C. R. Physique 18 (2017) 367–371

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Demain l'énergie – Séminaire Daniel-Dautreppe, Grenoble, France, 2016

ITER: A unique international collaboration to harness the power of the stars

ITER : une collaboration internationale inédite pour puiser l'énergie des étoiles

Bernard Bigot

ITER Organization, route de Vinon-sur-Verdon, CS 90 046, 13067 Saint-Paul-lès-Durance, France

ARTICLE INFO

Article history:
Available online 19 September 2017

Keywords:
ITER
Energy
Thermonuclear fusion
Tokamak
Plasma
Superconducting magnets

Mots-clés :
ITER
Énergie
Fusion thermonucléaire
Tokamak
Plasma
Électro-aimant supraconducteur

ABSTRACT

Harnessing the energy of thermonuclear fusion reactions is one of the greatest challenges of our time. Fusion, the nuclear reaction that powers the Sun and stars would provide mankind with a safe, environmentally benign, and virtually limitless source of energy.

RÉSUMÉ

Exploiter l'énergie libérée par les réactions de fusion thermonucléaire est l'un des plus grands défis de notre temps. En imitant les réactions physiques qui alimentent le Soleil et les étoiles, l'humanité pourrait accéder à une source d'énergie virtuellement inépuisable, sûre et respectueuse de l'environnement.

In the 1920s, physicists began unravelling the nuclear cycles by which Sun-like stars have been producing prodigious amounts of energy for billions of years. Three decades later, most developed nations had joined in the ambition to create a comparable reaction in a manmade machine.

In the core of Sun-like stars, gravitational forces create conditions of temperature, pressure and density that allow hydrogen nuclei to overcome electrostatic forces and fuse.

The fusion process is a mass-to-energy conversion reaction. In Sun-like stars, it is extremely slow – it takes about one billion years for a hydrogen nucleus to "get a chance" to fuse with another and initiate the complex chain of reactions that will eventually produce a helium nucleus and a considerable liberation of energy (see Fig. 1).

E-mail address: Bernard.Bigot@iter.org.

http://dx.doi.org/10.1016/j.crhy.2017.09.002

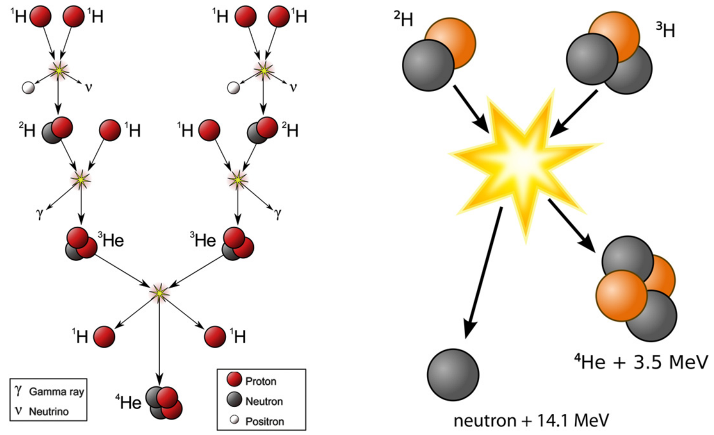

Fig. 1. (a) The "proton–proton chain" that was identified in the 1920s (Eddington) and fully described in the following decade (Bethe) is the complex and lengthy process that enables Sun-like stars to generate energy. (b) In a fusion reactor, the deuterium–tritium reaction is much simpler than in Sun-like stars, but produces the same result: two light nuclei fuse into one heavier one (helium), producing large amounts of energy in the process.

The fusion process as it occurs in the core of Sun-like stars cannot be replicated on Earth. But it can be imitated.

Physicists soon determined that a hot, ultra-low-density plasma (in the range of 150,000,000 °C) comprised of equal parts of deuterium and tritium (the two heavy isotopes of hydrogen) and confined by intense magnetic fields would provide an environment in which fusion reactions can occur (see Appendix A).

As early as the mid-1960s, "fusion machines" of various shapes, sizes and performance levels – such as pinch and mirror devices, stellarators, and tokamaks (a Russian acronym for Toroidal Chamber, Magnetic Coils) – were operating in the Soviet Union, the USA, the United Kingdom, Germany, France, and Japan.

However, the way to fusion power was to prove considerably more difficult, complex, and costly than anticipated.

As they explored the mind-boggling complexity of plasma physics and faced the technological challenges of building and operating fusion devices, physicists and engineers realized that no single nation, whatever its human, scientific and technological resources, could address the magnitude of the task alone.

In the 1970s, as large and promising tokamak projects were being developed in Europe (Joint European Torus), the US (Tokamak Fusion Test Reactor) Japan (JT-60) and the USSR (T-15), the international fusion community engaged in an international effort to design an even larger experimental machine – INTOR, the International Tokamak Reactor.

INTOR never saw the light of day, but paved the way to ITER, the International Thermonuclear Experimental Reactor (and the Latin word for "the way"), which is currently under construction in Saint-Paul-lès-Durance, some 40 km north of Aix-en-Provence, in southern France.

The ITER Project received a decisive political push in November 1985 when President Reagan and Secretary General Gorbachev met in Geneva and agreed on launching "*the widest practicable development of international cooperation in obtaining* [*fusion*] *energy, which is essentially inexhaustible, for the benefit for all mankind*."

Two decades of collaborative work ensued as the project's members – the USA, the USSR (later Russia), Europe (Euratom) and Japan, joined by China and Korea in 2003 and by India in 2005 – fine-tuned the design of the installation and eventually agreed on the location for its construction.

In October 2007, the ITER International Fusion Energy Organization (in short the ITER Organization) was officially established, and the dream of three generations of fusion physicists and engineers at last had a legal framework and a home to become reality.

ITER's mission is to build and operate a very large tokamak that will confirm the feasibility of exploiting fusion reactions for the production of energy by providing an integrated demonstration of the physics and technology required for a fusion power plant.

The ITER tokamak will be by far the largest fusion machine ever built (23,000 t, approximately 30 m high and 30 m in diameter) and the first to sustain a "burning plasma" in which the energetic helium nuclei (α particles) resulting from the fusion reactions dominate all other forms of plasma heating (Fig. 2).

Reaching the conditions necessary for fusion reactions to occur will require approximately 50 MW of heating power in the form of radiofrequency and microwaves, and neutral particle injection. Once fusion reactions are initiated, the "burning plasma" will deliver 500 MW of fusion power for durations of 300 to 500 seconds (see insert 2).

ITER is also designed to explore the physics basis for the continuous operation of fusion power plants by investigating "steady-state" plasma operation.

Strong magnetic fields, produced by a massive array of superconducting coils (10,000 t) will shape and confine the hot plasma within the tokamak's vacuum vessel (Fig. 3).

And like the ITER machine, the ITER collaboration is unique.

Fig. 2. (a) Little free space remains on the 42 hectares of the ITER platform. Sandwiched between the cooling tower zone and concrete batching plant at the northern end (far left) and the electrical switchyard to the south (far right) are the work areas for the Tokamak Complex (centre crane), the cryoplant (middle right, all grey) and the buildings for magnet power conversion (twin structures, right). Any free space is used for storage. At the top of the image, manufacturing is underway in on-site facilities for the cryostat and four of the machine's six poloidal field coils, too large to be transported by road. (b) The ITER tokamak will be assembled in this "well" at the centre of the Tokamak Complex building. The large openings in the walls of the "bioshield" – the thick steel and concrete structure that surrounds the machine – are "penetrations" that will allow system equipment such as magnet feeders, remote handling, heating and diagnostics to reach the machine.

Fig. 3. (a) Six ring-shaped coils circle the tomakak to create the poloidal magnetic field. Four of them, ranging from 17 to 24 m in diameter will be manufactured by Europe on the ITER site. Fabrication for poloidal field coil # 5 began in April 2017. (b) In La Seyne-sur-Mer, in the Var *département*, the French Company CNIM has produced 35 of the 70 needed "radial plates" for the tokamak's toroidal field coils.

It is the largest scientific cooperation project ever established, bringing together 35 nations representing more than half of the world's population and 85% of the planet's gross domestic product.

The contribution of the seven ITER Members is done essentially in-kind – China, the European Union, India, Japan, Korea, Russia, and the United States have each established a Domestic Agency that contracts with the industry to manufacture machine components and installation systems.

With the exception of the European Union, each Member's contribution represents approximatively 9% of the total value of the project. As "host Member", the European Union not only procures its share of components and systems; it is also responsible for delivering the 39 permanent buildings of the installation, which brings its contribution to approximately 45%.

Ten years have passed now since scrapers and earth-moving equipment began transforming a large stretch of national forest, granted by France to the ITER Organization, into the perfectly flat platform that would accommodate the ITER installation.

In the summer of 2010, building construction began in earnest. Seven years later, the progress accomplished, both on the construction site in Saint-Paul-lès-Durance and in factories throughout the world, is spectacular.

On the construction site, 2,000 workers are busy erecting and equipping the installation's buildings. Close to 6 billion euros in contracts (mainly for civil works) have already been awarded, half of them to French companies.

Visible from afar, the stainless-steel-clad Assembly Hall, rising 60 m high, and the adjacent Tokamak Complex, which form the heart of the installation, are now distinct features of the Durance Valley landscape.

A cryoplant (see Appendix B) – the largest in the world – to provide cooling fluids for the tokamak's superconducting magnetic system; twin buildings, 150 m long, for the magnet power conversion equipment; a 400-kV switchyard and its set of giant transformers along with several other buildings have all reached different stages of completion. Night and day, the ITER worksite is swarming with activity.

Activity is also intense in factories on three continents where the ITER components and systems are being manufactured. More than 40% (in value) of the total components and systems needed for First Plasma in 2025 have already been produced.

Buildings, components, systems, will soon coalesce into one the most complex installations ever conceived and constructed.

ITER, which will enter into operation in 2025, marks both the culmination of six decades of fusion research and the opening of a whole new chapter in the quest for unlimited energy. It is an opportunity to change the course of our civilization.

Building ITER is also a demonstration that nations, when confronted with a global challenge, can establish a completely new model for international collaboration. In ITER, scientists, engineers and administrators from 35 nations have demonstrated their ability to work together across national and cultural boundaries to accomplish a common goal.

Conclusion

ITER marks both the culmination of six decades of international scientific and technological effort and the opening of a new and decisive chapter in the history of fusion research. By demonstrating the feasibility of fusion energy, ITER will answer the question that has obsessed three generations of physicists and engineers. It will realize the Promethean dream of bringing the fire of the Sun down to Earth.

Acknowledgements

We would like to thank Robert Arnoux, co-author, with Jean Jacquinot, of the book *ITER, le chemin des étoiles ?*, edited by Édisud, 2006.

Appendix A. Power ratio $Q \geq 10$

Creating conditions for fusion in a deuterium–tritium plasma in ITER requires a considerable input of heating power ($\sim$50 MW) in the form of radio-waves, microwaves, and neutral particle injection.

The fusion of a deuterium nucleus (one proton, one neutron) with a tritium nucleus (one proton, two neutrons) produces a helium nucleus (two protons, two neutrons) and a neutron (see Fig. 1b).

The helium nucleus, or alpha particle, which carries 20% of the energy released (3.5 MeV), remains trapped inside the magnetic cage and transfers its energy to the plasma – "alpha heating" becomes dominant, a condition referred to as a 'burning plasma'.

The neutron, which carries 80% of the energy released (14.1 MeV) escapes and hits the inner walls of the vacuum vessel, where the kinetic energy of its impact is transformed into heat.

If ITER were an industrial fusion plant, the heat generated by the burning plasmas would be used to produce pressurized steam and, by way of turbines and generators, electricity. Only residual heat would need to be dissipated.

But as an experimental installation, not designed to produce electricity, ITER will need to evacuate and dissipate all the power the fusion reactions generate.

The primary mission of the ITER project is to produce $\sim$500 MW of fusion power for durations of 300–500 s with a ratio of fusion output power to input heating power (fusion gain), Q, of at least 10.

If plasma confinement characteristics are favourable, ITER would also be capable of exploring the 'controlled ignition' regime of tokamak operation (with $Q \sim 30$) in which power plant plasmas are expected to operate.

Heat will be removed from the vacuum vessel and its components by a closed-loop pressurized water circuit and eventually dissipated by the heat rejection system that comprises cold and hot basins with a total volume of 20,000 m^3 as well as an induced-draft cooling tower installation.

Appendix B. A large and complex cryogenic system

The ITER machine will rely on a large and complex cryogenic system comprising the cryoplant, which will produce the required cooling power, and a five-kilometre long cryodistribution system to distribute the cooling fluids. The cryogenic system will guarantee cooling and stable operation for the tokamak's magnets, its cryopumps, and its thermal shields over a wide range of plasma scenarios.

The magnets, all 10,000 tons of them, operate at high magnetic fields to confine and stabilize the plasma and require cooling with supercritical helium at 4 K ($-269\,^{\circ}$C). They will be surrounded by a large cylindrical cryostat (30 m in height, 30 m in diameter) and an actively-cooled silver-coated thermal shield with a forced flow of helium at 80 K (see Fig. 4). Large cryosorption panels cooled by 4 K supercritical helium are used to achieve the high pumping rates and vacuum levels.

The cryoplant system is comprised of three helium and two nitrogen refrigerators combined with an 80 K helium loop. Storage and recovery of the large helium inventory (25 t) is provided in warm and cold (4 K and 80 K) gaseous helium tanks.

Fig. 4. A large "thermos", the cryostat, will encase the machine and prevent heat exchanges between the ultra-cold superconducting magnet system and the environment. Procured by India, this 30-metre high, 30-metre in diameter is being assembled and welded in a dedicated workshop on the ITER site.

Three parties are associated in the procurement of the ITER cryoplant: Europe (the liquid nitrogen facility and auxiliary systems), India (the interconnecting lines and cryodistribution equipment), and the ITER Organization (responsible for the direct procurement of the liquid helium plant).