Fusion Power Plants

Developing fusion energy as a new source of energy represents a considerable challenge. The European Union, together with all ITER Parties, is currently engaged in the construction of the ITER device, which represents a scientific and technical undertaking of unprecedented magnitude. Successful ITER operation will demonstrate the scientific feasibility of fusion energy, leading to the construction of one or more DEMOs to demonstrate the technological and economic viability of fusion power

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The main focus of the European Fusion Research Programme in the field of thermonuclear fusion is the construction of ITER [1]. This is also the case for the other ITER Parties, namely China, India, Japan, Korea, the Russian Federation and the United States of America. ITER is indeed the main pillar of the European Roadmap for the Realisation of Fusion Energy [2], which outlines the European strategy between now and 2050.

The European Fusion Roadmap

ITER is expected to achieve most of the important milestones on the path to the first Fusion Power Plant (FPP), notably the qualification of a robust physics basis and the validation of key nuclear technologies, and the licensing of ITER will confirm the intrinsic safety features of fusion. Thus, ITER's success remains the most important overarching objective of the European fusion programme and the majority of the European Union's resources[1] on fusion are currently devoted to ensure that ITER is built within scope, time and budget. Significant resources are also expected to be devoted to ITER in the future to ensure completion of construction, to prepare future operation, and to train a new generation of scientists and engineers for its exploitation.

The European Fusion Roadmap foresees only one step, called DEMO, between ITER and the first FPP, in order to bridge the engineering and technological gaps between ITER and the first FPP. The main goals of DEMO are: (i) to produce net electricity for the grid at the level of a few hundred megawatts (MWs); (ii) to breed the amount of tritium needed to close its fuel cycle; and (iii) to demonstrate all the technologies for the construction of a commercial FPP, including an adequate level of availability.

DEMO (Figure 1) will require a significant amount of innovation in critical areas such as heat exhaust, materials and tritium breeding to demonstrate the technological feasibility of fusion power as an energy source. On the other hand, to design DEMO on the basis of the ultimate technical solutions in each area would postpone the realisation of fusion indefinitely. For this reason, a pragmatic approach is advocated in the Fusion Roadmap.

Both ITER and DEMO are tokamak devices, i.e. devices that use a powerful magnetic field to confine a plasma in the shape of a torus. There are other types of magnetic confinement schemes to contain the plasma, and the European Roadmap considers the stellarator as a possible long-term alternative to tokamaks. A stellarator is more complex than a tokamak from the engineering standpoint but it operates inherently steady-state (see below the discussion on steady-state operation in a tokamak).

Tokamaks and stellarators are devices that belong to the Magnetic Fusion Energy approach to generating fusion power by using magnetic fields to confine the hot fusion fuel in the form of a plasma. Magnetic confinement is one of two major branches of fusion energy research, the other being Inertial Confinement Fusion (ICF). The aim of ICF is to initiate nuclear fusion reactions by heating and compressing fuel pellets with very powerful laser beams. Because of its potential military applications, the European Union is not supporting this alternative line of research[2].

Fusion Power Plants

ITER and DEMO are the main devices foreseen to acquire the knowledge necessary to build the first FPP (Figure 2). To define the objectives of these devices it necessary to define the requirements of a FPP is, and this is the scope of the so-called 'reactor studies'. Following a series of preparatory activities in the 1990's, Europe performed a Power Plant Conceptual Study (PPCS) between 2001 and 2005 [3], and the five FPP tokamak models developed during the PPCS still constitute the European references. Major studies have also been performed in the USA since the early 1990's: the so-called ARIES studies [4].

What is the scientific gap between our knowledge today and the knowledge required to build the first FPP? The JET tokamak in Culham, UK, which is the most successful tokamak in operation today, has achieved an 'energy amplification factor' Q of 0.67, meaning that it produced 0.67 units of fusion power for 1 energy unit injected into the plasma. The main scientific goal of ITER is to achieve Q=10, i.e. ITER will produce 10 times more fusion power than the heating power required to sustain the plasma. Achieving this goal will demonstrate the scientific feasibility of fusion power. JET achieved Q=0.67 during a few, short pulses a few seconds long, ITER will achieve Q=10 on a regular basis with pulses 400s long. ITER is indeed the first fusion nuclear facility, classified as 'Installation Nucléaire de Base' number 174 by the French Nuclear Safety Authority.

The PPCS indicated that it is possible to conceive a FPP considering only modest extrapolations with respect to the ITER physics basis. The PPCS also highlighted the benefits resulting from a more advanced physics basis, allowing to consider either a smaller device to deliver the same output power or more power from a device of the same size, both resulting in a lower Cost of Electricity.

There are different routes that can be pursued to make progress towards developing concepts that allow for smaller devices. For instance, it would be particularly advantageous if the so-called 'energy confinement time', $\tau\varepsilon$, of the plasma could be improved. It is a key parameter, given by the ratio of plasma energy and the power needed to maintain the energy of the plasma in a steady state, and it measures the 'thermal insulation' of the plasma. The main cause for energy leaking out of a tokamak plasma and limiting $\tau\varepsilon$ is micro turbulence, i.e. small excursions of particles and fields in the plasma away from their equilibrium values, resulting in a net outward flow of energy.

The reason tokamak reactors need to be large is that increasing the size enhances $\tau\varepsilon$ (this is analogous to putting on another blanket over a bed when it is cold). However, if scenarios can be developed that yield improved energy confinement at a given size (analogous to making the blanket in the bed more effective, e.g. using wool rather than cotton), it would be possible to design smaller fusion reactors. This is possible under certain circumstances, by tailoring the profile of the current flowing through the plasma. In this case it is possible to induce a transition to a state whereby the plasma develops a narrow layer in its middle region where the micro turbulence is strongly reduced. This acts like a bottle neck for the outflow of energy and inside this layer the plasma temperature and density can be greatly enhanced, resulting in an improved energy confinement. Furthermore, the strong gradients in plasma pressure associated with the region of reduced turbulence lead to a self-generated current, called the 'bootstrap current', that can potentially

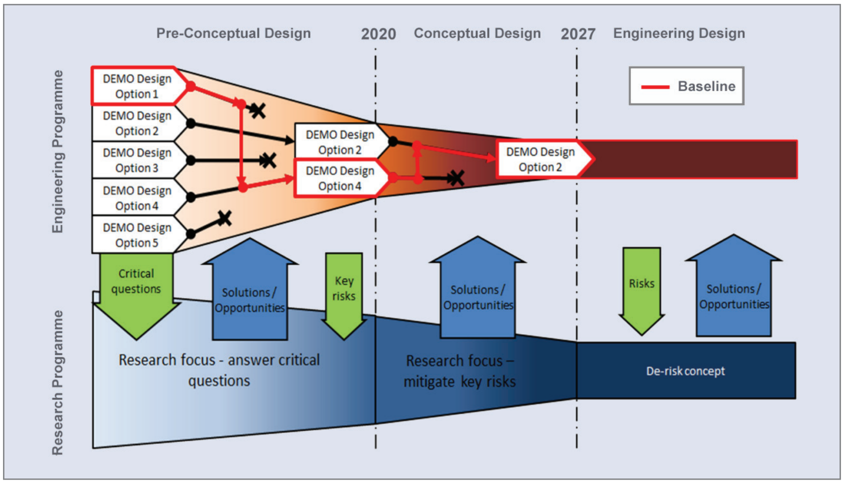

Fig. 1 DEMO development in Europe, proposed plan for the next 10 years according to the latest revision of the Fusion Roadmap
Source: courtesy of EUROfusion

account for a significant fraction of the current needed for the plasma confinement in a tokamak. This kind of scenario with a region of reduced turbulence in the mid-range of the plasma is often called an advanced scenario, and its development will require dedicated machines such as JT60-60, currently under construction in Japan under the framework of the bilateral agreement between EURATOM and Japan [5].

The European Power Plant Conceptual Study

The major requirements to be satisfied by a FPP, developed in cooperation with European Industry at the beginning of the PPCS, were:

Safety and waste disposal:

- no need for an emergency evacuation plan, under any accident driven by in-plant energies or due to the conceivable impact of ex-plant energies;
- no active systems required to achieve a safe shutdown state;
- no structure should approach its melting temperature under any accidental conditions;
- adopt 'defence in depth' and, in general, ALARA (As Low As Reasonably Achievable) principles as widely as possible;
- minimise the production of radioactive waste, with no waste requiring geological disposal after an intermediate storage of less than 100 years.

Operation:

- operation should be steady state with power of about 1 GWe for base load;
- lifetime should be about 40 years with the possibility of further extension up to 60 years for parts which are not replaceable;
- maintenance procedures and reliability should be compatible with a plant availability of 75–80%.

Economics:

- since public acceptance is becoming more important than economics, economic comparison should be made with energy sources with comparable acceptability.

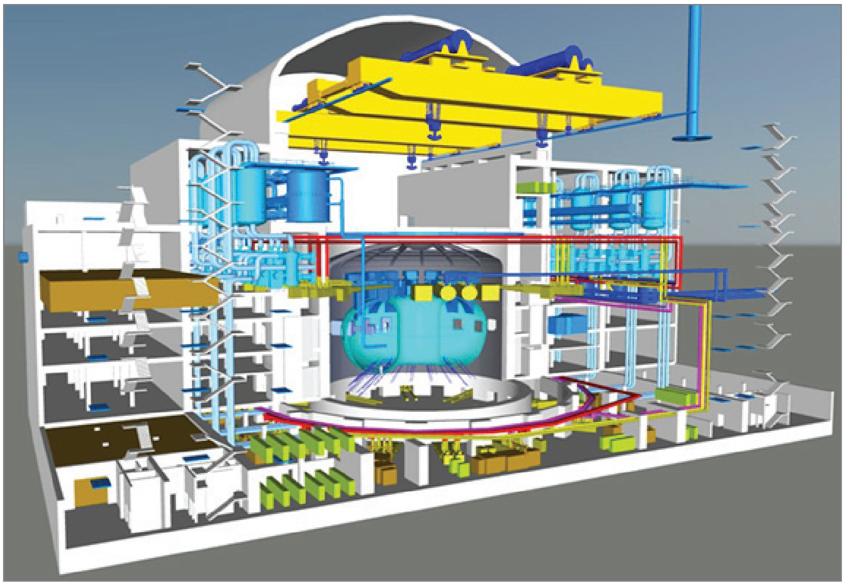

Fig. 2 Conceptual layout of Fusion Power Plant. The overall building size is comparable to that of a fission plant of similar power production capacity
Source: courtesy of EUROfusion

The PPCS confirmed that it was possible for future tokamak FPPs to satisfy these requirements and concluded that even the models developed assuming limited extrapolations could be economically acceptable with major safety and environmental advantages. It is important to note that later studies confirmed these findings. The PPCS also highlighted the engineering and technological challenges to be resolved before considering the construction of the first FPP.

DEMO and the main challenges of Fusion Technology

The DEMO studies currently underway [6] aim at addressing all critical issues identified during the PPCS.
A plasma is an electrical conductor. It is therefore possible to induce an electric current in it by slowly increasing the current through the electromagnetic winding constituting the so-called Central Solenoid coil (Figure 3), which is inherently a pulsed process. Steady-state operation in a tokamak requires driving the plasma current non-inductively with the help of systems able to inject considerable power into the plasma, either by injecting 1 or 2 MeV neutral beams into the plasma or by heating the electrons or the ions using Electron or Ion Cyclotron Resonant Heating at frequencies of, respectively, 170 GHz and 50 MHz. Because of the low plug efficiency of these systems, i.e. the ratio between the total energy required to operate these systems and the energy eventually injected into the plasma, operating a tokamak steady-state would require to recirculate a considerable fraction of the electricity generated – of the order of several 100's of MW for a gross electricity production of ca. 2 GWe, resulting in a net power output between 1 and 1.5 GWe (the exact figure depends from other design choices, in particular the primary reactor coolant, water or helium). On the other hand, plasma discharges of several hours duration, with short interruptions of ca. 10-20 minutes between them, should be possible with less than 100 MW of additional power injected into the plasma. The current preference today, at least in Europe, is therefore to consider pulsed or, more accurately, quasi-continuous operation for DEMO.
Achieving a high availability will be a major challenge of fusion power. Indeed, the high energy neutrons (14 MeV) produced during the deuterium-tritium fusion reaction will activate the whole core of the FPP reactor, thereby imposing the use of robotics technologies for all maintenance operations inside the main reactor vessel and for most maintenance operations within the secondary vacuum vessel (the cryostat). Handling components weighting up to 100 tons and positioning them with millimetric accuracy are tasks well beyond the current state-of-the-art. In-vessel maintenance operations in ITER will already require the use of robotics technologies and will constitute a major feasibility demonstration for the deployment of these technologies in a fusion environment. Any intervention inside the main reactor vessel will require several weeks before and after the intervention proper to free the access path for the remote devices and to condition the machine – e.g. detritiation before the intervention and first wall conditioning after the intervention. In other words, any intervention will last at least 3 or more months. To achieve a reasonable availability, it is therefore essential to aim for the highest possible reliability of the major reactor components and systems to minimise the number of remote interventions, scheduled and unscheduled.
The fuel used in the fusion reaction is a mixture of deuterium and tritium, both hydrogen isotopes. The natural abundance of deuterium in hydrogen is one part per 6500, but tritium is virtually non-existent in nature because of its relatively short half-life of 12.3 years. Tritium must therefore be produced, and the preferred scheme is to 'breed' tritium in DEMO and in the FPP from lithium. Lithium[3] or lithium compounds will be placed in the 'blanket', the component located inside the main vessel of the FPP and surrounding the plasma. Tritium breeding is one of the major technological challenges of fusion technology and, again, ITER is the essential facility in the

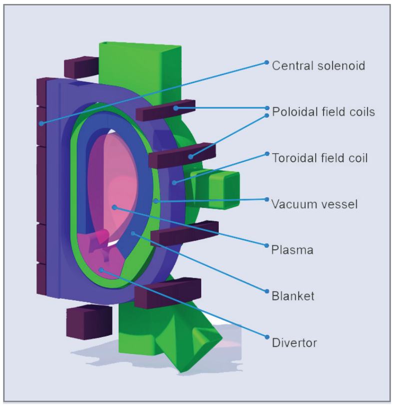

Fig. 3 3D view of the main components of a tokamak power plant: the 3 coil systems – central solenoid, toroidal fiels coils and poloidal field coils; the main – or primary – vacuum vessel; the blanket – where tritium will be bred and where most of the energy carried by the neutrons produceed by the fusion reaction will be captured; the divertor – the key component for the power exhaust; and the plasma itself
Source: courtesy of EUROfusion

strategy for the development of reactor-relevant breeding blankets: different Tritium Breeding Modules will be installed and tested in ITER in order to assess and qualify possible tritium breeding processes.

In a fusion plasma, the energy injected to heat the plasma and the energy produced by the fusion reaction must be removed from the system at the rate at which they are created, the impurities released from the reactor inner walls must not inhibit the fusion reaction and must be removed, and the reactor itself, primarily the inner walls, must not be damaged by the fusion reaction or by the power exhaust processes. These three considerations define the power exhaust issue. To quantify the problem, consider the global power balance in a FPP with 100 MW of auxiliary heating power and generating 1.5 GW of fusion power. Since 80% of the D-T fusion power is released in the form of neutrons, this leaves 100 + 300 = 400 MW transferred to the plasma. Assuming that a substantial fraction of this power – say 50% for the first FPP, although a percentage in excess of 80% can be achieved with advanced scenarios – can be radiated in the core of the plasma by bremsstrahlung, synchrotron and line radiation, 200 MW will have to be exhausted by the reactor 'first wall' and 200 MW by the 'divertor'. In addition to significant physics issues related to the core radiation and to the transport of power to the divertor region, power exhaust imposes very stringent materials requirements.

Fusion Materials

The last major challenge of fusion energy is the development of functional and structural materials able to resist the harsh nuclear environment. Materials developed for fission applications may not be suitable because the ratio of He production (in atomic parts per million—appm) to dpa (displacement per atom) will differ considerably. For instance, the ratio in steels will be approximately 40 times higher in a FPP and in DEMO and the corresponding gas-production level is expected to enhance swelling and brittleness of the materials. Therefore, EUROFER steel – a reduced-activation ferritic-martensitic steel – was developed specifically for fusion applications to minimise the corresponding degradation of properties and to reduce its activation level in order to limit the amount of radioactive waste generated in a FPP. Another challenge for the materials facing the plasma is the extreme heat loads in some specific regions, up to 10-20 MW/m^2, leading to the use of tungsten as both structural material and armour protection material. This heat-load is comparable to the highest loaded part of the space shuttle during re-entry in the atmosphere (10 MW/m^2 for a few minutes only).

In DEMO the structural material of the blanket will have to operate up to 20 dpa during phase 1 and, after replacement of the complete blanket, up to 50 dpa during phase 2. In a FPP the blanket has a target limit of 100-150 dpa, corresponding to 5 full-power-year of operation. A significant R&D programme is in progress in Europe and in all countries with an important fusion development programme to develop and to qualify suitable materials.

Conclusions

Developing fusion energy as a new source of energy represents a considerable challenge. The European Union, together with all ITER Parties, is currently engaged in the construction of the ITER device, which represents a scientific and technical undertaking of unprecedented magnitude. Successful ITER operation will demonstrate the scientific feasibility of fusion energy, leading to the construction of one or more DEMOs to demonstrate the technological and economic viability of fusion power. The development of fusion power plants model is an essential activity in the overall fusion development strategy, necessary to identify the long-term R&D programmes that must be launched today.

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[1] ITER is currently financed through the EU Multiannual Financial Framework 2014-2020 whist the EU Fusion Research Programme, in addition to ITER, is financed through the Framework Programme Horizon 2020

[2] A small number of fusion start-up companies have been set up in North America and in the EU during the last few years investigating alternative concepts to achieve the production of energy from fusion with smaller devices and with a faster timescale. The physics and technological bases considered are not always clearly defined and, when they are, they rely on some extreme – although theoretically possible – assumptions. The creation of these start-ups demonstrates however the growing interest of private capital in fusion energy

[3] The U.S. Geological Survey produced in 2015 a worldwide estimate of lithium 'reserves' of 13.5 million tons and 39.5 million tons of 'resources', which is a less firm category than 'reserves.' Forecasts about the availability of lithium for FPP are strongly dependent on the hypotheses related to lithium use in other areas, in particular batteries. However, the total lithium content of seawater is very large and is estimated as 230 billion tonnes, where the element exists at a relatively constant concentration of 0.14 to 0.25 parts per million

REFERENCES

1. https://www.iter.org/

2. Fusion Electricity, a roadmap to the realisation of fusion energy, https://www.euro-fusion.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf

3. D. Maisonnier, Power plant conceptual studies in Europe, *Nuclear Fusion* 47 (2007) http://iopscience.iop.org/article/10.1088/0029-5515/47/11/014

4. http://www-ferp.ucsd.edu/ARIES/DOCS/bib.shtml

5. V. Tomarchio et al., Status of the JT-60SA project: An overview on fabrication, assembly and future exploitation, *Fusion Engineering & Design* 123 (2017), http://www.sciencedirect.com/science/article/pii/S0920379617305859

6. G. Federici et al., Overview of the design approach and prioritization of R&D activities towards an EU DEMO, *Fusion Engineering & Design* 109 (2016), http://www.sciencedirect.com/science/article/pii/S0920379615303835