The European In-Kind Contribution to ITER

ITER – "the way" in Latin – is a major step in the development of fusion energy. Its objective is to demonstrate the scientific and technological feasibility of fusion energy. The European Union (including Switzerland), Japan, China, Korea, the Russian Federation, India, and the USA are part of this international scientific project. The ITER machine is under construction at Cadarache in the south of France

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The ITER Agreement
The ITER Agreement was officially signed in Paris in November 2006 by Ministers from the seven ITER Parties. This document established the detail of the construction, exploitation and decommissioning phases, as well as the financing, organization and staffing of the ITER Organization. From that moment on, the staff was increased to the current number (about 800 persons), the nuclear licensing process was initiated, site preparatory works were carried out, and procurement agencies in each ITER Party (the Domestic Agencies) were established.

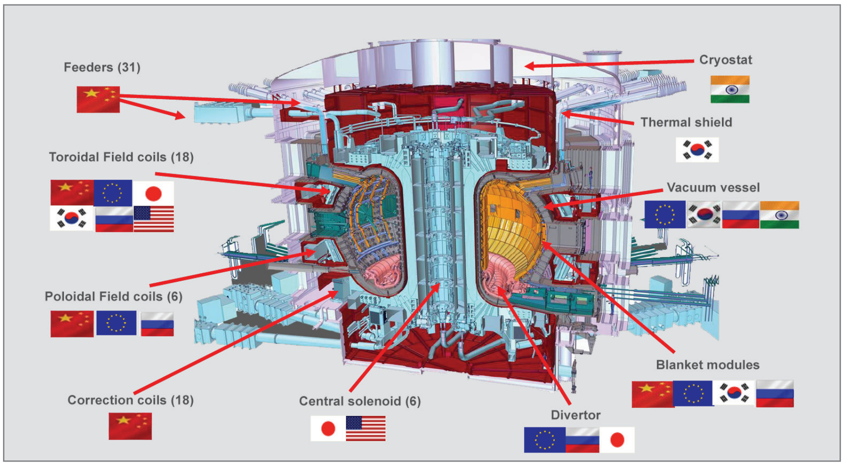

Fig. 1 In-Kind components from ITER Parties
Source: courtesy of ITER IO

Fusion is the process that powers the sun and other stars and makes life on Earth possible. It consists in fusing together light atoms (i.e. Deuterium and Tritium – isotopes of Hydrogen) to make heavier ones (i.e. Helium). On earth it is not possible to replicate the extreme pressure within the sun. Consequently, to allow fusion to happen much higher temperatures are necessary, over 100 million degrees. During fusion reactions a small amount of mass is converted into energy, in accordance with Einstein's well-known equation.
The attractiveness of fusion is due to its many advantages. The basic fuels (deuterium and lithium, the latter used to breed tritium) are abundant, it generates no greenhouse gas emissions and has a low impact on the environment with no long-lasting radioactive waste. Fusion reactors are also inherent safe because meltdown or runaway reactions are impossible.
ITER uses magnetic confinement through very high magnetic fields to give the plasma a toroidal shape inside the machine vessel and to contain it long enough and away from the walls of the container to allow fusion to occur.
The current ITER schedule foresees first plasma at the end of 2025 and the start of full Deuterium-Tritium operations in 2035.

Sharing of Procurements

The procurement of the components by the Parties to the ITER project is based on the principle of the in-kind contribution. The components that make up ITER have been divided into 85 procurement “packages” which are distributed among the seven parties to the ITER Agreement (see box) to achieve the agreed level of contribution from each of them. F4E provides, on behalf of Europe, components to ITER that amount to about 45% of the overall value of the project. The obligation of all the Parties is summarized in Figure 1.
The technical specifications and the details of each item to be delivered to the ITER project are included in a Procurement Arrangement (PA) that is signed by the directors of both ITER and of the responsible Domestic Agency (DA), representing the specific ITER Party. The design of the component at the moment of the signature of the PA, when it is handed out to the DA, can be at different levels of development. Therefore the DA work may also include a part of design on top of the manufacturing.
The planning of the work from design, if included, to manufacturing and delivery of the component is constantly updated through a

What ITER will do

The amount of fusion energy a tokamak is capable of producing is a direct result of the number of fusion reactions taking place in its core. The larger the vessel, the larger the volume of the plasma and therefore the greater the potential for fusion energy.

The ITER Tokamak will be a unique experimental tool, capable of longer plasmas and better confinement. Due to the presence of tritium and to the production of neutrons, ITER is a nuclear installation under French law, which means that strict safety and quality requirements are obligatory.

ITER main features:

- ITER is designed to produce a ten-fold return on energy (Q=10), or 500 MW of fusion power from 50 MW of input power. ITER will not capture the energy it produces as electricity.
- To demonstrate the integrated operation of technologies for a fusion power plant. Scientists will be able to study plasmas under conditions similar to those expected in a future power plant and test key technologies for the future reactor.
- To achieve a deuterium-tritium plasma, a "burning plasma", one in which the heat from the fusion reaction is confined within the plasma efficiently enough for the reaction to be sustained for a long duration.
- One of the missions for the later stages of ITER operation is to demonstrate the feasibility of producing tritium from lithium in the machine as the world supply of tritium, one of the fuels, is not sufficient to cover the needs of future power plants.
- To demonstrate the safety characteristics of a fusion device, the control of the plasma and of the fusion reactions with negligible consequences to the environment.

detailed schedule that every DA has to provide to the ITER organization on a monthly basis. Milestones, such as design reviews, manufacturing steps, acceptance tests and delivery, are identified and monitored to detect any potential delay and risk that can then be mitigated through specific actions.

The ITER Organization is responsible for the specifications and the design of the components. The project defines lifecycle phases (Conceptual Design, Preliminary Design, Final Design and Manufacturing Design), when reviews are carried out together by IO and DAs to confirm the readiness of the component to move to the next phase. The responsibility of the cost of the components lies instead fully on the DAs.

In the specific case of Europe, on the basis of the specifications detailed in the PA, F4E starts a procurement procedure for European industries, sometimes in consortia with fusion laboratories, to competitively bid for the work. F4E contracts with the tenderer that provides the best offer in terms of quality and/or price. Work, mostly pre-PA investigations and analyses, is also contracted out to European Fusion Laboratories that have the know-how in many scientifically advanced systems (e.g. plasma heating systems, diagnostics) required by the machine.

Europe has budgeted €$_{2008}$ 6.6bn until the end of 2020 according to the July 2010 decision of the EU Council of which most is earmarked for contracts placed by F4E with European industry, SMEs and research laboratories. The budget to be made available to F4E after 2020 will be discussed at EU level in the forthcoming two years.

The Strategy – from Construction to Operation

The current ITER strategy foresees a 'Staged Approach' as a means of improving focus and optimising resources. This involved having up to four phases of ITER assembly and operation so as to reduce technical risks (Figure 2). As a consequence, since early 2016, F4E concentrate resources (funding and staff) on the activities critical to the achievement of First Plasma. To that end non-First Plasma projects were either suspended or slowed down in order to make resources available for the critical First Plasma projects and improve the confidence of remaining within the available budget.

In 2016 the ITER Organization obtained approval *ad referendum* (i.e. subject to domestic processes of obtaining approval) of the schedule and the resources covering the full period 2016-2035 with a First Plasma at the end of 2025.

The F4E top-level schedule is underpinned by comprehensive lower-level 'Detailed Work Schedules' of approx. 65,000 activities, encompassing the individual activities to be conducted at cost account level.

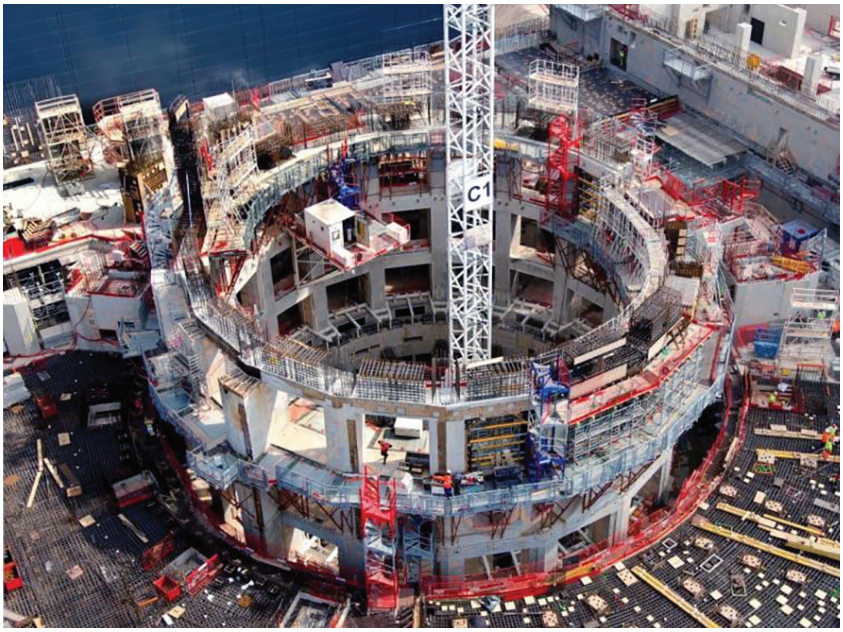

Fig. 3 Tokamak Building bio-shield under construction
Source: courtesy of ENGAGE

Status of the Contributions to the ITER Project

ITER is under construction in Cadarache in the south of France. Europe as the Host Party and France, as Host State, have specific responsibilities for the success of the Project. Europe bears 45% of the construction cost including all the buildings. It will provide 34% of the cost of operation, deactivation and decommissioning of ITER.

The following subsections present a brief report on the first-of-a-kind technological systems for ITER, some of which are still in the design and development phase, which Europe is responsible for. The ITER schedule requires installation of some of these systems, fully or partially, before First Plasma.

Site and Buildings

Thirty-nine buildings and areas will house the systems necessary for the operation of ITER. The 'Tokamak Complex' will house the main ITER components, and will be one of the largest buildings of its type ever constructed: 60 metres tall (with an additional 20 metres underground), 120 metres long and 80 metres wide; requiring 16,000 tonnes of iron reinforcement bars, 150,000 m^3 of concrete and 7,500 tonnes of steel.

The two levels of the Tokamak Complex below ground are complete and work is in progress on the other levels, including the thick cylindrical concrete bio-shield which will surround ITER (Figure 3).

Civil construction works on the 60 metres tall Assembly Hall, adjacent to the Tokamak Complex, are complete. Installation of the main cranes in the building, capable of lifting a combined weight of 1,500 tons, was successfully accomplished. Two auxiliary cranes, able to lift 50 tons each, are also in place.

Vacuum Vessel

The ITER plasma, where the fusion reactions will take place, will be held under vacuum inside a special double-walled container, the Vacuum Vessel. This toroidal (i.e. doughnut-shaped) vessel will be twice the size and eight times the volume as that used in the largest existing fusion device: it is over 19 metres across and 11 metres high. It will weigh in excess of 5,000 tonnes, similar to the Eiffel Tower.

Europe is currently responsible to deliver five out of the nine 'sectors' of the vessel, the others being manufactured by the Korean Domestic Agency.

The work has progressed with the

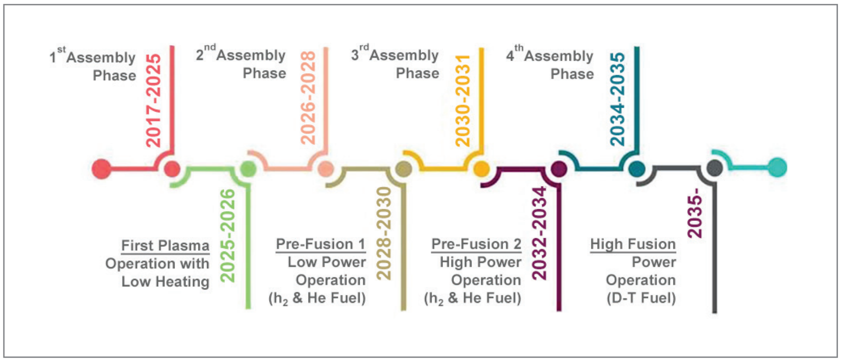

Fig. 2 ITER Staged Approach

completion of the first subassembly early 2017. Manufacturing activities are being carried out at two main locations in Italy as well as in other European countries where main subcontractors are located.

Magnets

A system of 30 superconducting magnetic coils will 'confine' (i.e. hold in place) the extremely hot plasma inside ITER and prevent it from touching the walls of the container. These will be among the largest and most powerful superconducting magnetic coils ever made. Europe is responsible for providing 10 of the 19 'Toroidal Field' (TF) coils for ITER, 20% of the Nb_3Sn superconductor used in the TF coils, five of the six 'Poloidal Field' (PF) coils, 11% of the NbTi superconductor used in the PF coils and nine 'pre-compression rings', which keep the coils in place during operation.

Fabrication and verification of all superconducting strand under the responsibility of Europe is complete (97 tons out of the 500 tons required for ITER) and fabrication of the superconductor itself was completed: 19 kilometres for the Toroidal Field coils and 7 kilometres for the Poloidal Field coils.

As the Toroidal Field coils are concerned, each of them, weighing 310 tonnes, will comprise a superconducting 'Winding Pack', mounted in a stainless steel case. To form the Winding Pack, seven smaller modules are stacked together and impregnated with a special resin. In turn, each of these smaller modules consists of a D-shaped stainless steel plate with grooves machined in a spiral path on both sides. The spiral grooves support a 700-metre long length of superconductor, wound into the required shape, heat-treated and electrically insulated before insertion in the grooves.

In 2016, the first ever Winding Pack was completed (see Figure 4), with the involvement of more than 600 people from at least 26 companies across Europe.

As for the five Poloidal Field coils under Europe's responsibility, four are fabricated by European industry in the Poloidal Field coil factory at the ITER site. One will be fabricated in China under F4E contract, using facilities and staff at the Institute of Plasma Physics, Chinese Academy of Sciences-ASIPP. An engineering integrator supports F4E in fabricating the coils manufactured in Europe.

Manufacture and commissioning of the tooling to wind the coils is complete, both in China and at the ITER site. The production line in Cadarache will allow fabrication on site of the largest Poloidal Field coils for ITER, up to 25 metres in diameter, which are too big for transportation to the site.

Fig. 4 The first-ever Winding Pack for the Toroidal Field coils
Source: courtesy of ASG Superconductors, La Spezia, Italy

In-Vessel Components

Whilst the ITER magnets will confine most of the hot plasma, some particles and radiation will inevitably escape from this magnetic 'cage'. To protect the Vacuum Vessel and the external systems from this energy flux, its inside surface will be covered by 440 special blocks, called Blanket Modules.

Each module is made from a Shield block and a First Wall panel. Europe will provide 215 First Wall panels. There is also a device at the bottom of the Vacuum Vessel, called the Divertor, which will allow the removal of the excess heat and plasma 'ash' keeping the plasma clean enough to continue operation. This particle flux escaping the plasma is hitting components specially designed to handle very high heat flux. Europe is responsible for many key components of the Divertor, in particular the Inner Vertical Target and the Cassette Body.

Work is in progress to manufacture and test prototypes for qualification of potential suppliers within European industry of the Blanket First Wall and Divertor components. Notable achievements include the manufacture of two reduced-scale Blanket First Wall prototypes and the successful high heat flux testing of two qualification 'Semi-Prototypes', meeting key milestones in the manufacturing process and the ITER First Wall qualification programme.

Regarding the Divertor components, F4E completed the first stage of the procedure for the qualification of potential suppliers for the 'Inner Vertical Target' with the successful manufacture of mock-ups for high heat flux testing.

Test Blanket Modules

Europe is developing, together with European laboratories and industrial suppliers, two concepts of Test Blanket Module to be tested in the ITER machine. This component is necessary to develop a necessary feature of all future fusion reactors, the generation of their own tritium. The Test Blanket Module is not only a technically complex device but must also operate reliably in an extremely harsh environment (heat, neutrons and magnetic fields).

A recent key achievement was the fabrication of 27 tonnes of EUROFER steel by European industry. EUROFER is a special type of steel, which does not become as radioactive as other steels when exposed to neutron irradiation. Manufacturing of mock-ups and qualification prototypes of the Test Blanket Module will use this steel.

Remote Handling

Remote Handling will play an essential role on ITER once the plasma produces significant radiation from the fusion reactions and robotic tools become necessary to conduct inspections and to repair components close to the device. This is especially challenging since some of the items to be manipulated weigh up to 50 tonnes and all need precision positioning. Europe will provide a significant fraction of the Remote Handling systems on ITER; the Divertor Remote Handling System, the Cask and Plug Remote Handling System, the Neutral Beam Remote Handling System and the In-Vessel Viewing System.

Design work has started for these systems as well as tests of key technologies and components for the Divertor Remote Handling System. A multi-year programme to industrialise state-of-the-art technologies needed for the ITER Remote Handling systems is in progress.

Cryoplant and Fuel System

The ITER Cryoplant, a complex system and one of the largest of its type in the world, will provide the cryogenic fluids necessary to cool several ITER components, most notably the superconducting magnets. Europe is responsible for the Liquid Nitrogen Plant and Auxiliary Systems, representing about one-half of the Cryoplant, along with part of the network to distribute and regulate the cryogenic fluids; the front-end Cryodistribution lines and Cold Valve Boxes. Some of the components of the plant, such as the large "quench" tanks, have already been delivered to the ITER site.

Europe is also responsible for all the main Cryopumps of ITER, which use cryogenic fluids to keep a high vacuum in, for example, the Vacuum Vessel by condensing-out ('pumping') gases such as oxygen or nitrogen.

Fig. 5 Neutral Beam Test Facility in Padua, Italy
Source: courtesy of Consorzio RFX

One of the fuels for the fusion reaction in ITER will be tritium. As well as being an expensive resource, tritium is radioactive. Careful management and recycling of tritium on ITER is therefore essential. This is the purpose of the Tritium Plant, to be provided by Europe; consisting of a Water Detritiation System and a Hydrogen Isotope Separation System. Six large tanks, forming part of the Water Detritiation System, have already been delivered to the site and installed in the Tokamak Complex. These were the first European in-kind components to be installed on ITER.

Plasma Heating Systems

To create fusion in ITER, the plasma needs to reach over 100 million degrees. By passing a large electrical current through the plasma, which also helps to hold it in a magnetic ‘cage’, it is possible to reach 20-30 million degrees. Since this is not enough on its own, ITER relies on three additional heating systems to increase the temperature to the required value.

Neutral beam heating & current drive - One of the most reliable ways to heat plasmas in present-day fusion experiments is to fire a beam of fast, uncharged particles into the plasma – called Neutral Beam Injection. ITER will have two (or three if needed) Neutral Beam Injectors and Europe is responsible for providing most of their components. Neutral Beam Injectors work by generating an electrically charged form of Deuterium (‘ions’) in an ‘ion source’. A high voltage accelerates a beam of these ions to a high energy. Collisions with Deuterium gas neutralise ions in the beam to create the high-energy neutral beam.
To develop and test the Neutral Beam Injectors a dedicated facility is under construction in Padua, Italy – the Neutral Beam Test Facility (Figure 5). The facility, which includes also in-kind contributions from Japan and India, hosts two test beds:

- SPIDER (Source for Production of Ions of Deuterium Extracted from Radio Frequency plasma) where the ion source will be tested up to an acceleration voltage of 100,000 volts; and
- MITICA (Megavolt ITER Injector & Concept Advancement) which will test the injector up to the full acceleration voltage of one megavolt (1 MV) and power of 16.5 megawatts (16.5 MW).

Installation is complete of most of the SPIDER components and the start of experiments is foreseen in 2018. As for MITICA, manufacturing of all the main components has mostly started and the start of the experiments is foreseen in 2021.

Radiofrequency Heating System - Another way to heat up the plasma is to use radio waves to make the ions and electrons in the plasma vibrate. ITER is using two systems: Ion Cyclotron Heating, which heats the ions, and Electron Cyclotron Heating, which heats the electrons. Each system comprises power supplies, radio wave generators, transmission lines to transport the radio waves and antennae inside the Vacuum Vessel to launch them into the plasma. Water-cooled, stainless steel ‘port plugs’ house both the Electron Cyclotron Heating and Ion Cyclotron Heating antennas and couple them to the Vacuum Vessel.
Europe is responsible for providing two equatorial port plugs (each housing one Ion Cyclotron Antenna) and four upper port plugs (each housing one Electron Cyclotron Upper Launcher), together with ex-vessel components of both the Electron Cyclotron Upper and Equatorial Launchers and control systems for the Electron Cyclotron plant and Upper Launchers.
Europe is also responsible for providing eight sets of power supplies for the Electron Cyclotron Heating system and six gyrotrons, with their superconducting magnets and auxiliaries.
Gyrotrons are high power radio wave generators in the mm-wave region of the electromagnetic spectrum. Factory acceptance testing is underway for the first Electron Cyclotron power supply unit and initial testing of a gyrotron manufactured by European industry is meeting its performance targets.

Plasma Diagnostics System

Operating ITER successfully will require the availability of comprehensive information on the behaviour of the fusion plasma. This information will allow the safe operation of ITER, optimisation of the plasma configuration for maximum performance and comparisons between that performance and our theoretical understanding. Around fifty different systems (‘Diagnostics’) will measure parameters of the plasma, together with those of the First Wall Blanket Modules and Divertor. Europe is responsible for twelve Diagnostics and eight ancillary systems. So far, 28 European research laboratories and 20 European SMEs are involved in the design, development and/or manufacture of these systems.

Conclusions

As Europe's Domestic Agency for ITER, F4E is contributing to most of the core components of the tokamak and the ancillary systems. A First Plasma is currently foreseen at the end of 2025. The work is in progress both at the site and in the European Industry and laboratories to provide the agreed in-kind contributions to the project. Since 2007 contracts and grants have been placed by F4E with industries and research organisations reaching by the end of 2016 a total investment of about € 3.7bn spread all over Europe.

Acknowledgments

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