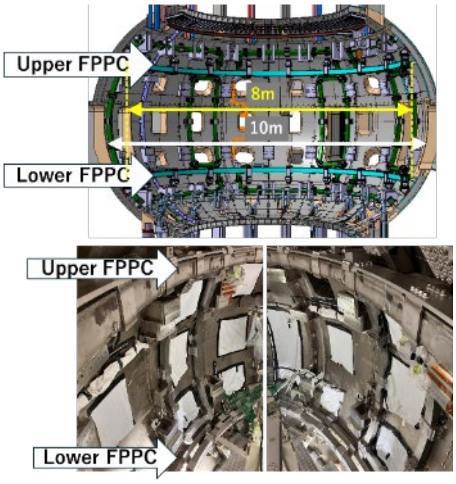
National Institutes for Quantum Science and Technology
Mitsubishi Electric Corporation
23rd December 2025

Completion of the Fast Plasma Positioning Control Coil for stable confinement of the world's largest plasma
Fabrication of an 8-meter coil inside the JT-60SA vessel with ±2 mm accuracy

【News Highlights】
- Two Fast Plasma Positioning Control Coils (FPPCs) for maintaining stable plasma during the plasma heating experiments scheduled to begin in 2026, have been completed for JT-60SA—the world's largest superconducting tokamak— jointly constructed by Japan and Europe in Naka City, Ibaraki Prefecture.
- The FPPC is an 8-meter-diameter copper coil, installed inside the JT-60SA vacuum vessel (inner diameter 10 meters). During fabrication, engineers successfully overcame the technical challenge of winding coil within the confined environment of vacuum vessel, achieving positional and shape accuracy within ±2 millimeters.
- The technology developed with JT-60SA contributes to the fabrication of in-vessel coils for ITER, currently under construction in southern France. Going forward, the advanced technology for stable control of the world's largest plasma using the FPPC at JT-60SA will serve as an important foundation for advancing plasma control technologies amid intensifying international competition, and for establishing the autonomy and high reliability of DEMO reactors.

The National Institutes for Quantum Science and Technology (President: KOYASU Shigeo; hereinafter referred to as "QST") and Mitsubishi Electric Corporation (President & CEO: URUMA Kei; hereinafter referred to as "Mitsubishi Electric") have successfully completed the fabrication of two Fast Plasma Positioning Control Coils*[1] (FPPCs)—a core technology for high-speed, high-precision plasma position control—for JT-60SA*[2] as part of the Broader Approach Activities*[3], which is a joint project between Japan and Europe.

During its first plasma test in 2023, JT-60SA achieved a massive plasma volume of 160 cubic meters. In the upcoming plasma heating experiments scheduled to begin in 2026, the newly completed FPPCs for plasma control, with the goal of reaching a plasma current of 5.5million amperes (5.5MA).



Completion of FPPC inside JT-60SA

Each FPPC is a copper coil measuring 8 meters in diameter, installed at two locations inside the JT-60SA vacuum vessel (inner diameter 10 meters). The current supplied to the FPPC—up to 5,000 amperes (5 kA)—is controlled at high speed within just 10 milliseconds, enabling precise regulation of the plasma's position and shape. QST carried out the fundamental design of the FPPC's performance and the in-vessel coil fabrication. Mitsubishi Electric subsequently devised new fabrication methods to realize this design, and through close collaboration, the two organizations successfully established the final coil positioning process. As a result, the FPPC was successfully completed with positional and shape accuracy within ±2 millimeters, which is a requirement to achieve stable plasma control.

The fabrication method developed in this project will contribute to the production of in-vessel coils for ITER*[4], currently under construction in southern France. Furthermore, the plasma control using FPPC at JT-60SA will enable prior validation of the plasma control planned for ITER, serving as a foundation for advancing plasma control technologies amid intensifying international competition, and establishment of AI-driven autonomous plasma control. In this way, the successful completion of the FPPC marks an important step forward in advancing fusion energy research and development worldwide.

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【Overview】

Figure 1 illustrates the full structure of JT-60SA, and the plasma confined within. Superconducting coils generate a magnetic "cage" that traps the plasma inside. To enhance fusion output, it is essential to improve plasma confinement performance and raise the plasma temperature to several hundred million degrees Celsius.

Although particles such as ions and electrons within the plasma are confined by magnetic fields, they gradually diffuse outward due to collisions and eventually escape to the vessel walls. To enhance confinement performance under these conditions, it is essential to optimize the plasma shape so that its own pressure suppresses particle diffusion and extends the path length before particles reach the wall. It is now confirmed that a vertically elongated, triangular cross-sectional shape is particularly effective in improving plasma confinement.

The newly developed FPPC is a coil designed to maintain the plasma's triangular shape and are installed at two locations inside JT-60SA vacuum vessel (upper and lower FPPC as shown in Figure 1). If the plasma becomes unstable and begins to deviate from its ideal configuration, the FPPCs adjust the magnetic field by precisely controlling the current flow, enabling fine-tuned regulation of the plasma's position and shape.

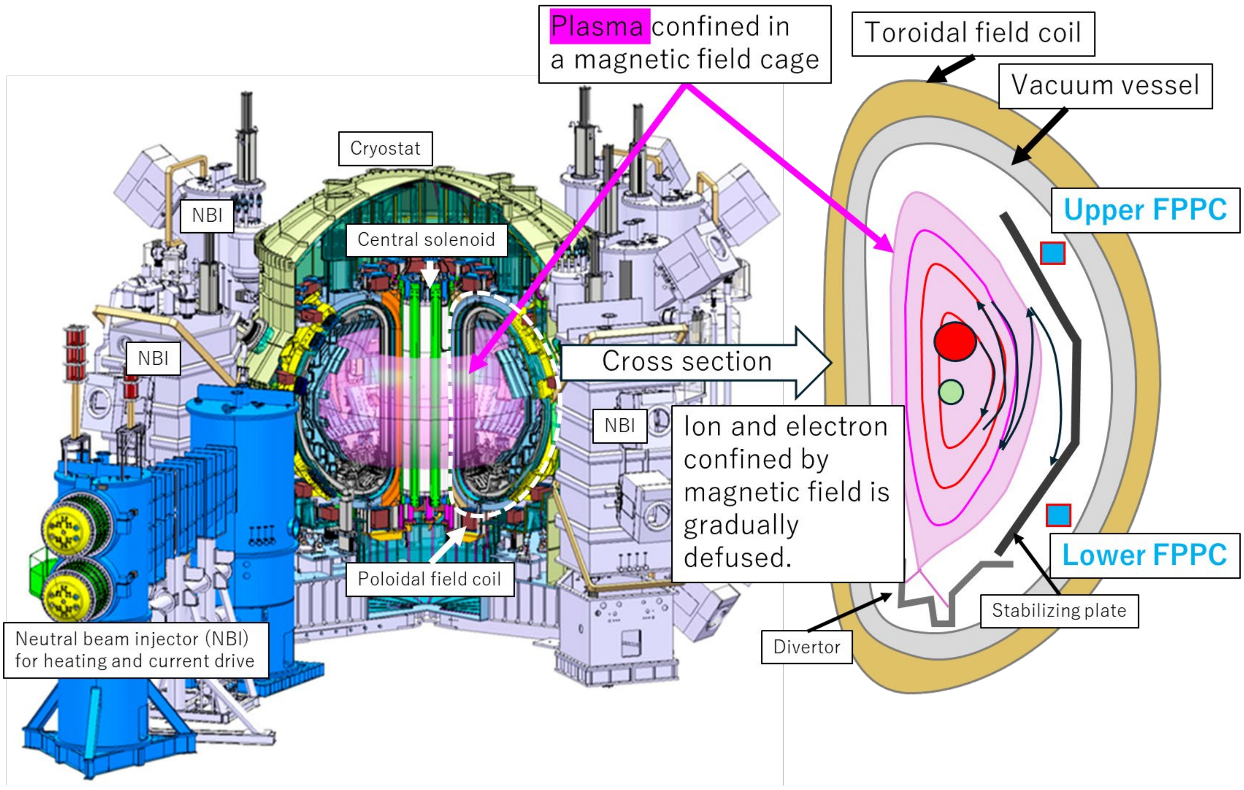

Figure 1. JT-60SA and appearance of plasma from inside

【Design of FPPC】

As shown in Figure 2, the FPPCs are installed at two locations—upper and lower—inside the vacuum vessel (inner diameter 10 meters) that confines JT-60SA plasma. The installation process begins with mounting Error Field Correction Coils (EFCCs) along the entire inner wall of the vacuum vessel to compensate for manufacturing and assembly deviations in the vacuum vessel and superconducting coils. Within this complex interior—filled with protruding structures such as the EFCCs—the FPPCs are fabricated

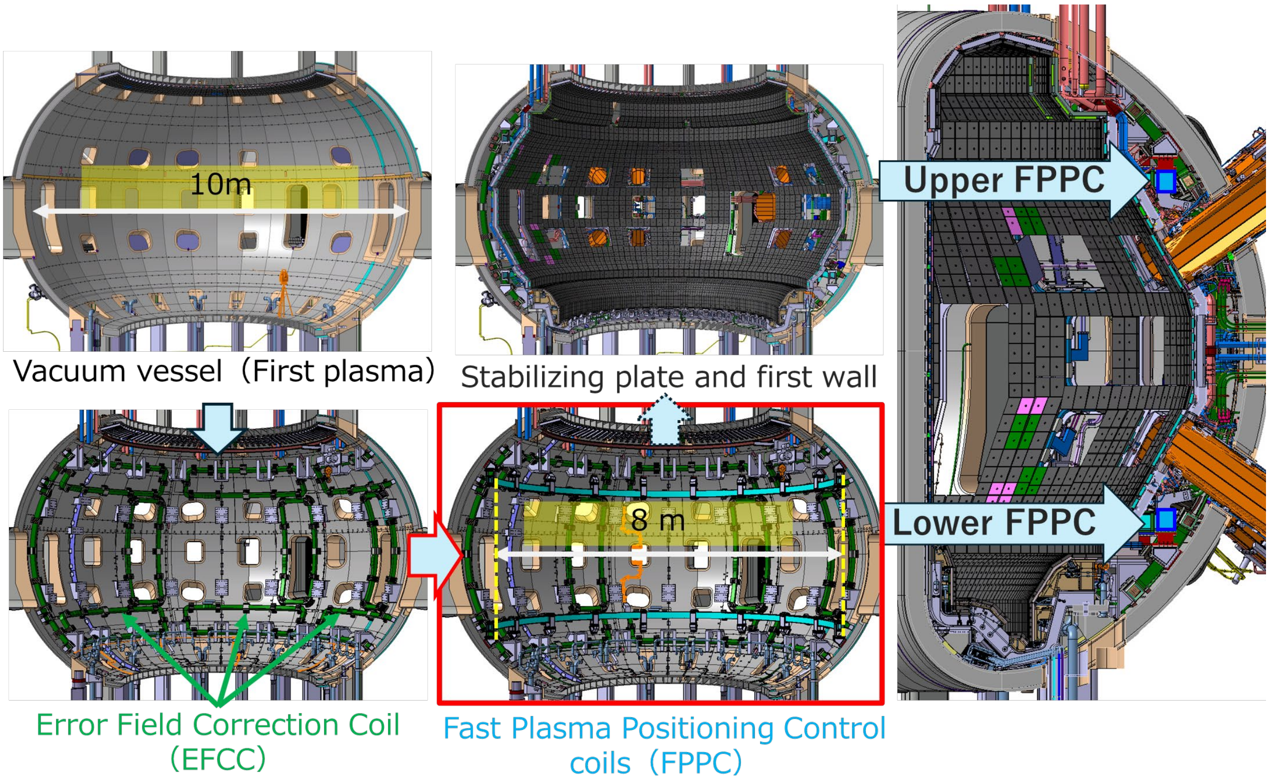

Figure 2. Installation Process for JT-60SA vacuum vessel components (left) and the position of the FPPC (right)

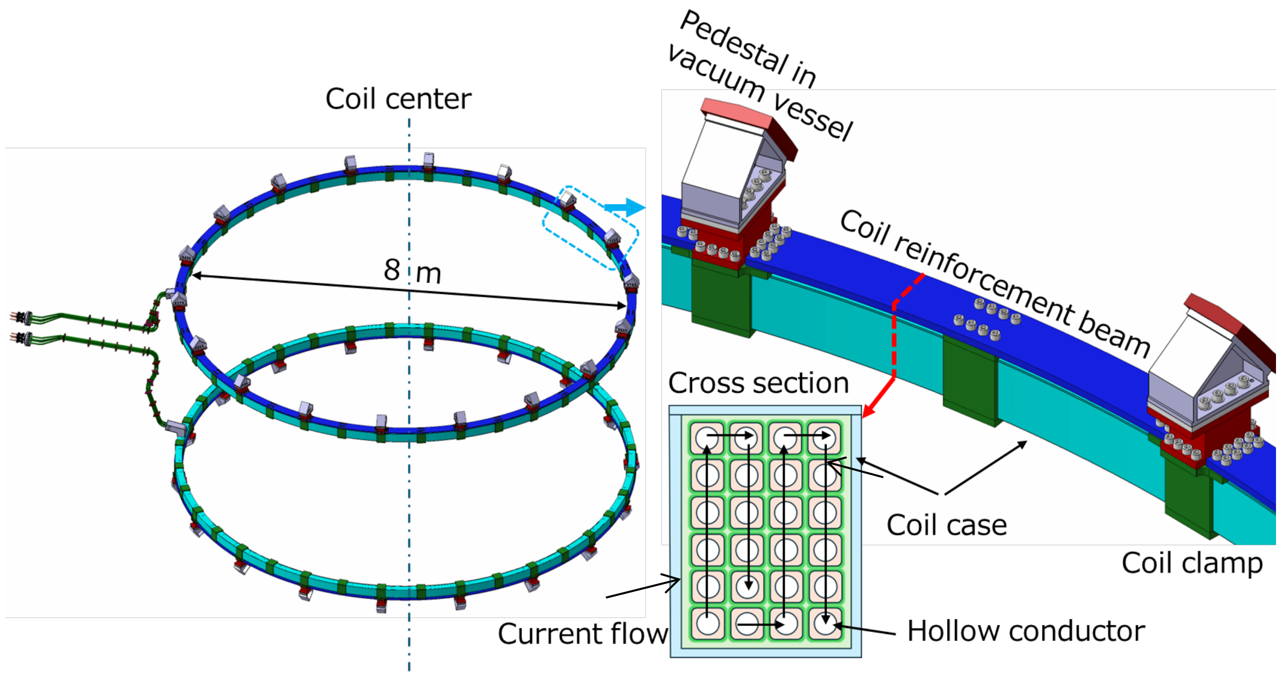

Figure 3. Design of FPPC

and securely fixed to the vessel wall. Next, a metal stabilizing plate is installed to prevent direct contact between the FPPCs and the plasma. Finally, cooling pipes and carbon tiles are attached to the stabilizing plate to remove plasma heat.

The basic design of the FPPCs was implemented by QST. As shown in Figure 3, each FPPC measures approximately 8 meters in diameter and consists of 23 turns of hollow conductors—tubular structures that allow water to flow through for cooling. Approximately 600 meters of conductor material is used to fabricate a single FPPC. To ensure electrical insulation between conductors, each hollow conductor is wrapped with radiation-resistant resin-impregnated tape. Once wrapped, the conductors are enclosed in a coil case, which is then sealed by welding. The standard design also accounts for extreme operating conditions, including baking at 200° C prior to plasma operation and the intense electromagnetic forces generated during plasma disruptions. To withstand these stresses, the coil case is reinforced and firmly fixed to the vacuum vessel. On the other hand, in order to stably control the plasma, it was necessary to minimize magnetic field errors, requiring the central position, radius, and height of the coil with a diameter of 8 meters to be manufactured with an accuracy of ±2 millimeters for a coil.

【Fabrication of FPPC】

Typically, coils are manufactured by winding conductors at specialized coil fabrication facilities. However, in this case, the coil needed to be nearly the same size as the already-completed JT-60SA vacuum vessel that confines the plasma. This required the winding process to be performed inside the vacuum vessel rather than in a factory.

During the basic design phase, QST developed a configuration in which the conductor would be placed outside the vacuum vessel, drawn into the vessel, and winding machine installed inside. Mitsubishi Electric, a company with extensive experience in manufacturing superconducting and copper coils, was contracted to fabricate the FPPC. Following QST's design, Mitsubishi Electric installed an uncoiler (Figure 4①) outside the vacuum vessel to feed the conductor, guide rollers (Figure 4②) to direct the conductor through the connecting port, winding machine of insulation tape (Figure 4③) to wrap insulation material around the conductor, and a turntable (winding frame) (Figure 4④) installed inside the vessel for winding the coil. To ensure uniform winding, the conductor had to be pulled and wound while maintaining a consistent height. However, since the size and position of the ports were predetermined and the vessel contained EFCC and other structures, it was not possible to place equipment in ideal positions. As a result, concerns arose during coil fabrication regarding conductor bending, distortion, and irregular taping pitch of the insulation.

To address these issues, the turntable's (Figure 4 ④) rotation speed was made adjustable to match the conductor feed rate from the external uncoiler with the winding speed inside the vacuum vessel, preventing sagging. Regarding conductor distortion, the coil could only be arranged in a configuration where it pressed firmly against the winding frame on the turntable, raising concerns of deformation. The frame was therefore reinforced to achieve high strength, limiting radial shrinkage to less than 0.5 millimeters. For irregular taping pitch of insulation, a position-holding mechanism was added to the winding machine of insulation tape (Figure 4③), ensuring that the insulation could be applied with consistent taping pitch.

During the shaping process after the coil was mounted in its case, initial attempts were unsuccessful, as pressing one part of the coil caused deformation in other areas. QST and Mitsubishi Electric therefore discussed countermeasures and agreed to reinforce the positioning jigs integrated into the 18 fixed supports used for final installation. By monitoring minute changes with dial gauges and performing measurements with a laser tracker, shaping and positioning were carried out simultaneously.

As a result, the technical challenge of positioning the coil center, radius, and height within ±2 millimeters of the target values was overcome. This achievement marks the establishment of a high-precision coil fabrication technique within the confined environment of a vacuum vessel.

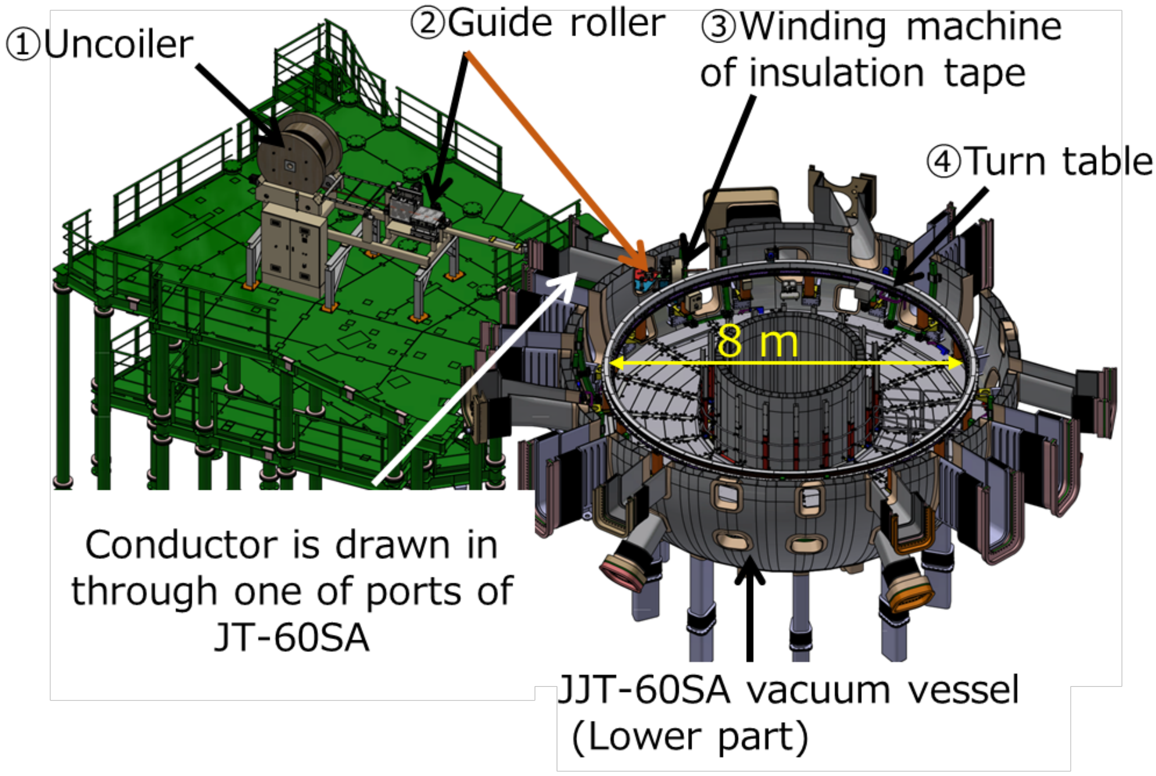

Figure 4. On-site Fabrication of the FPPC in JT-60SA

【Conclusion】

The FPPC constructed this time will be used in JT-60SA's plasma heating experiments, scheduled to begin in 2026. It will stabilize and maintain the plasma using a control program jointly developed by Japan and Europe. The plasma control technology achieved through JT-60SA and the FPPC is advanced enough to serve as a pre-validation platform for the plasma control systems planned for ITER, and will contribute to the establishment of advanced plasma control technologies amid intensifying international competition. Furthermore, this technology lays the foundation for future autonomous control systems, including AI-based solutions, anticipated in future energy DEMO reactors. The successful completion of the FPPC marks a significant milestone in advancing global fusion energy research and development.

【Glossary】

*[1]···Fast Plasma Positioning Control coil：FPPC

The Fast Plasma Positioning Control coil (FPPC) is a coil used in tokamak-type fusion devices to rapidly and precisely control the vertical position of the plasma, thereby maintaining its stability. As the superconducting coils used to confine plasma have a slow response and cannot keep up with rapid changes in the plasma, FPPCs are responsible for plasma control. In JT-60SA, the FPPC is installed at the top and bottom of the vacuum vessel, which measures 8 meters in diameter—making it the largest FPPC vacuum vessel in the world. While similar coils are used in experimental devices in China and South Korea, their sizes are approximately half that of JT-60SA's. Since ITER will also incorporate FPPCs, the fabrication of JT-60SA's large FPPC inside the vacuum vessel for JT-60SA serves as an important reference case.

*[2]···JT-60SA（JT-60 Super Advanced）

JT-60SA is the world's largest tokamak-type superconducting plasma experimental device as of today, constructed at the QST facility in Naka City, Ibaraki Prefecture, Japan. It was constructed as a joint project of the satellite tokamak jointly implemented by Japan and Europe as a Broader Approach (BA) activity and the tokamak domestic priority device project that has been under consideration in Japan. JT-60SA's purpose is to support research for ITER to achieve its technological goals and supplementary research for ITER toward DEMO reactors and human resource development.

JT-60SA uses powerful superconducting coils cooled to approximately -269 degrees Celsius (absolute temperature approximately 4K) to generate a magnetic cage capable of confining plasma that can reach 100 million degrees. The "tokamak-type" refers to a method of plasma confinement using magnetic field. It combines superconducting coils to generate a circumferential toroidal magnetic field and a radial poloidal magnetic field, creating a magnetic field that follows the shape of doughnut. ITER is also a tokamak-type device.

URL: https://www.jt60sa.org/wp/

URL: https://www.qst.go.jp/site/jt60/5150.html（Japanese）

*[3]…Broader Approach Activities（Broader Approach：BA）

The Broader Approach (BA) activities are a joint initiative between the European Atomic Energy Community (Euratom) and Japan, aimed at accelerating the realization of fusion energy. These activities are designed to complement the ITER Project and promote the advancement of fusion energy research and development. It includes the construction of a satellite tokamak device, the development of durable materials for future devices through the International Fusion Materials Irradiation Facility (IFMIF), and preliminary work on the future Demonstration (DEMO) reactor. The Satellite Tokamak Project aims to enhance the efficiency of research and development under the ITER Project while conducting complementary studies toward the realization of a demonstration (DEMO) reactor by upgrading Japan's existing tokamak experimental device into a superconducting plasma experimental device.

URL: https://www.ba-fusion.org/ba/Fast Plasma Positioning Control coil：FPPC

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*[4]…ITER Project

With the international cooperation of seven Parties: Japan, Europe, Russia, the United States, China, Korea, and India– the project aims to demonstrate the scientific and technological feasibility of fusion energy through the construction and operation of ITER. The target of the project is to obtain fusion energy that is 10 times larger than the input energy of the external heating system (Q≧10). Currently, the site is in Saint-Paul-les-Durance, France, and the ITER Organization, an international organization for the project implementation, is leading the construction of buildings and the assembly of components for the start of operation. Also, the manufacturing of various ITER component devices has been advanced by each of the seven parties.

*[5]…DEMO

A DEMO reactor is a next-generation device that will demonstrate the power generation and economic feasibility of fusion energy. Currently, conceptual designs for DEMO reactors are being developed in various countries around the world.