a temperature of around 150 million K, and therefore a very low density of around ten mg/m^3) and an energy confinement time on the scale of one second.

In spite of the recent progress made on the Livermore facility for the first route, we will only discuss magnetic confinement here, which is by far the most relevant for the construction of power reactors. Even if, as we shall see, the road to a commercial reactor is still a long one, the stakes are enormous, because a fusion reactor with a power of 1 GW electric power, would consume only 100 kg of deuterium and 150 kg of tritium[d] per year, instead of 700 000 tonnes of oil, or 30 tonnes of uranium enriched to 3% uranium 235.

Before turning to the milestones that have marked the very significant progress made since the start of research, and listing the stages still to be completed before the first reactors can be commissioned, let's take a look at the principle of magnetic confinement and its specific features.

Magnetic confinement

The medium to be confined under the extreme temperature conditions described above is in the state of a fully ionised plasma. It can therefore be confined in a magnetic cylinder of suitable shape, in fact a closed toroidal configuration. The confinement of charged particles in such a configuration imposes a particular winding of the magnetic field lines, by combining toroidal and poloidal[e] components on the isobaric surfaces, thus constructing nested magnetic surfaces forming an onion skin structure (fig. 1).

Tokamaks and stellarators are the two most promising toroidal

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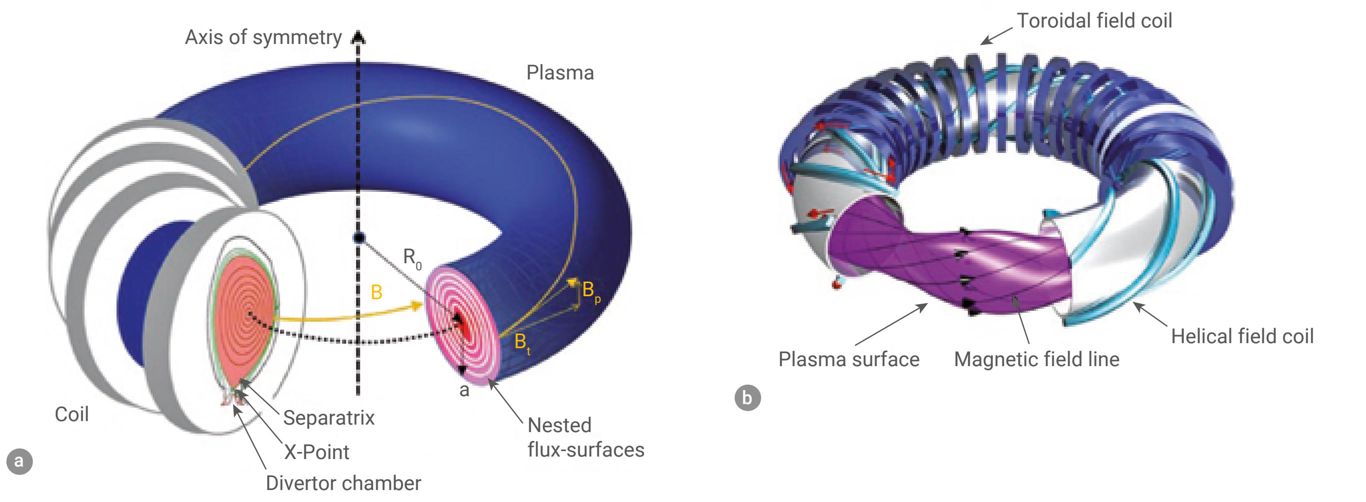

1. Magnetic configurations of the tokamak and stellarator.
(a) Schematic of a tokamak plasma, of major radius R_0 and minor radius a, with toroidal B_t and poloidal B_p components of the field; four of the coils supplying the toroidal component of the field are shown in grey on the left; the cross-section on the right shows the nested flux-surfaces for a circular cross-section; the section on the left shows (in green) the separatrix surface (last closed magnetic surface) for an elongated cross-section with the X-point and the *divertor*(g) chamber for removing impurities.
(b) Diagram showing a stellarator plasma with a three-dimensional structure, the coils producing the helical field (in light blue), those producing the toroidal field (in dark blue) and the resulting magnetic field lines twisted into a helix (in violet).
(Figure reproduced with the kind permission of Christian Brandt, Institute of Plasma Physics, Garching) [4].

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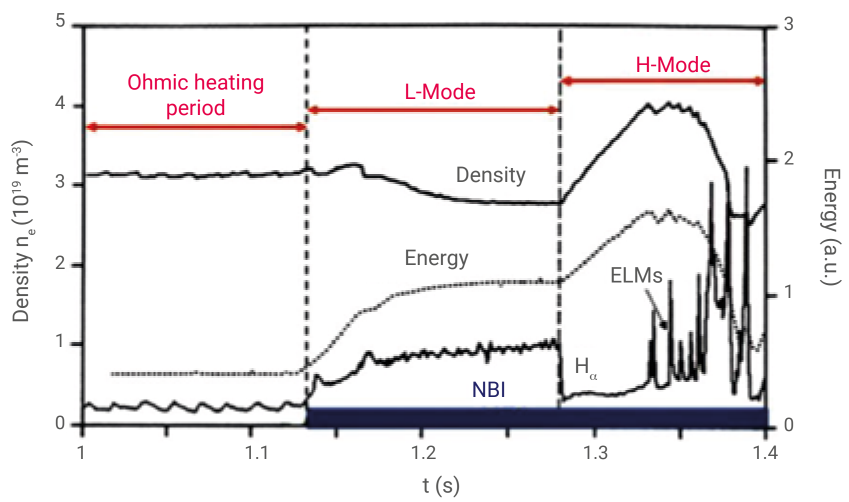
geometry confinement concepts for achieving fusion by magnetic confinement. The tokamak concept, on which ITER is based, is the most studied and the most advanced to date. As the poloidal component of the magnetic field is generated by a very strong toroidal current flowing through the confined plasma itself, this greatly simplifies the design of the external coils, which only need to produce the toroidal component of the magnetic field.

However, the stellarator concept has a number of advantages when it comes to building a commercial reactor designed for continuous operation. In such a configuration, the entire confinement magnetic field (toroidal and poloidal components) is generated by external windings. This avoids the very high plasma current inherent in the operation of a tokamak, which is a potential source of instabilities that need to be controlled to avoid a sudden loss of confinement. Despite greater construction difficulties and inadequate confinement properties in the first projects, the great progress made in complex methods for optimising magnetic configurations has made it possible to define various optimised stellarator geometries that differ in type and degree of symmetry and have excellent confinement properties.

Plasma heating

The magnetically confined plasma must be heated to an energy of around 15 keV (corresponding to a temperature of 1.75 10^8 K). However, in a tokamak configuration, heating by the Joule effect produced by the current cannot exceed 10^7 K, because the resistivity of the plasma decreases as its temperature rises (it becomes non-collisional). This is why two

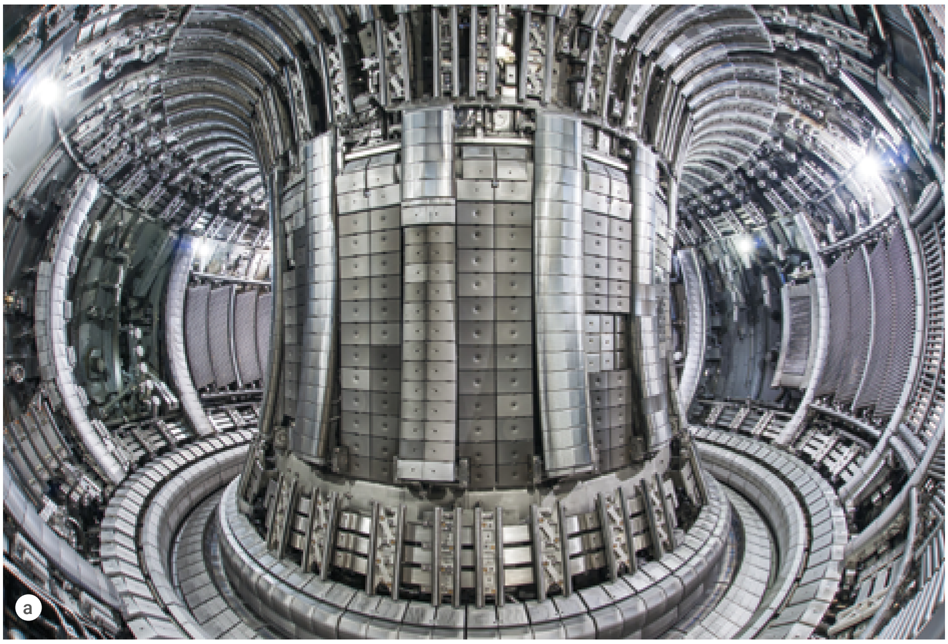


2. Historical diagram of the ASDEX tokamak, showing one of the first transitions to H mode.
Two periods of the discharge are shown: the ohmic heating period, followed by the period with neutral beam heating (NBI, in blue). The plasma first enters L-mode with a moderate increase in energy content but degraded confinement (density decreases), followed by a sudden and spontaneous transition to H-mode with improved confinement (energy and density increase significantly). Later in the H-mode phase, ELMs (Edge Localized Modes) develop, repeatedly destroying the H-mode edge transport barrier (density and energy decrease) [4].

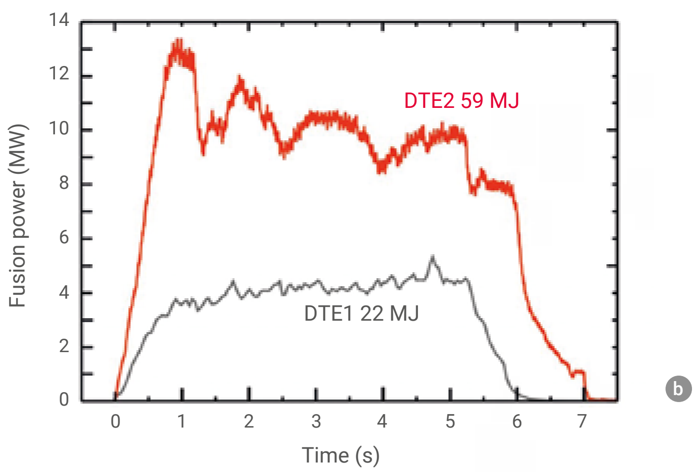
powerful alternative auxiliary heating methods were developed in the 1970s. One consists of injecting high-energy particles into the plasma, using powerful "neutral" injectors (neutral deuterium atoms), while the other consists, using adapted antennae, of injecting high-energy. frequency radio power that can be transferred to the plasma by resonance with certain eigenmodes and certain classes of particles (electrons, ions). This second method also makes it possible to generate current in the plasma and finely control its parameters (e.g. current, density, temperature) and their spatial distribution.

A key milestone in the progress towards ignition was the discovery of a fundamental phenomenon of self-organisation of the plasma beyond the ohmic regime. This is referred to as the 'L-H transition', i.e. from a low-confinement (L) mode to a high-confinement or improved (H) mode, resulting in a strong stiffening of the radial profiles of the plasma parameters. This transition was first demonstrated and studied in the ASDEX tokamak (at Garching near Munich) by F. Wagner [4] during neutral injection heating experiments (fig. 2). This discovery represents a fundamental step on the long road to ignition in a magnetically confined plasma, because the existence of the H mode makes it possible to achieve better confinement of the very hot plasma, for which energy losses result from turbulence at the edge of the plasma. It is then possible to approach ignition conditions without having to increase the size of the machines[f] unreasonably.

The study of these enhanced confinement modes has led to a better understanding of the turbulent transport of energy and particles in these plasmas, and in particular how edge turbulence and plasma flows developpent in a self-consistent manner and how transport barriers associated with the stiffening of profiles are formed and maintained. We have also learned how to control relaxation phenomena such as ELMs (Edge Localized Modes).



3. The European JET tokamak.
(a) View inside JET.
(b) Fusion power as a function of time. In December 2021, JET produced a total of 59 MJ of fusion energy over a period of five seconds, with an average fusion power of around 11 MW (DTE2). It had already held the world record of 16 MW of fusion power since 1997, and had supplied 22 MJ of fusion energy for more sustained stationary firings of 5 seconds, in H mode, corresponding to an average power of 4.5 MW (DTE1).



The world's best results to date have been obtained in the European tokamak JET (fig. 3) at Culham near Oxford, in an H-mode operating configuration. In 1997, during a historic campaign, the world record of 16.1 MW of fusion power, corresponding to an amplification factor $Q = P_{fus}/P_{ext} \sim 0.75$, was first obtained on a short plasma pulse of one second. Thanks to this high confinement mode, stationary 5-second shots then provided a total fusion energy production of 22 MJ, corresponding to an average power of 4.5 MW (see the DTE1 curve in Figure 3). The very good news, with a view to the ITER experiments, is that these results were not only reproduced but also improved during a very recent campaign on the modified JET reactor (see curve DTE2 in figure 3). All the components in contact with the plasma[g], which

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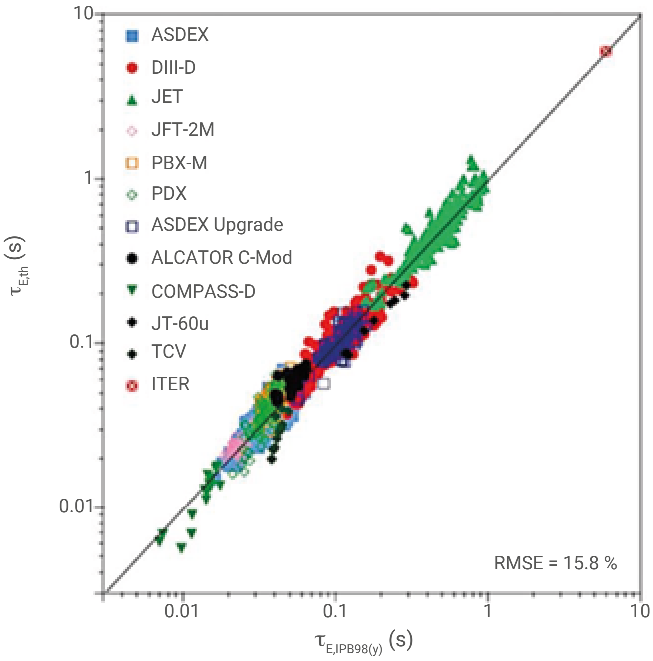

4. The performance of many machines around the world, measured by the plasma thermal energy confinement time in H-mode ($\tau_{E,th}$), compared with the predictions of the scaling laws ($\tau_{E,IPB98y}$). We note the robustness of these power laws and the confirmation of the growth of τ_E with the volume and intensity of the magnetic field. The expected value for ITER is shown at the top right. [4]

since the first tokamaks. Each new generation, characterised in particular by an increase in size, marks a clear improvement in performance. For example, τ_E has improved by a factor of 10,000, and the improvement is of the same order for the triple product $nT\tau_E$. This diagram also illustrates the relevance of scaling analyses to express the dependence of τ_E on numerous parameters: plasma current, toroidal magnetic field, heating power, density, geometric parameters, etc. The abundant international database was used to produce this diagram using multidimensional regression, which extrapolates to the expected value for ITER: 6 seconds. The robustness of the scaling laws established makes us very confident that ITER will achieve this objective.

Table 1 shows the main characteristic parameters of the JET and ITER tokamaks, and illustrates the relationship between performance, measured by time τ_E, and the size of the machines.

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were initially made of carbon and had the unfortunate property of trapping hydrogen, were replaced by beryllium and tungsten, the same materials as those chosen for ITER.

Progress towards ITER

The diagram in Figure 4 gives an immediate indication of the progress made in terms of characteristic confinement time (the parameter τ_E)

The ITER project: objectives and challenges

Final assembly of the machine is under way at the Cadarache international site, and we refer readers to

	JET	ITER
Major radius R_0	3 m	6.20 m
Minor radius a	1.25 m	2 m
Plasma volume	100 m³	830 m³
Magnetic field	3.4 T	5.3 T
Plasma current	5 MA	17 MA
Windings	Copper	Superconductor / cryostat He
Total auxiliary heating	38 MW	50 MW
Fusion power	16 MW	500 MW

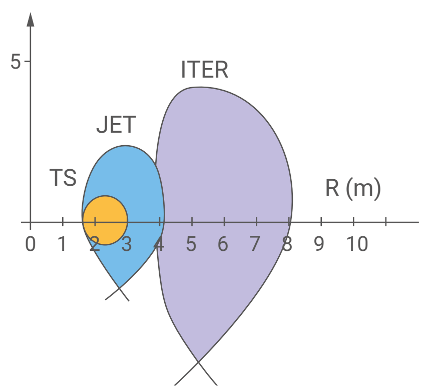


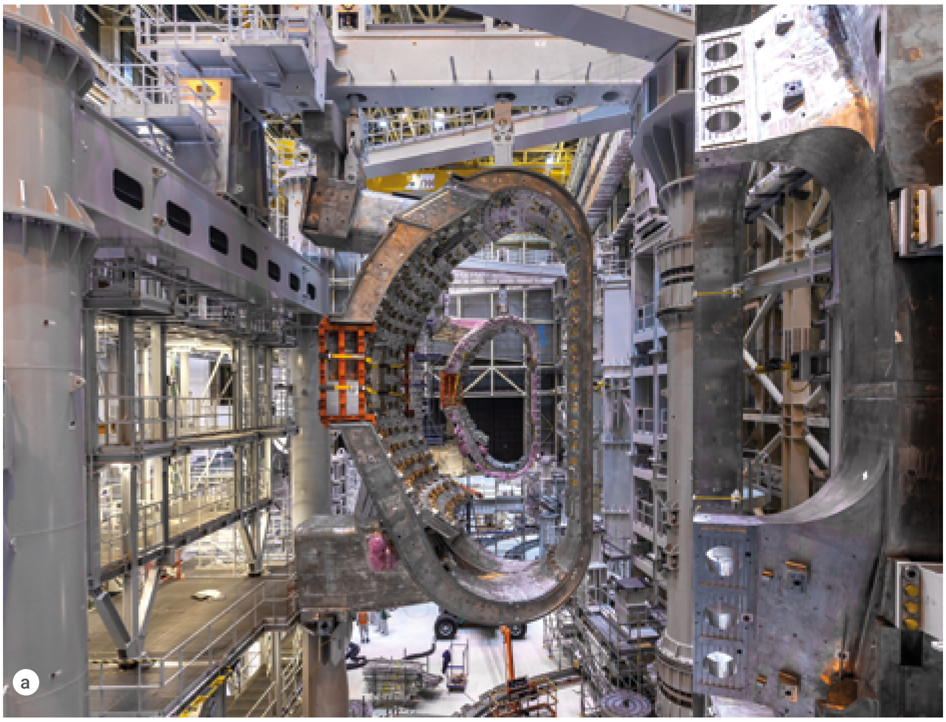
Table 1. **comparison of the JET and ITER tokamaks.**
Right: poloidal sections of the Tore Supra (TS) [1], JET and ITER tokamaks.

the official website (www.iter.org/fr/actualiteshistory) and to references [1] and [4]. We can only briefly summarise the objectives of the programme here, with a first plasma probably around 2027 and the first full-power deuterium-tritium experiments ten years later.

ITER (fig. 5) should be the first machine in the world to exceed the fateful Q = 1 threshold and reach Q = 10 over discharges lasting 400 seconds, with plasmas producing 500 MW of fusion power for 50 MW of external heating power. The main objectives of this research reactor are: (i) to explore stationary plasma regimes, where heating is dominated by α-particles (helium nuclei) produced by fusion reactions: plasma stability, neutron flux; (ii) control of the 'combustion' and evacuation of the 'ash' constituted by the helium produced.

The technological challenges are many, and ITER will be the essential test bed for the main components of the future power reactor. These include (i) remote handling and remote control techniques; (ii) the operation of the *divertor*[g] and the very crucial issue of heat dissipation on its plasma facing components, subjected to fluxes of the order of 10 MW/m^2 but which can transiently exceed 20 MW/m^2; (iii) the testing of tritium blanket modules; (iv) the reliability of all the complex external heating systems (neutral injectors in particular).

ITER must be able to establish the feasibility of a commercial fusion reactor, and to this end validate most of the technological solutions to be implemented. The only essential area in which a complementary facility will be needed is the development of structural materials capable of withstanding the very high fluxes of 14 MeV fusion neutrons. Solid leads exist, but they require a special installation to be tested and developed, which is planned from the start of the international ITER programme. After the initial study phase, which has just been completed, construction of this special facility, called IFMIF-DONES (International Fusion Materials Irradiation Facility - Demo Oriented Neutron Source), is due to start soon in Granada, Spain.



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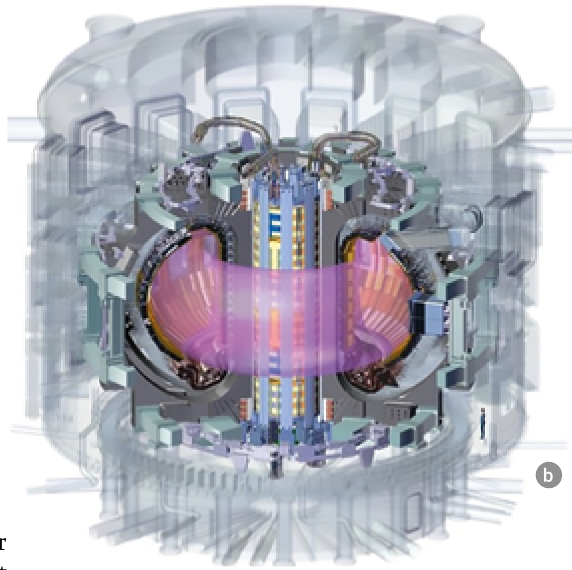

5. The ITER experimental reactor
(a) Assembly (25 January 2023).
(b) Schematic view of ITER, with its central solenoid. This huge electromagnet plays a central role in initiating the current and controlling the shape of the plasma during operation.

Alternative approaches to tokamak and innovative projects

The stellarator route and the Wendelstein 7-X device

We indicated at the beginning of this article why a stellarator-type configuration could eventually prove advantageous for a commercial reactor, despite the greater complexity of design and construction than for tokamaks. The largest and most advanced machine of this type in the world is the Wendelstein 7-X stellarator (fig. 6, www.ipp.mpg.de/w7x) in operation in Greifswald (Germany) since 2015. This is a so-called quasi-symmetrical magnetic configuration, with superconducting coils for quasi-stationary operation, as in the case of ITER.

The results of the first series of experiments are very encouraging and have already confirmed that, given the same size and magnetic field, the confinement properties of stellarators are as good as those of tokamaks.

After a major transformation of the machine, completed in December 2021, to equip it with actively cooled *divertors* (see note f), new campaigns with discharges lasting 30 minutes and at full heating power will be able to begin. The ultimate aim is to demonstrate that a stellarator configuration is a viable alternative to a

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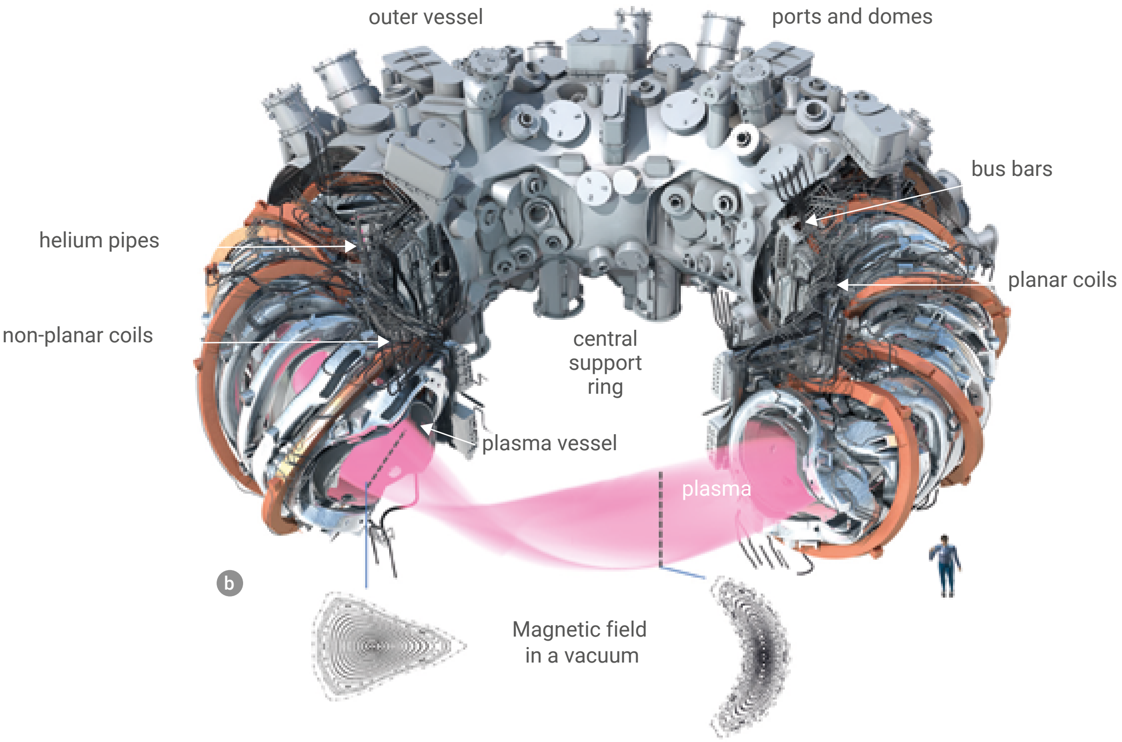

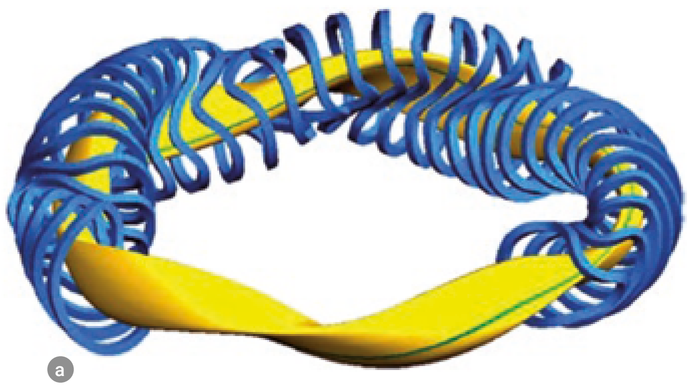

6. The superconducting Wendelstein 7-X stellarator [4, 5].
(a) Left: drawing from a numerical model of the coils (in blue) and plasma (in yellow) [5].
(b) Right: schematic diagram of the stellarator. The NbTi superconducting coils (50 of which are non-planar and 20 planar) are cooled with liquid helium. The major radius R_0 is 5.5 m and the aspect ratio $A = R_0 /a$ is 10. The plasma volume is 30 m³. The last closed magnetic flux surface is shown in magenta.

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tokamak, and to validate the design and configuration of a power reactor-class machine called HELIAS.

Innovative projects and breakthrough technologies

We have recently seen the creation of private or semi-private companies with the ambition of bringing power reactor projects to fruition very quickly, thanks to the implementation of breakthrough technologies. The most important of these technologies is, unsurprisingly, the use of high-temperature superconductors (HTS), which could be cooled with liquid nitrogen and would double the intensity of the magnetic field. This last point is essential, because fusion power varies roughly as the fourth power of this intensity. It would then be possible to considerably reduce the size of the machines, the importance of which we have already seen in terms of energy confinement time. To illustrate this major turning point in the world of fusion, we give a brief description of two projects, one for a tokamak-type configuration and the other for a stellarator-type configuration.

The SPARC project (https://cutt.ly/cfs-fusion-energy), led by MIT and the *start-up* Commonwealth Fusion System (CFS). It is the result of pooling the well-established skills of the MIT teams in the world of tokamaks and the advances made in the use of high-temperature superconductors by CFS. SPARC is a compact tokamak with a major radius of 1.85 m and a minor radius of 0.57 m, a very strong magnetic field of 12.2 T, and a plasma current of 8.2 MA, with which they aim to achieve an amplification factor of Q = 2... in 2025.

The ambitious Chartreuse **stellarator project**, led **by** Grenoble-based *start-up* Renaissance Fusion (https://renfusion.eu/technology). Here too, the first objective is to manufacture HTS-type superconducting windings, using a highly innovative deposition and etching technology that greatly simplifies the construction of a stellarator-type configuration. Achieving twice the field strength would also make it possible to reach reactor conditions within the dimensions of the W7-X machine. For example, while HELIAS, with a field strength of 5 T, would have a large radius of 22 m, Chartreuse with a field strength of 10 T would have a radius of just 6 m. But Renaissance Fusion is also aiming to meet another major challenge for the fusion reactor, by using a flow of liquid metal on the inside wall of the stellarator, to ensure both the generation of tritium and the absorption of fusion neutrons.

Conclusion

Considerable progress has been made since the beginning of research into the control of fusion energy by magnetic confinement. This research is now entering a decisive stage with the imminent completion of the construction of ITER, which will enable us to study the conditions in which the plasma is dominated by the power of fusion reactions. It is the essential experimental reactor for developing the key technologies for future commercial reactors.

Private investment in innovative projects by *start-ups* offers hope of progress in breakthrough technologies, in particular high-temperature superconducting magnets at very high magnetic fields. If these projects are successful over the next ten years, the first grid-connected reactor could be up and running sooner than expected.

At a time when hydrogen, if produced on a massive scale by electrolysis, is considered to make an effective contribution to the defossilisation of energy, it is worth pointing out that a 1 GW fusion reactor would produce 8 TWh of electricity per year by fusing 100 kg of deuterium and 150 kg of tritium... would enable electrolysis to produce... 160,000 tonnes of hydrogen! ▮

“ITER should be the first machine in the world to exceed the fateful Q = 1 [amplification factor] and reach Q = 10 over discharges lasting 400 seconds, with plasmas producing 500 MW of fusion power for 50 MW of external heating power."”

(a) For more details on this fundamental criterion, and more generally on fusion by magnetic confinement and the ITER project, see the article by Jean Jacquinot [1].

(b) This corresponds to the fusion reaction: ^{2}H+ ^{3}H→ ^{4}He (3.56 MeV) + ^{1}n(14.03 MeV), in which 20% of the energy released is carried away by a helium nucleus (particle α) and 80% by a neutron.

(c) This energy confinement time should not be confused with an operating time. It corresponds to a characteristic time for the plasma to cool down after the energy supply has stopped, and thus measures the quality of the confinement, in a similar way to the time it takes for a house to cool down after the heating has been switched off.

(d) Or rather 100 kg of deuterium and 300 kg of lithium, as tritium will be produced *in situ* by interaction between fusion neutrons and lithium.

(e) Toroidal/poloidal: respectively along the great circle and the small circle of the torus.

(f) Increasing the characteristic size of the machines lowers the surface area to volume ratio, which is favourable to the power balance for reactions that take place in volume, whereas the losses are on the surface area.

(g) These plasma-facing components have a decisive role to play. They must absorb and evacuate the flows of heat and particles from the plasma. This is a major challenge for a reactor operating in continuous mode, where these components subject to stationary flux of the order of MW/m^2 must be actively cooled. This is particularly important in the case of the *divertor*, which is designed to collect most of the flow of heat and charged particles leaving the plasma, subject to even more extreme flux conditions.

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