The European Fusion Technology Programme in support of ITER

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Abstract
The European Fusion Technology Programme is largely devoted to the support of the ITER design and to the preparation for its construction. The activities are carried out by the European fusion associations and industry in the framework of EFDA. The work in both design and R&D has been performed on a wide spectrum of topics with successful results in all areas. These positive results complement those achieved by the other partners and create a good confidence in the success of the ITER project.

Abrégé
Le Programme Technologique Européen pour la Fusion est largement dévolu au soutien de la conception du projet ITER et à la préparation à sa construction. Les activités sont réalisées par les associations européennes pour la fusion et par l'industrie dans le cadre de l'EFDA. Le travail de conception et de R&D est effectué sur un large nombre de sujets et a déjà rencontré le succès dans tous les domaines. Ces résultats positifs complètent ceux réalisés par les autres partenaires et créent un climat de confiance pour le succès du projet ITER.

Samenvatting
Het Europees Fusie Technologie Programma is sterk verbonden met de ondersteuning van het ITER-ontwerp en met de voorbereiding van zijn opbouw. De aktiviteiten worden uitgevoerd door de Europese verenigingen voor fusie en door de industrie in het kader van de EFDA. Zowel het basisconcept als de R&D werden uitgevoerd op en groot aantal onderwerpen en hebben overal successen geboekt. Deze positieve resultaten vervolledigen diegene, die door andere partners werden bereikt en scheppen een vertrouwensklimaat voor het succes van het ITER-project.

Introduction

The European Fusion Technology Programme includes a range of activities, the majority of them specifically related to the design and construction of the "Next Step" machine, ITER, the rest covering the developments needed in view of constructing a demonstration reactor and the commercial fusion reactor. These design and R&D activities are carried out by the European Associations and Industry, in the framework of the European Fusion Development Agreement (EFDA). An EFDA Team, located in Garching near Munich, is responsible for the co-ordination at European level in order to achieve the best integration of all available resources.

This contribution will focus on those activities within the European Fusion Technology Programme specific to the ITER machine.

The ITER project

ITER represents the "Next Step" in the worldwide fusion effort. An international team has been working on the design of this machine for about ten years, providing the participating teams (i.e. Canada, Europe, Japan and the Russian Federation) with a Final Design Report in 2001, giving all the necessary details for the construction [1]. Negotiations for the construction started in 2002 and now they see seven countries (i.e. Canada, China, Europe, Japan, Republic of Korea, Russian Federation and the United States of America) participating in the discussions to finalize the necessary construction agreement.

ITER will demonstrate the scientific and technological feasibility of fusion as an energy source. The ITER tokamak shall produce and sustain burning plasmas delivering substantial amounts of fusion energy for a meaningful time duration (pulses of 400 MW for 400 s).

It is of paramount importance that the ITER design is validated by R&D work which must also prepare the cost effective manufacturing of the components and the operation of the machine.

These R&D activities cover a wide spectrum of topics in the European Union, including Switzerland, and in the candidate countries and have been grouped in fields and projects under the EFDA responsibility.

The budget invested by the European Union, both Commission and Associations, during the ITER preparatory phase, is of about 415 MEuro for all ITER–related technology work in Associations and industry. Out of this figure, 94 MEuro have been spent in industrial contracts.

The strong involvement of the European industry in the ITER design has been mostly channeled through the EFET (European Fusion Engineering and Technology) [2] consortium, formed by the leading European nuclear industries.

It must be noted that, since the inception of the ITER project, care has been applied in order to gain adequate know-how for the European laboratories, universities and industry in all the critical areas of the project to master the critical fusion technologies and to be able, in case of need, to proceed alone in the construction of an ITER-type experiment, drawing on direct laboratory and industrial experience.

In parallel to the ITER activities, the European Fusion Technology Programme includes the development of the nuclear components and the advanced materials [3] needed to build an economically competitive demonstration reactor (DEMO), allowing the European industry to improve its knowledge in view of the construction of the future power plants.

The Technology Programme for ITER

Vessel/In-Vessel

This field is concerned with the design and R&D of the nuclear core of the machine including the vacuum vessel and the plasma facing components, divertor, shielding blanket and first wall. A major area of activity is the study and development of the maintenance system of ITER.

In the past years relevant mock-ups and prototypes of the different components, using specifically developed technology, have been manufactured to test their capability in performing satisfactorily and reliably in conditions approaching as far as possible their real operating environment. Full-scale facilities have been assembled and operated to demonstrate remote handling capabilities.

Fabrication methods for the shielding blanket were proven. A divertor cassette integration prototype, including dummy vertical target, wings and the gas box liner, was completed and tested.

The aim is now to continue the design and R&D efforts in order to guarantee the procurement of reliable and economic series components. Therefore, results have to become available on a schedule compatible with the ITER procurement scenario.

Fig. 1: Front and rear views of the shield block prototype

Vacuum Vessel (VV)

The main target for this area is to prepare the EU Industry to take part in the procurement of all or part of the vacuum vessel sectors and their assembly. The vacuum vessel is a crucial element of the machine also from the regulatory point of view as it represents the first containment. The procurement of the vacuum vessel will start as soon as the construction of ITER will be decided and the construction license will be obtained.

Improved welding and cutting techniques have been developed in Europe to obtain satisfactory performances with the required tolerances.

The construction of a segment of the vacuum vessel reproducing the main characteristic features and presenting the technological problems to be mastered has been assigned to industry.

The work on electron beam welding of the VV sectors has already provided encouraging results. The feasibility and limits of depth for partial penetration e-beam welding in all positions have been satisfactorily proven.

As far as the vessel assembly is concerned, significant advances have been made in developing reliable methods for the inspection of the VV field joint welds with ultrasonic devices.

Blanket / Shield

The wall of the plasma chamber of ITER is covered by a set of shielding blanket modules. Each module is formed by a shielding block carrying four to six primary first wall (PFW) panels facing the plasma. The shielding blocks have to shield the vacuum vessel and the magnets from the fusion neutron flux and to exhaust the neutron energy to the cooling water. The primary first wall panels must collect the energy radiated by the plasma or deposited by the plasma particles impinging on the wall. Owing to the pulsed nature of ITER operation (30,000 cycles are foreseen), the problem of thermo-mechanical fatigue must be adequately solved.

Hot isostatic pressing (HIP) of stainless steel powders has been developed as a satisfactory fabrication route for the shield block to avoid welds as the primary coolant barrier (Fig.1).

The aim of the work for the plasma facing components (PFCs), was to consolidate the design and fabrication procedure through fabrication and test of prototypes [4].

Detailed transient thermal mechanical analyses have confirmed the good engineering margins to sustain external loads.
Recently, a set of panel prototypes made from CuCrZr and dispersion strengthened (DS) copper with HIPed Beryllium (Be) tiles has been successfully fabricated. Further prototypes are planned.

Development of Be/Cu alloy joining is still carried out to further increase the engineering margins to off-normal operation conditions.

Thermal fatigue tests at 0.8 MW/m^2 surface heat flux of four PFW mock-ups and panels are being carried out on the test facilities at ENEA Brasimone (Italy).

Divertor

The ITER divertor is designed to exhaust the energetic particles (helium) produced in the fusion reactions and part of their energy. It forms a sort of crown located at the bottom of the vacuum vessel and it is split in a large number (54) of elements, the cassettes, to allow installation and remote maintenance. Each cassette is made of a body carrying a set of plasma facing components.

The aim of the activities carried out in this area has been the consolidation of the design and the exploration and choice of reliable and reduced cost fabrication procedures for the cassettes bodies and the plasma facing components [4].

Studies include thermohydraulic analyses as well as neutronic, electromagnetic and thermomechanical calculations. The main issues being addressed are the capability to exhaust the concentrated heat bursts deriving from potential plasma edge instabilities and the mechanical resistance of the PFC attachments to the cassette body against the electromagnetic loads causing fast vertical plasma displacements (VDE).

High heat flux tests on small scale mock-ups with carbon fibre composites (CFC) and W armour simulating fast plasma transients have been carried out. These test results demonstrate that the component design is capable to meet the requirements for their specific use on the dome/liner and on the vertical targets.

Several mock-ups and material samples have been irradiated at 0.2 and 1.0 dpa, 200 °C to verify their behaviour under real operating conditions and the post-irradiation testing is being carried out at the JUDITH test facility at the Forschungszentrum Jülich (Germany).

Active Metal Casting (AMC®) was developed as a new process in joining technology. A medium scale vertical target prototype was manufactured following this approach (Fig. 2), integrating a W macro-brush armour and CFC monoblocks with a DS-Cu heat sink. The component sustained 1000 cycles at 15 MW/m^2 and 2000 cycles at 20 MW/m^2, on the W and CFC armoured region, respectively. On the CFC region a critical heat flux test was performed up to 30 MW/m^2.

Cu Cr Zn was confirmed as the preferred heat sink material for plasma facing components.

Thermal fatigue tests of a full-scale vertical target prototype manufactured by industry are scheduled for this year at the FE200 facility at Framatome (France).

A Material Database for licensing purposes is being established.

Remote handling

The main target of work in this area has been to complete the exploitation of the big facilities built in Europe to test the concept of the divertor remote handling system with the aim to check its reliability and to finalise the design according to the final ITER design.

Europe had the full responsibility of demonstrating the feasibility of remote operations on the divertor.

The successful results of the Divertor Test Platform (Fig. 3) and of the Divertor Refurbishment Platform have proven the adequacy of the selected approach and the validity of the concept.

Recent activities on the Divertor Test Platform (DTP) involved extensive and repetitive use of the main in-vessel prototypes under fully remote operating conditions to assess their reliability and operability over operational periods comparable to divertor replacement in ITER [5].

The development of the handling system to operate the ports of the machine has also been considered. This includes solving the problem of the alignment and docking of the casks used to carry the activated components extracted from the machine to the hot cell to allow their refurbishment.

In the framework of the Remote handling programme, also the problem of finding or developing radiation tolerant components is in progress. Tests on radiation hard glasses (for windows and lenses) and on motors have been successfully accomplished.

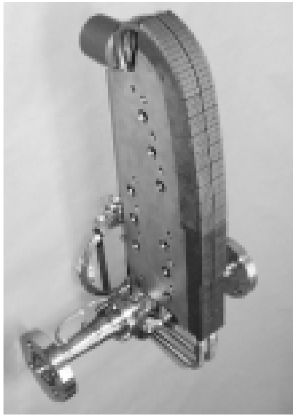

Fig. 2: Divertor vertical target medium scale prototype

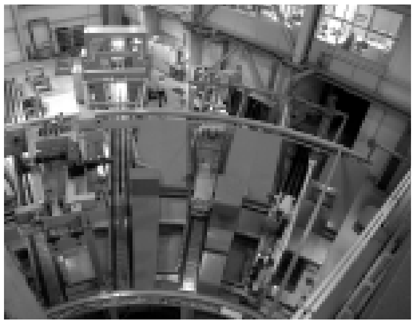

Fig. 3: Divertor Test Platform at ENEA Brasimone (I)

The development of a laser based in-vessel viewing and metrology proof-of-principle system continues in a satisfactory manner with the construction, commissioning and extensive testing of the optical and control elements being undertaken. This activity has provided good results in terms of both image resolution and metrology accuracy [6].

Robotic systems are being developed for working under the operating conditions of the vacuum vessel. Among them, a 10 kg payload articulated robotic arm due to operate from a viewing penetration [7].

Magnets

The main achievements of the European associations and industry in this area include the production of strands and cables and the jacketing of the conductors for the manufacture of both the Central Solenoid Model Coil (CSMC) and the Toroidal Field Model Coil (TFMC).

Europe has been responsible for building and testing the TFMC in view

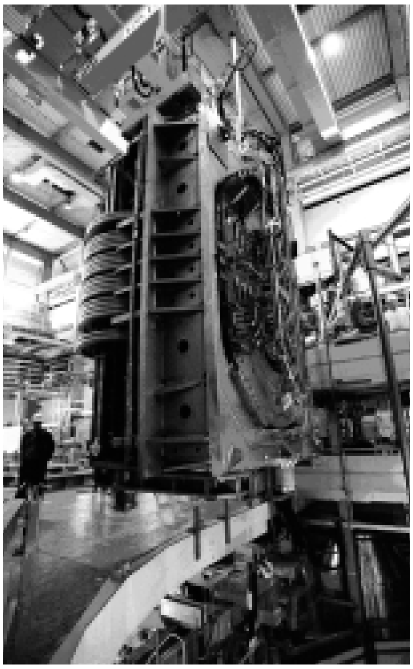

Fig. 4: The Toroidal Field Model Coil assembled with the Large Coil Task (LCT) coil is being lowered into the Toska facility

of demonstrating the feasibility of the conceptual design of the toroidal field coils.

The European associations have been accompanying the industrial effort with design and development work and the operation of test facilities such as SULTAN (CH) and TOSKA (D).

The work on the TFMC (Fig. 4) has been very successful [8]. A current of 80 kA, larger than the nominal current foreseen in ITER, was achieved during the first testing phase of the TMFC installed alone in the TOSKA facility. During a second phase, conducted this year, the mechanical integrity of the structure, at mechanical stress levels comparable with the ITER coil, was tested in a background field produced by the LCT (Large Coil Task) coil. The successful results in testing the TFMC have confirmed that the ITER magnets can be constructed and operated successfully.

The CSMC has been built in collaboration between Japan and USA and tested with equally satisfactory results in Naka (Japan).

As far as the mechanical structure of the machine is concerned, work on the toroidal field (TF) coil cases has demonstrated the suitability of forged parts on the coil case and the manufacturing process has been investigated with the fabrication of four full scale models.

In the poloidal field (PF) coils area, Europe is producing an insert made with the PF prototype conductor, to be installed inside the CSMC and tested in 2004 at the Naka facility. The purpose of the insert is to test the PF conductor as a long length and in a pulsed field.

Additional work was accomplished by the associations in the design, fabrication and testing of joint samples and in strand qualification.

Recent work has focused on the preparation of the specifications for the magnets procurement, due to start as soon as the construction of ITER is agreed.

Safety and environment

Activities on safety and environment are now mainly focused on licensing issues.

In the past years a number of nuclear codes have been adapted to the fusion environment and used for accident simulation work. A large part of ITER-related work has been devoted to assess the codes used in safety-related computations by comparing those treating the same problems and by well-aimed validation experiments.

In Europe such experiments are CORELE, for the evaluation of release and transport of corrosion products in water loops, and EVITA, for ice formation on cryogenic plates in case of water inlet.

Complementary studies were launched to assess and deepen the findings referred to the generic site in the ITER Generic Site Safety Report (GSSR), in anticipation of EU licensing requirements.

Safety-related experiments to investigate air in-break events in cryopumps are being launched in the TIMO facility at the Forschungszentrum Karlsruhe (Germany).

Some other experiments are aiming at studying dust mobilisation and transport.

Analyses carried out by industry and associations in accident sequences have provided useful feedback to the ITER team to consider additional fast plasma shut down systems.

All site-related licensing tasks are being carried out in the framework of the European ITER Site technical Study group (EISS). The support of the activities carried out by this EFDA group is very important for the dialogue with the licensing authorities.

A Licensing Working Group, formed by industrialists, regulators and members of technical safety organisations was set up in Europe to reach a consensus by all interested parties on safety and environment-related problems.

Tritium breeding and materials

Most of the activities carried out in this area are on long term R&D for DEMO and the future prototype reactor.

This is especially true for all the materials development and the activities for the design of the International Fusion Materials Irradiation Facility (IFMIF). IFMIF is a test facility which would produce neutrons with a suitable energy spectrum to allow the necessary material tests. The international partners are currently developing the design of this facility, but its construction still needs to be agreed.

The breeding blanket programme has been focused on the development of two European test blanket modules which are planned to be tested together with those provided by the other parties, in the ITER port plugs during the second phase of operation. The two concepts which are being studied in Europe are:

– the He-cooled lithium lead (HCLL);
– the He-cooled Pebble Bed (HCPB) [9].

Tasks have been carried out including design features, such as neutronic evaluation and behaviour during disruptions, and fabrication processes. Corrosion and chemical reactivity tests have been performed, small-scale mock-ups have been manufactured and thermo-mechanical behaviour and swelling analyses performed. The conceptual design of the two types of blanket modules has been decided. The engineering design phase is now under way.

The target of the fuel cycle activities [10] is the validation of specific features of the reference ITER design and the development of its enhancements. Pumping tests of the ITER Model Cryopump (Fig. 5) on the typical exhaust gas mixtures were completed at the facility at the Forschungszentrum Karlsruhe [11]. Pumping tests at higher temperatures were also carried out.

Tests of torus exhaust gas processing at the Caper facility (FZK), also in direct connection with the infrastructure of the Tritium Laboratory Karlsruhe, were carried out demonstrating the capability of reaching the desired level of tritium removal from the ITER gas exhaust.

Areas of activity related to fuel cycle included water detritiation and waste handling.

Physics integration and heating systems technology project

The Physics Integration field in EFDA is concerned with the development of technology for the diagnostics, the physics of heating and current drive systems, plasma edge and plasma operation and the coordination of the physics R&D programme conducted on the experimental machines in the European Associations.

The Heating Systems Technology Project takes care of all engineering issues linked to the design and construction of the heating and current drive systems.

ITER has up to now retained all four major heating and current drive systems developed until now, i.e. Electron Cyclotron Resonance Heating (ECRH), Ion Cyclotron Resonance Heating (ICRH), Neutral Beam Injection (NBI) and Lower Hybrid (LH) waves. Critical aspects of these relevant technologies therefore need to be dealt with in the Technology Programme. They include the development of a 2 MW, continuous duty coaxial gyrotron at 170 GHz. This component would have twice as much power capability than the existing design with favourable implications on complexity and cost of the system. Preliminary developments have taken place in the associations, industrial involvement is now being pursued in order to ensure the transfer of knowledge for the subsequent production.

As far as the NBI is concerned, a single gap accelerator and a radio frequency (RF) plasma source are being developed for the 1 MeV negative ion beam system.

Development of an ITER relevant ICRH antenna is being carried out on JET, while a prototype antenna for the LH, to be used in the ITER steady state phase, will be tested in the forthcoming months in FTU, the tokamak at the ENEA Frascati (Italy) laboratory (Fig. 6).

As far as diagnostics are concerned, investigations are carried out to assess the properties of candidate materials to be used as windows, insulators and optical transmission components also under irradiation.

Concerning the physics of the interaction between the plasma and the walls of the plasma chamber, studies to provide a better understanding of the processes of erosion and codeposition and tritium retention continue to be carried out both theoretically and through experiments on the existing European tokamaks, JET in particular. Analyses were also undertaken in the field of control and plasma magneto-hydro-dynamic instabilities. Improved 3-D modeling of disruption processes was performed to enhance the predictive capability for ITER.

The remote participation infrastructure is also being further developed to promote tele-collaboration among research centers in the exploitation of the EU fusion facilities, e.g. JET, in view of the forthcoming ITER requirements.

System studies

This area groups together activities which are aimed at interacting with the general public in respect to the possible use of nuclear fusion as a future energy option [12, 13].

The socio-economic tasks, in support of the ITER project, have been covered in the area of "Fusion and the Public Opinion".

The aim of these tasks was to monitor the reaction of the population when confronted with the presence of a project such as ITER in their area.

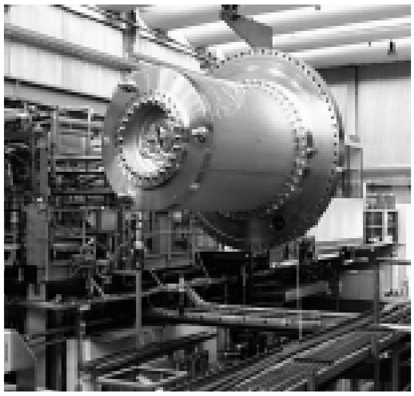

Fig. 5: The ITER model cryopump at the Forschungszentrum Karlsruhe (D)

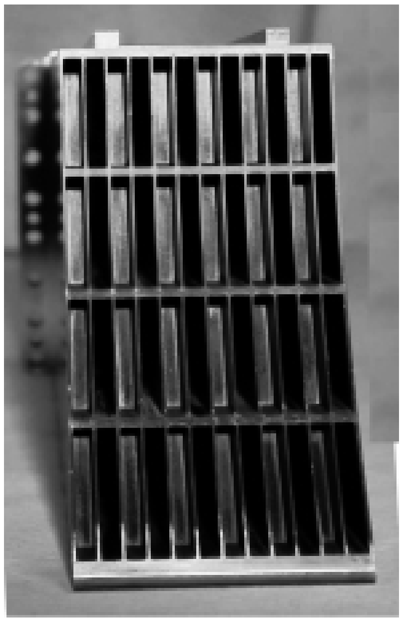

Fig. 6: The passive-active multijunction at ENEA Frascati (I)

"Focus Groups" have allowed to check the attitude of the population in the Cadarache (F) area. Results have shown a positive response, but at the same time with the request of having independent information on the advantages and disadvantages of such an installation.

Previous activities (using the "European Awareness Scenario Workshop" methodology) in Italy, a country which had proposed a site for ITER a few years ago, have demons-trated that, when the population is properly informed and involved in the decision, the acceptability of fusion finds a good support.

Current activities in the public opinion area foresee some well-focused workshops, a "Focus Group" on fusion and risk perception as well as investigations to explore in secondary schools the awareness of the energy and environmental issues and of the possible role of fusion in the long term.

All these activities use the ITER project as the main source of information and of basic assumptions.

Public information is another topic in the "System Studies" area. Activities concentrate here in preparing and spreading information on the current progress in the ITER project and on the features of this facility.

General public, media and politicians are the target of the activity which is carried out with the help of written material (i.e. brochures, info sheets,…), interviews and specific exhibitions.

Educational activities centered on ITER for students at secondary schools are planned in the forthcoming months.

ITER site preparation activities

The European ITER Site technical Study group (EISSg) was established in October 2000 to prepare the technical basis for European ITER site proposals [14, 15] and in order to assist the European ITER negotiators providing further information as required.

The main objective of the EISS activities was to conduct and co-ordinate the design work needed to assure the compliance of both European sites with the ITER site requirements and design assumptions. Work was performed for both proposed European sites: Cadarache [16] in France and Vandellós [17] in Spain.

A major achievement was reached in January 2003 when the final report of the Joint Assessment of Specific Sites (JASS), jointly conducted by the parties in the ITER negotiations, considered all four proposed sites, including the two European ones, as suitable ones to host the reactor.

A second objective of the EISS activities was to prepare the necessary documentation to initiate the formal licensing process of ITER both in France and Spain. The first steps in this sense were already undertaken in both countries by submitting the first set of reports to the designated authorities.

Conclusions

The European Fusion Technology Programme is largely centered to support the ITER design and to prepare its construction. Work has been carried out in all possible areas and successful results have been achieved in all the fields. These results complement the ones achieved by the other partners and contribute to create a good confidence in the success of the ITER project.

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