THE ITER PROJECT: PUTTING FUSION TO THE TEST

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ABSTRACT

The long-term objective of the European fusion programme is to harness the power of fusion to help meet mankind's future energy needs. The next step towards this goal is the international ITER-project, which has to demonstrate the scientific and technological feasibility of fusion energy by generating 500 MW of fusion power, ten times more than is put in the reactor, for a sustained period of time. ITER is not an end in itself: it is the bridge toward a first demonstration power plant that will deliver large-scale electrical power to the grid.

Fusion has some key features which make it an attractive option in a future energy mix: inherently safe; waste which will not be a burden for future generations; no emission of greenhouse gases; and the capacity for large scale energy production. In addition, the required raw materials for the fuel are abundantly and widely available around the world. The combination of these features gives fusion the potential to make a substantial contribution to satisfying world energy demand later this century, and beyond.

On the 28th of June, 2005, the ITER-partners decided unanimously to construct ITER in Europe, near Cadarache in the South of France. The partners in the project are the EU, Japan, China, India, Korea, the Russian Federation and the USA, together representing more than half of the global population.

Europe has achieved a position of pre-eminence in fusion through its extensive fusion research programme, which is coordinated on a European level by the European Fusion Development Agreement (EFDA) and the European Commission. This paper gives a short introduction to fusion as an energy source, and discusses the current status of the European Fusion Research Programme, with a focus on the preparations for the ITER project.

1. INTRODUCTION

With an increasing world population and a growing economy, the demand for energy is sure to grow. New solutions will be required for providing a targeted answer to both the energy demand and the emission problems associated with our present energy system. Fusion energy, the energy source of the sun and the stars, has seen remarkable progress over the last decades, and is now ready to move out of the laboratory, and to be considered as a credible energy option for clean, large-scale power generation.

1.1 The fusion process

In a fusion reaction, two light atomic nuclei fuse together to form heavier ones, as is shown in figure 1. The fusion process releases a large amount of energy, which is the energy source of the sun and the stars. In stars, heavier elements are formed by consecutive fusion reactions starting from hydrogen, a process that continues until the element iron is reached, which is the most stable of the elements. The formation of even heavier elements such as gold and uranium requires a net input of energy, which is only accomplished in the most extreme of circumstances: supernovas.

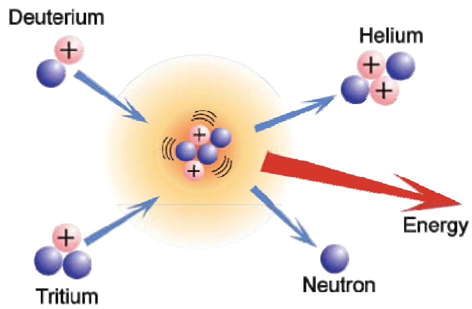

Figure 1: Two nuclei, here deuterium and tritium, fuse together to form helium, a neutron, and a large amount of energy.

A fusion reaction does not happen easily. The nuclei of atoms have a positive electric charge, and equal charges repel. But if two nuclei manage to get close enough together in spite of the repelling force, another force manifests itself: the nuclear force. The nuclear force is extremely powerful, but only acts on very small distances. The strong nuclear force pulls the nuclei together to form a new atom.

To bring the two nuclei close enough together, they need to collide with a very high speed, which means that the temperature of the gas must be high. If a gas is heated beyond a certain temperature, the electrons are separated from the atoms which they belong to, and together they form a gas of charged particles, in which the electrons and nuclei move independently. That state is called a *plasma*. In the centre of the sun, fusion reactions occur at 15 million degrees Celsius.

Because the nuclear force is so strong, a single fusion reaction releases an enormous amount of energy, millions of times more than a single chemical reaction. One kilogram of fusion fuel can generate the same amount of energy as 10.000.000 kilograms of coal. An electricity generating power plant working on this principle therefore only needs a very small amount of fuel.

2. FUSION ON EARTH

2.1 The deuterium-tritium fusion reaction

Although many different fusion reactions are possible, only a few of them are interesting for the application of fusion as an energy source on earth. Those are the reactions that will still occur at a relatively low temperature. The fusion reaction that is easiest to accomplish on earth is the reaction between deuterium and tritium, two isotopes of hydrogen. As shown in figure 1, a deuterium and a tritium nucleus can combine to form a helium nucleus, a neutron, and energy.

Deuterium is the stable isotope of hydrogen, with one extra neutron in its nucleus, tritium is the unstable isotope of hydrogen, and has two extra neutrons. To produce enough fusion reactions, the deuterium-tritium mixture has to be brought to a temperature of 150 million degrees, ten times higher than the temperature in the centre of the sun.

2.2 Confining a hot plasma

As there are no materials that can withstand such a high temperature, a way must be found to keep the hot plasma away from the walls of the plasma vessel. If the plasma would touch the wall, the plasma would cool down, and fusion would stop. To accomplish this isolation from the walls, a strong magnetic field is applied to the plasma. The charged particles in the plasma follow the magnetic field lines. The magnetic field lines can be organised in a circular way, such that the plasma does not touch the inner wall of the vessel. This technique is called *magnetic confinement*. In modern fusion experiments, the plasma is confined in a doughnut-shaped vessel with magnetic coils called a *tokamak*, as shown in figure 2.

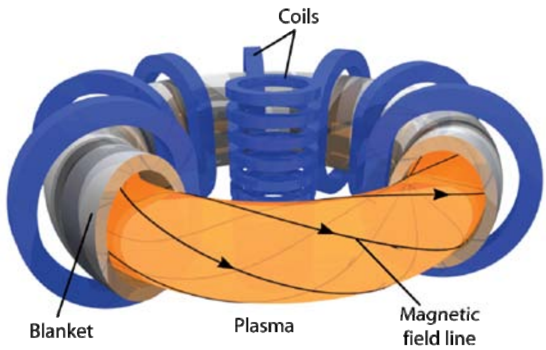

Figure 2: The principle of a tokamak. The plasma is contained in a doughnut-shaped vessel, also called a 'torus'. Using superconducting coils (blue) a magnetic field is generated, which causes the plasma particles to run around in circles, without touching the vessel wall. In reality, a number of other coils are present, that produce subtle changes to the magnetic field.

3. FUSION AS AN ENERGY SOURCE

When fusion comes available as an energy source, what will be its characteristics? Will it be clean and safe? What is the waste, and how large is a typical unit? In short: a fusion power plant will generate about 1000-1500 MW of electricity. In the plant, lithium is turned into the intermediate fuel tritium, which is heated to 150 million degrees together with deuterium. Fusion reactions produce helium, an inert gas which is the 'waste' of the reaction, and neutrons. The neutrons fly into a blanket surrounding the plasma, where they react with lithium to produce tritium, and where they transfer their energy to a cooling medium. The energy can be used to generate electricity, or, for example, to produce hydrogen.

3.1 Fuels

Fusion is a particularly attractive energy source as it uses fuels that are abundant and available around the globe. The primary fuels used in fusion are deuterium and lithium. Deuterium is a hydrogen isotope, which can be readily extracted from water (there is around 33g of deuterium in every cubic metre of water), and lithium is an abundant light metal — for example used in lithium-batteries — from which tritium can be generated inside the reactor. The lithium from one laptop battery, combined with the deuterium in 100 litres of water, can cover the electricity use of an average European citizen for 30 years.

3.2 Safety

Fusion power plants will be inherently safe. Although the plasma in a fusion power plant will have a volume of 1000 cubic meters or more, the total amount of fusion fuel in the vessel is very small: only two grams, enough for just a short time of operation. If the fuel supply is closed, the reaction stops without problems within seconds. Fusion is not a chain reaction and can therefore not run out of hand: in the normal situation, the fusion process runs at the fastest possible rate, and any deviation from this optimum leads to a decrease in energy production.

The intermediate fuel, tritium, is a radioactive substance, and fusion power plants are constructed in such a way that a safe handling of the tritium is ensured, which is subject to appropriate laws and regulations. Techniques and expertise to handle tritium safely already exist.

As tritium is produced inside the plant in a closed circuit, the total amount of tritium present can be limited to about 1 kg. Outside the plant, no transport of tritium is needed, except for a new fusion power plant, which needs to be 'primed' with tritium the first time it is used; after that it can produce its own supply.

3.3 Environmental impact

Although the products of the fusion process (helium and neutrons) are not radioactive, the structural materials of the vessel are activated by the neutrons. If proper materials are used, the half life of such waste can be limited to about 10 years, meaning that after a period of 100 years the radioactivity drops to a value of a 10.000th of its initial value, and can be largely recycled. The design of new, so called *low-activation* materials that are needed for this aim, is an important and active part of the international fusion research. Fusion produces no actinides, which form the long-lived waste of fission power plants.

3.4 Costs of fusion power

In April 2005, EFDA has released the *European Fusion Power Plant Conceptual Study* (PPCS). The study defines four future fusion power plant models illustrative of a wider range of possibilities, spanning from near-term to very advanced, and addresses questions related to safety and environmental impact, economics, and development needs. The study is available on the EFDA website.

In the study, the costs of future fusion electricity were computed from detailed plant models using well-attested industrial costing techniques. Although cost estimates so far ahead are highly dependent on technological and financial assumptions, the study concluded that the cost of electricity from the models is in the range of estimates for the future costs from other renewable sources, obtained from the literature.

4. THE CURRENT STATUS OF FUSION RESEARCH

In the fifty years that research on nuclear fusion has been carried out, enormous scientific and technological progress has been made. Fusion scientists now manipulate plasmas of hundreds of millions of degrees, in large fusion devices.

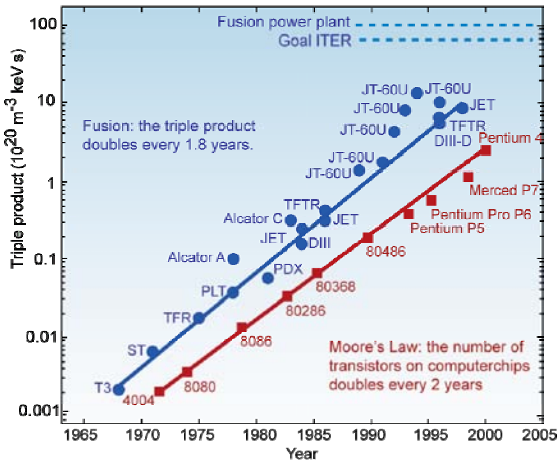

Figure 3: The progress of fusion research through the years, measured by the triple product, which is an indication of the performance of a fusion plasma. Please note the logarithmic scale on the vertical axis. For comparison, the development of computer chips is indicated.

Figure 3 shows the progress of the so-called 'triple product', a figure-of-merit which measures the performance of a fusion plasma. The triple product has seen an increase of a factor of 10.000 in the last thirty years, and another factor of 6 is needed to arrive at the level required for a power plant. In the figure, the progress is compared to that of computer chips.

4.1 European fusion research

Reaching the aims of fusion research requires a sustained, long-term and large scale research effort, which would be impossible to sustain for any single European country. That is why all the Member states of the European Union collaborate in a single European research programme, which is coordinated by the European Commission through Euratom. The Swiss Federation and Bulgaria are also part of this programme.

Individual research institutes in the Member States have "contracts of association" with Euratom — the international legal framework under which EU Member States cooperate in the fields of nuclear fission and fusion research — in which the long-term commitments and work plans are laid down. This has lead to a research programme that is coordinated and integrated on a European level.

In 1999, the European Fusion Development Agreement (EFDA) was created to provide a framework for national fusion research parties to participate in collective activities, such as the Joint European Torus (JET), the world's largest fusion experiment. EFDA's activities include fusion technology R&D, the exploitation of the JET facilities, and contributions to international collaborations, such as the ITER-project. EFDA was established as a framework contract between Euratom and the research institutes associated to the European Fusion Programme.

4.2 The Joint European Torus – JET

JET, based in Culham, Great Britain, is the central research facility of the European Fusion Programme. The focusing of significant European fusion research funding on JET has made it the preeminent fusion facility in the world and allowed Europe to take major strides in fusion research. JET is complemented by a number of specialized smaller devices run by more than twenty individual EU member states.

JET construction began in 1979 and operations started in 1983. All of its original planned operational goals have been met in time and cost. Since 2000, a new way of operating has been put in place under the EFDA agreement: JET is now collectively used by teams of visiting scientists from across Europe. The JET programme is led by the EFDA Associate Leader for JET and a small coordination team. A new scientific programme has started, and JET now hosts a large number of international research efforts.

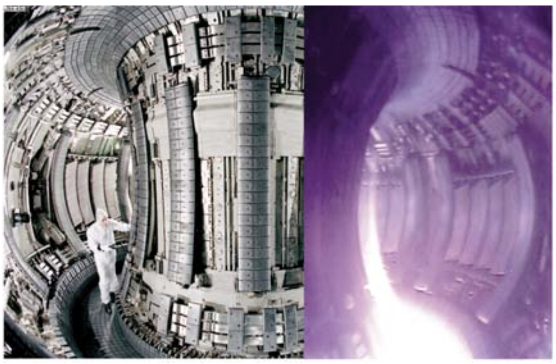

Figure 4: A look inside the plasma vessel of the Joint European Torus (JET). JET is located in Culham, GB. The plasma is shown on the right.

JET has produced significant fusion power in deuterium/tritium plasmas — up to 16 MW — in the short pulses characteristic of existing experimental devices. 'Break-even' conditions, where the fusion output power equals the external input power required to heat the plasma, were almost reached. Moreover, JET has demonstrated that fusion devices can be operated safely with tritium fuel and that activated structures can be maintained and modified using remote handling techniques.

Thanks to the success of JET and other experiments, the world fusion community is now ready to take the "Next Step" of constructing a larger device, ITER, which will produce plasmas under reactor conditions of high power gain and provide a reliable basis for proceeding to a demonstration reactor, capable of producing electricity.

5. THE ITER PROJECT

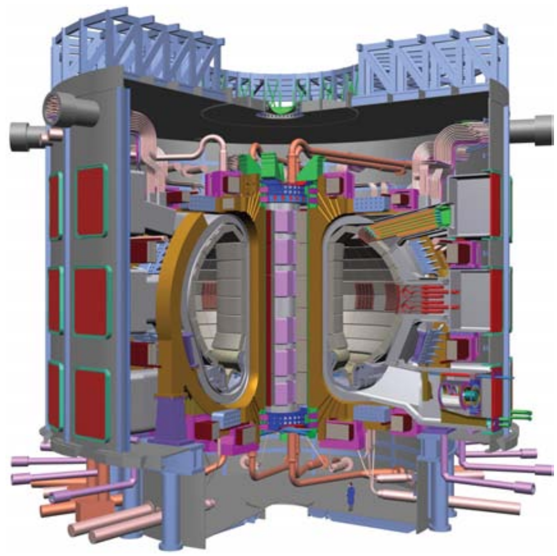

Figure 5: The ITER machine. The man in the bottom shows the scale.

While significant progress has been made with JET and other fusion experiments, it was clear from an early stage that a larger and more powerful device would be needed to create the conditions expected in a fusion reactor and to demonstrate its scientific and technical feasibility. ITER is an international research and development project with the aim to demonstrate the scientific and technological feasibility of fusion energy.

ITER has twice the size of JET in its linear dimensions (see figure 7), which means it has a plasma volume that is almost ten times larger. ITER is truly a global project: the current partners in the ITER project are Europe, Japan, the Russian Federation, China, India, Korea and the USA.

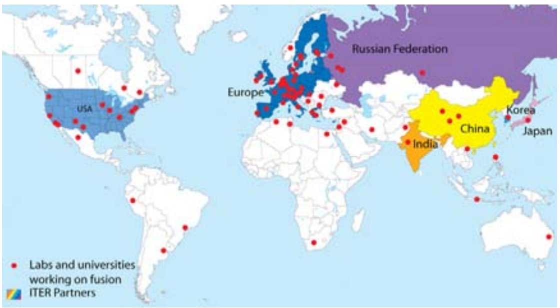

Figure 6: Countries participating in the ITER project. The dots indicate fusion research institutes.

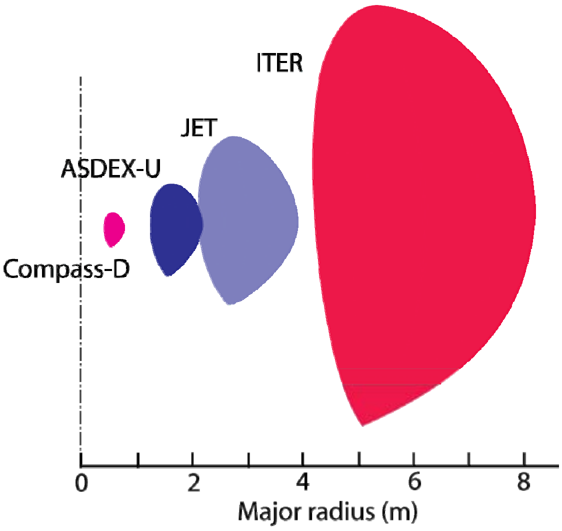

Figure 7: the size of the plasma in different fusion experiments across Europe. The ITER plasma is twice the size of JET in its linear dimensions.

ITER will allow the study of plasmas in conditions similar to those expected in a electricity-generating fusion power plant. It is designed to generate 500 MW of fusion power for extended periods of time, ten times more then the energy input needed to keep the plasma at the right temperature. It will therefore be the first fusion experiment to produce net power. It will also test a number of key technologies for fusion including the heating, control, diagnostic and remote maintenance that are expected to be needed for a real fusion power station.

The construction costs of ITER are estimated at 4.7 billion Euro over 10 years, a large part of which will be awarded in the form of contracts to industrial companies. Another five billion Euros are foreseen for the 20-year exploitation period. Europe will contribute a major share of the costs. The contributions of the partners will for the largest part consist of components for the machine, so-called *in kind* contributions.

ITER will be a machine of the tokamak type in which the torus-shaped fusion plasma is confined by strong magnetic fields (see Fig. 5). The device's main objective is to demonstrate prolonged fusion power production in a deuterium-tritium plasma. Compared with current conceptual designs for future fusion power plants, ITER will include most of the necessary technology, but will be of slightly smaller dimensions and will operate at about one-fifth of the power output level.

In June 2005, the partners in the project decided unanimously to choose the European site at Cadarache, in the South of France, as the location for the construction of ITER. The design of ITER is ready for the start of construction to begin, and the first plasma operation is expected in 2016.

5.1 A key element in a long term strategy

The long-term aim of fusion research and development in Europe is to create power station prototypes demonstrating operational safety, environmental compatibility, and economic viability. The strategy to achieve this long-term aim includes a number of different elements: first of all the development of a larger experimental reactor (the *Next Step*, which role will now be played by ITER), followed by a demonstration reactor called *DEMO*.

In addition to these two devices, the strategy includes the study of improved concepts for future fusion devices, and accompanying physics and technology R&D activities which also involve European industry. Finally, studies are performed on the socio-economic aspects as well as the safety and environmental aspects of fusion power, which focus on the potential contribution of fusion to sustainable base-load power generation.

5.2 History of the project

The idea for ITER originated from the Geneva superpower summit in November 1985 where Premier Gorbachov, following discussions with President Mitterand of France, proposed to President Reagan that an international project be set up to develop fusion energy for peaceful purposes. The ITER-project subsequently began as a collaboration between the former Soviet Union, the USA, the European Union and Japan, and was later enlarged to China, the Republic of Korea and to India.

Conceptual and engineering design phases led to an acceptable detailed design in 2001, underpinned by $650M worth of R&D, which was carried out by the ITER parties to establish its practical feasibility. The design of ITER, resulting from this unique international collaboration, is the first complete design of a fusion device of conventional power station size, based on well-established and proven technology. This design provides a detailed engineering plan ready for implementation.

Figure 8. Many components and techniques that are needed for ITER have already been tested by industry, such as this model of the ITER Toroidal Coil, assembled in the Toska facility in Karlsruhe, Germany.

The physics and technology experiments conducted in many fusion devices worldwide have provided a solid physics base for extrapolation to the ITER scale. A number of key high-technology components, such as superconducting coils, have been developed specifically and manufactured by industry and are ready for production.

The recent decision to construct ITER in Cadarache in the South of France allows the project to move on to its construction phase. In the mean time, agreement has been reached on the sharing of the costs and the in-kind contributions to the project between the different Parties. The way is now open for the signing of a joint implementation agreement, which will allow the international ITER Organisation, based in Cadarache, to be established. The ITER organisation will be responsible for all aspects of the project: the licensing procedure, hardware procurements mostly provided *in kind* by the Parties, the twenty-year operation period, and ultimately for decommissioning of ITER at the end of its lifetime.

In the first months of 2006, the top management team of ITER has been named. The Director-General of the project will be Kaname Ikeda, formerly Ambassador for Japan in Croatia. The Project Construction Leader will be Dr. Norbert Holtkamp, born German, and former director of accelerator systems at the Spallation Neutron Source in Oak Ridge, USA. Current expectations are that the ITER organisation should be established around the end of 2006, and following licensing, begin construction in 2008, with a view of obtaining the first plasma in 2016. This will be followed by an exploitation phase lasting about 20 years.

5.3 The European contribution

Europe has been at the forefront of fusion R&D for the past 50 years, and with hosting ITER, Europe is in a favourable position to maintain its leading role. During the ITER-project, the industrial companies that will construct the European part of the ITER-device will use high-tech know-how developed in fusion research institutions around Europe. It is expected that a lot of technological innovation will result from the exploitation of this knowledge, which opens many opportunities for high-tech companies to participate fruitfully to the project.

In order to manage and provide their contribution to the ITER project, each of the partners needs to establish its own domestic agency, which is responsible for the delivery of the components to ITER. A European domestic agency is being established for this purpose. This new organisation will be called 'Fusion for Energy', and will be located in Barcelona, Spain. This new organisation will also provide Europe's contribution to other international fusion research efforts, and, in the longer term, support a programme of research and development activities to prepare for the construction of prototype fusion reactors.

6. FINAL REMARKS

Climate change, environmental degradation due to fossil fuel use, security of supply and energy poverty are all very serious issues that must be faced. The transition towards a sustainable energy supply is surely one of the major challenges of this century, and all available sources will have to play a role in the future sustainable energy mix; we do not have the luxury of choice.

With its inherent environmental and safety advantages, such as no emission of greenhouse gases, fusion should be seen as an important element in any global strategy designed to allow sustainable development. As fusion is particularly suited for large-scale base load electricity production, it is the ideal complement of other renewable sources in the future energy mix. Fusion technology, brought to fruition, will be an asset of the utmost value to give to our descendants.

More information can be found on the following websites:

- www.efda.org
- www.jet.efda.org
- www.fusion.org.uk
- www.iter.org