MAGNETIC CONFINEMENT CONTROLLED FUSION RESEARCH: STATUS AND OUTLOOK

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More than 88% of the primary energy production in the world is based on fossil fuels. The disadvantages are well known: risk of irreversible changes to the climate system, limited reserves, dependency in supply. New technologies need to be developed, aiming at contributing to an energy mix that will meet the global energy demand with acceptable levels of risk, in terms of pollution and safety. Controlled fusion research aims at developing such a technology since the successful development of fusion energy holds the promise of a safe means for large scale electricity production, with very large and well distributed resources, limited radioactive waste and no atmospheric pollution.

1. WORLD ENERGY REQUIREMENTS AND FUSION ENERGY

At present, the world average energy consumption per capita is around 2.4 kW, with 88% generated by burning fossil fuels: gas, coal and oil. However, these resources are finite, are not optimally used, and produce carbon dioxide (CO_2) increasing the risk of irreversible climate changes. Moreover, world energy consumption is likely to double[1] or even triple in the next 50-100 years, according to estimates made by IIASA and the Worldbank as seen in figure 1. The world population is increasing rapidly and could reach 10 billion by 2100.

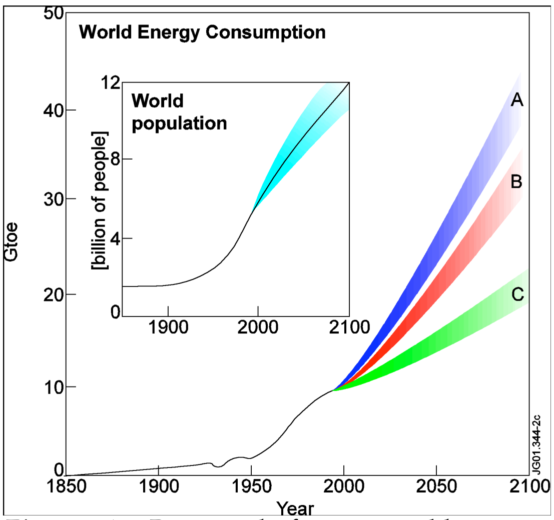

Figure 1. Past and future world energy consumption assuming the shown population increase and different models for economical development. A: optimistic economical growth, B: moderate economical growth, C: economical progress including strict environmental regulations for greenhouse gas emissions.

New economies are also developing quickly, with China and India (together about 2 billion people) as the two largest. If the average per capita consumption in those two countries would increase in 50 years to 1/2 of the current (western) consumption, the total world energy consumption would double[2,3].

Such levels of energy demand could possibly be met by the present sources of energy for the next 50-100 years, but this would further increase the risk of serious consequences for global environment. The overall concentration of CO_2 in the atmosphere has increased by 40% in the last 100 years and with the expected increasing use of energy, it is predicted to at least double within the next 50 years[4]. A global warming of the planet has been observed in the last 100 years and there is growing evidence that climatic changes are due to a greenhouse effect resulting from CO_2 emmision[5].

Essentially, there are two main classes of energy sources free from greenhouse gas emission and able to curb these trends: renewable energy sources and nuclear power. A sustainable energy policy should be based on an optimal blend of these sources together with energy saving measures.

Renewable energy sources[6,7], such as wind and solar power are important, but their technical potential is insufficient to meet more than a fraction of the worldwide energy demand, as they suffer from small (3-10 W/m^2) power densities and intermittent availability and are subject to local climatic conditions. Solar and wind power plants producing significant amounts of power would require immense investments in land and need backup power systems and/or large scale energy storage, reducing further their potential.

Nuclear fission is a viable energy source which should take a larger share in the energy mix. The current nuclear reactors are based on the fission of Uranium (^{235}U)[8]. Although, Uranium resources are limited longer term use of nuclear fission is possible with a new generation of reactors that make use of more advanced and complex fuel cycles[9]. Special care will have to be taken with long term environmental concerns of the high level radioactive waste with a long half life time (10000 years).

On the longer term, nuclear fusion could provide a safer way of producing large quantities of energy with low level radioactive waste and no atmospheric pollution. The most promising reaction which is currently pursued is the one between the hydrogen isotopes Deuterium (D) and Tritium (T), resulting in the production of a ^4He nucleus (alpha particle) and a neutron (n), schematically:

(1) $D + T \rightarrow {}^4He\ (3.5MeV) + n\ (14.1MeV)$

Most of the energy of this reaction is carried by the neutron, about 80%, with the remaining 20% by the alpha particle. The total amount of energy released (17.6MeV) in this reaction per unit mass of fuel, it is about 5 times larger than the energy released from the fission of ^{235}U fuel (releasing about 200MeV per ^{235}U atom). This explains why a minimal amount of fuel releases an enormous amount of energy. To cover the electricity needs of an average European during his whole lifetime (80 years), only 20g of D and 30g of T are needed.

The main advantage of nuclear fusion is the abundance of the fuels, lithium (abundant in the earth crust) and deuterium (from sea water) which are available worldwide. Both isotopes of lithium can be used to produce the artificial isotope tritium, according to the following reactions:

(2) ${}^6Li + n \rightarrow {}^4He + T + 4.8MeV$

(3) ${}^7Li + n \rightarrow {}^4He + T + n - 2.5MeV$

As Deuterium is available in enormous quantities in sea water (0.015% of natural occurring Hydrogen), the limiting factor in the D-T reaction are the reserves of lithium on earth. However, these will suffice for thousands of years of energy production based on the D-T reaction, even if all world electricity production would be produced from D-T fusion reactions.

Fusion could offer several advantages which are listed below. There is no risk of runaway of the reaction and therefore no major accident can result from a loss of control of the plant. The fuel cycle, i.e. the generation and subsequent burning of tritium, is completely contained within the reactor and there is thus very limited need for transportation of radioactive fuels. While radioactivity will result mainly from activation of the reactor metallic structure by the 14 MeV neutrons, it can in principle be mitigated by developing appropriate materials. However, fusion research is still at an experimental stage and large scale electricity production from nuclear fusion is projected only for the second part of the century.

2. MAGNETIC CONFINEMENT CONTROLLED FUSION

The difficulty in realizing any fusion reaction is the mutual repulsion of the nuclei. To overcome this, the kinetic energy of the reacting particles needs to be very large, equivalent to full ionised gas "plasma" temperatures of 100-200 million degrees for the D-T reaction. To generate these required temperatures and confine the reaction at the high temperatures needed for fusion, the D and T particles can be confined by the use of magnetic fields, known as "magnetically confinement". Alternatively, fusion can be achieved by the compression of capsules using intense laser light or beams and it is known as "Inertial confinement". The magnetic confinement scheme is the main focus of the European Fusion Programme. Magnetic confinement fusion research uses mostly toroidal devices. If a simple solenoid bent to form a torus is used, due to the inhomogeneity of a purely toroidal magnetic field, a charge separation takes place in the plasma. The resulting electrical field combines with the toroidal field creating an outward directed force, pushing the plasma to the outer wall. To overcome this problem and to obtain stable confinement, a helical magnetic field configuration has to be used.

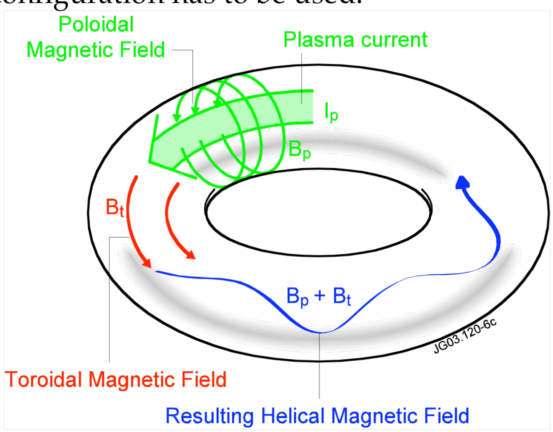

Figure 2 Diagram showing the Helical configuration of the Magnetic field in a Tokamak, obtained by combining poloidal and toroidal magnetic fields.

Two main lines exist: the stellarator and the tokamak. In the stellarator the helical magnetic field is produced externally to the reactor chamber, using twisted magnetic field coils, while in a tokamak this is done using a large toroidal plasma current induced by a transformer. The toroidally induced plasma current generates a poloidal magnetic field. The combination of these two fields results in twisted field lines, leading to the desired helical magnetic configuration, as shown in figure 2. The tokamak[11] is the most advanced configuration today. The word Tokamak is an acronym for the Russian description "toroidalnaya kameras magnitnami katushkami" meaning toroidal chamber with magnetic fields.

The toroidal plasma current also provides part of the heat needed for the reaction, due to Ohmic heating via the Joule effect. However, as the resistance of the plasma decreases with increasing temperature, the Joule effect alone is insufficient to provide the high temperatures required for fusion. Auxiliary heating systems are needed, which include the injection of high energy neutral particles and radio frequency waves.

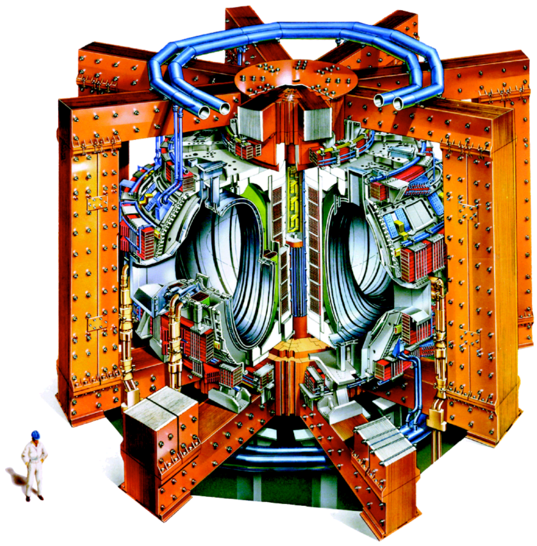

Figure 3 Diagram of the main components of the JET machine.

Present tokamaks approach the plasma parameters required for thermonuclear fusion, in terms of temperature (T), plasma density (n) and energy confinement time (τ_E the timescale for the energy to escape the magnetically confined plasma), using the combination of heating by the plasma current, high power electromagnetic fields and injection of fast neutral particles.

3. PRESENT STATUS: TOWARDS BREAK-EVEN IN JET AND THE DEFINITION OF ITER.

The largest tokamak in the world is JET[12] (Joint European Torus, figure 3), with main parameters: major radius 2.96m, toroidal magnetic field of up to 4 T, plasma current of up to 7MA and maximum auxiliary heating power coupled to the plasma of about 30MW.

JET is the only tokamak in the world capable of D-T operation and able to use Beryllium, one of the candidate wall materials for a next step fusion device. JET has also a unique remote handling system for non-manned in vessel interventions as required in the activated environment of a fusion reactor. JETs has been accompanied by other large tokamaks in the world: JT-60, (JAERI Tokamak 60) and its later upgrade JT-60U[13] in Japan, and TFTR[14] (Tokamak Fusion Test Reactor) in the USA, which was capable of using D-T fuel and has stop operating in 1997.

Other medium size devices currently in operation in the world include ASDEX-Upgrade (Germany)[15], FTU (Italy)[16], MAST (United Kingdom)[17], TORE-SUPRA (France)[18] and NSTX[19], DIII-D[20], C-MOD[21] in the United States of America.

Apart from TORE-SUPRA, all the operating tokamaks above use copper coils for the generation of the necessary magnetic fields. New tokamaks with super conducting coils are in construction in China (EAST, SUNIST)[22] and South Korea (KSTAR)[23].

Controlled fusion research made significant progress since the 1950s, when the first concepts were developed in small fusion experiments. JET, which started operation in 1983, was a giant step compared to the near table top size tokamaks existing previously, and has enabled large progress in the knowledge needed to realize a fusion reactor.

An important parameter to characterize the progress in fusion research is the power amplification factor Q, defined as the ratio between the fusion power released from fusion reactions and the externally supplied heating power. Break-even corresponds to Q=1, ignition to Q=∞. The achievable value of Q depends mainly on the product of the plasma density (n) and the energy confinement time (τ_E), also known as the Lawson parameter[25], and on the plasma temperature. The Lawson parameter determines a condition for break-even or ignition, by comparing the heat

released by the alpha particles to the heat lost by the plasma and is given approximately by:
$n\tau_E > 4\ 10^{19}\ m^{-3}$ s for break-even
$n\tau_E > 2\ 10^{20}\ m^{-3}$ s for ignition.

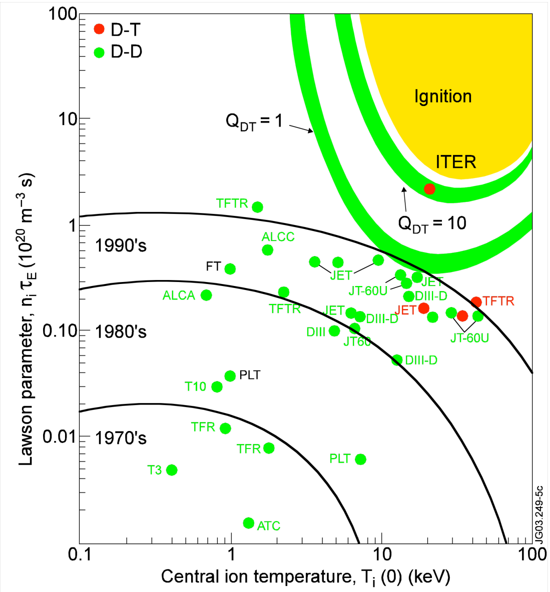

Figure 4 The Lawson parameter ($n\tau_E$) obtained on various tokamaks over the last 30 years. The performance obtained in deuterium-tritium plasmas in JET and TFTR are shown in red, while results from pure deuterium experiments carried out in many fusion devices around the world are shown in green. The green curves give the condition for Q=1 (break-even), Q=10 (the value projected for ITER) and Q=∞ (ignition) as a function of the central temperature of the plasma ions.

The progress obtained with JET and other large devices is clearly illustrated in figure 4, compiling values for the Lawson parameter $n\tau_E$ and the power amplification Q for fusion reactions in pure deuterium and D-T plasmas. Comparing the results from early experiments such as the T3 and ATC tokamak (left bottom corner) with those obtained in the large devices operating with tritium (TFTR and JET) close to breakeven, shows that progress against the Lawson parameter has been of 3 orders of magnitude since the early 1970s, culminating in the demonstration of significant power production from D-T fusion reactions in 1994 in the TFTR experiment (10MW)[14] and in 1997 in JET (16MW)[26], as illustrated in Figure 5.

The 10MW pulse of TFTR was heated with about 40MW of external power, corresponding to Q=0.25; in the 16MW fusion power JET experiment, 22MW of external heating power was used, leading to Q=0.7 (close to break-even).

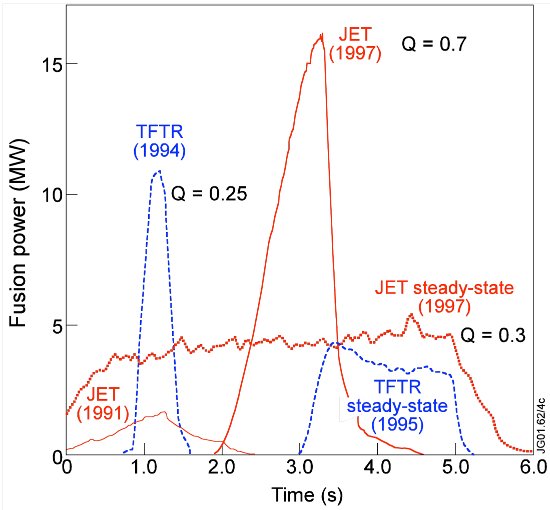

Figure 5 Fusion power as a function of time for the Deuterium-Tritium experiments carried out in JET (1991,1997) and TFTR (1994-1995).

Extrapolations of these results are difficult, due to the fact that fusion plasmas are unavoidably very turbulent. This results from the large temperature gradient which needs to be realized and maintained between the centre of the device (200 million degrees) and the wall (300-400 degrees). The turbulent processes that characterise the fusion plasma are very complex and the extrapolation of the confinement properties to future devices is done using similarity confinement studies.

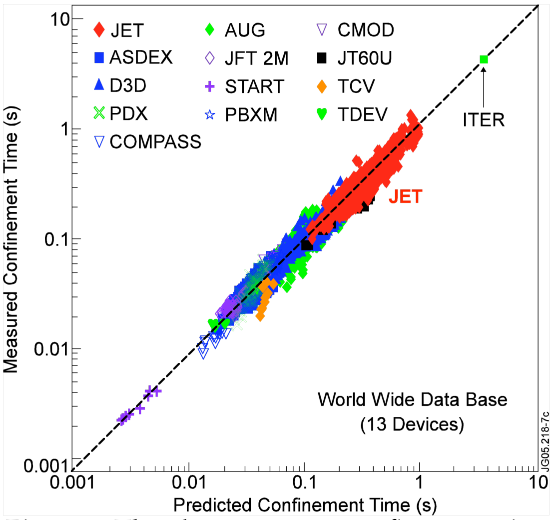

Figure 6 The plasma energy confinement time projected for ITER using the scaling from the international confinement Tokamak database.

These studies are carried out in a large number of fusion experiments with different sizes. Thereby energy confinement data are compiled as a function of the plasma parameters[27] and a non-linear fit leads to scaling laws for the energy confinement time. This allows extrapolation within statistical margins of the existing data to ITER, the next experimental step currently under preparation (figure 6).

Figure 6 shows the importance of the JET data, located at the high end of the international confinement database and closest to the confinement value projected for ITER[28]. ITER (International Thermonuclear Experimental Reactor) (figure 7), is the next step fusion device, whose construction should be conducted over the next 10 years, has the following parameters: minor radius: 2m, elongation of the plasma cross-section: 1.86, major radius: 6.2m, toroidal magnetic field: 5.3T, volume of the plasma chamber: about 800m^3, plasma current: up to 17MA, auxiliary heating power coupled to the plasma: maximum about 50MW. The device will be equipped with superconducting coils, linear dimensions about twice those of JET, and designed to produce at least 500MW of fusion power, equivalent to a power amplification factor Q of 10.

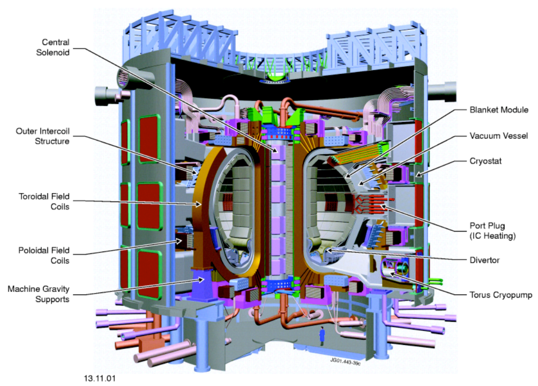

Figure 7 Current ITER design showing the main components.

Beyond the realisation of Q>10, its principal aims are to test essential technologies in reactor relevant conditions and demonstrate safety and environmental acceptability of fusion as an energy source. ITER will be built on the site of Cadarache (France) in an international collaboration between Europe, the Russian Federation, China, Japan, South Corea and the USA, with possible contributions from other countries.

4. CONTRIBUTIONS FROM JET TO PLASMA SCIENCE AND ITER.

A. Burning plasma physics

One of the key areas of controlled fusion research is the ability to sustain the plasma burn by the heat released by the alpha particles. These studies will be made possible by the size of ITER and the consequent large confinement time. In ITER fusion reactions will take place at a sufficient rate to allow with the plasma to be dominantly heated by alpha particles. While in the most performing D-T fusion plasmas in JET, the alpha heating power fraction reached about 10% of the total heating power, in ITER this will be about 70% in plasmas with Q=10 fusion power amplification (figure 8)[29]. ITER will therefore be the first experiment to explore this burning plasma state.

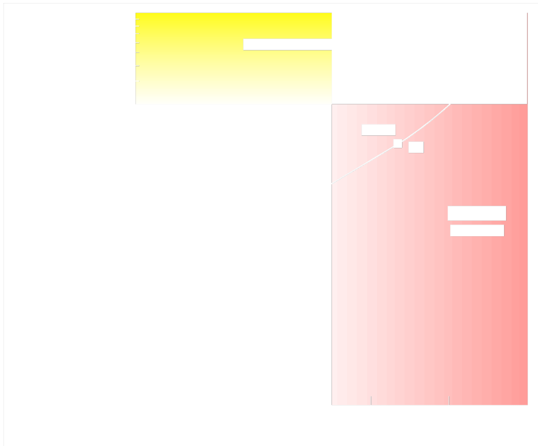

Figure 8 shows the ITER operation point aiming at a power amplification Q >10; corresponding to a fraction of plasma self-heating by fusion born alpha-particles larger than 0.66. This will represent a significant qualitative step, when compared with present machines operating space such as JET.

The first direct evidence of plasma heating by alpha particles has been obtained on JET D-T plasmas in 1997.

Figure 9 shows a pulse with a 5s phase of ~5MW continuous fusion power production from D-T reactions, with a record[12] fusion energy of 22MJ.

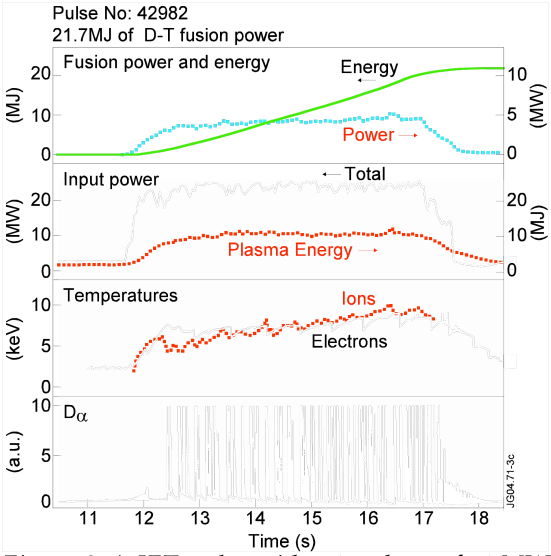

Figure 9 A JET pulse with a 5s phase of ~5MW continuous fusion power production from D-T fusion reactions, with a record fusion energy of 22MJ, showing the fusion power, input power, election and ions temperatures.

Figure 10 shows a clear demonstration of plasma heating from alpha particles from the fusion reaction. The electron plasma temperature is plotted as a function of the alpha heating power, generated in plasmas with various D-T fuel plasma mixtures. The highest electron temperature under these conditions is obtained with a near optimum D-T fuel mixture (between 40/60 and 50/50 D/T), demonstrating efficient plasma heating from the fusion alphas[30].

More recently, in 2003 and 2004 the first direct measurements of the presence of fast alpha particles in the plasma was shown, using gamma-rays spectroscopy[31].

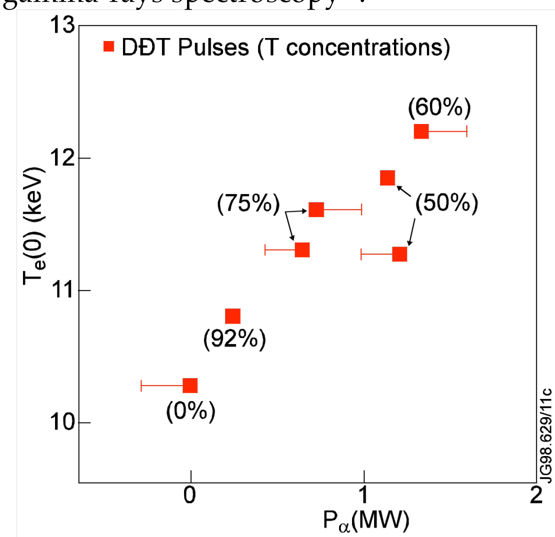

Figure 10 shows the electron plasma temperature as a function of different levels of Alpha particle power, generated in similar plasma conditions by different D-T fuel plasma mixtures, demonstrating efficient plasma heating from the fusion Alphas.

Gamma rays from a nuclear reaction between fast alpha particles and Beryllium impurities in JET are detected along a set of vertical and horizontal lines of sight. Using tomographic techniques a 2D representation of the alpha particle distribution was then obtained using both the vertical and horizontal gamma-ray cameras installed at JET as can be seen in figure 11.

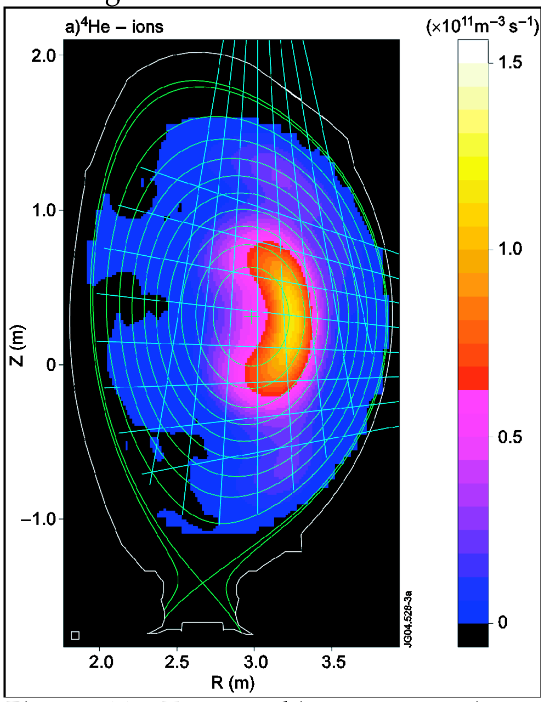

Figure 11: Tomographic reconstruction of 4.44MeV γ-ray emission from the reaction $^{9}Be(\alpha,n,\gamma)$ ^{12}C showing the distribution of alpha particles in a JET plasma

B. Preparing ITER auxiliaries at JET.

Due to its size and the capability of handling Beryllium and Tritium, JET is the ideally suited to test and develop some of the ITER auxiliaries. In particular, two important areas of research are being investigated at JET, the coupling of radio frequency (RF) waves to the plasma for heating, migration of materials in the main chamber and tritium retention. A number of enhancements to the JET machine are being or will installed for this proposed.

In particular, in the main operational scenario for ITER, conditions in the edge of the plasmas can show rapid variations in density on a timescale of a few microseconds. Conventional antennas used for heating via radio frequency (RF) waves have difficulties to cope with such conditions, and deliver only a fraction of the power from the generator to the plasma. A new design has been tested successfully (figure 12) on JET at low power, and currently an ITER like high power prototype antenna is in construction, designed to deliver 7.2MW and intended for operation from 2006 onwards.

Another upgrade planned for JET consists in replacing the current Carbon first wall by an all metal wall consisting of Beryllium in the main chamber and Tungsten in the divertor, as proposed for ITER. This new material will induce differences in the way JET is operated, and the lessons learned will lead to an accelerated use of ITER.

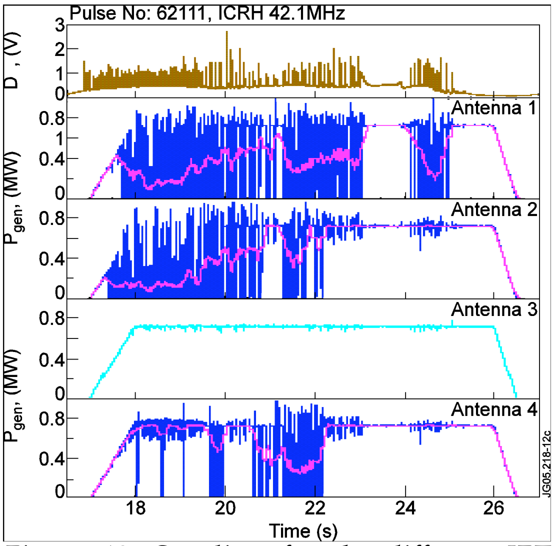

Figure 12 Coupling for the different JET ICRH antennas showing the excellent power coupling properties of the new ITER-like design in Antenna 3.

5. ON THE WAY TO ITER AND A FUSION POWER PLANT.

A. Construction and Operation of ITER

Following the design phase, which included the successful testing of the main components prototypes, ITER is ready to be built. In particular, the mock-ups of the main components of ITER, central solenoid, super conducting magnets, remote handling and heat load bearing divertor modules have been constructed and tested to and beyond the required specifications. ITER large super-conducting magnets prototypes[32] have been constructed and successfully tested using both Nb_3Sn and NbTi coils. The ITER Central Solenoid Demo Coil set a new super conducting magnet world record in terms of combined magnetic field and operating current[33]. The ITER Vertical Target Medium-Scale Prototype[34] was constructed and tested successfully with the Tungsten macrobrush demonstrated at 15 MW/m^2 x 1000 cycles and CFC monoblock tested at 20 MW/m^2 x 2000 cycles. An ITER remote handling test facility was constructed in Italy, which includes the central cassette carrier, divertor port, dummy cassette and plug handling vehicle.

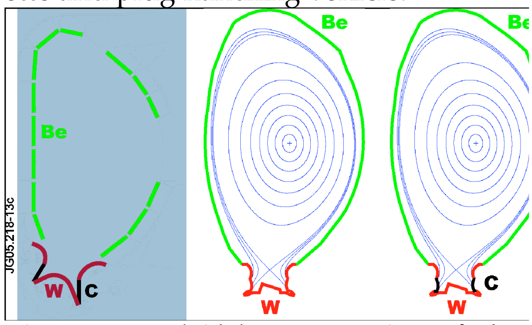

Figure 13 Poloidal cross section of the ITER (a) and JET (b,c) vessels showing possible choices of wall materials for ITER and future JET experiments, including Carbon (C), Tungsten (W) and Beryllium (Be).

B. Material development and testing

The tokamak fusion reactor will require radiation shielding since it has a radioactive inventory consisting of tritium and reactor materials activated by the fusion reaction neutrons. However, tritium has a very short half life of about 12 years, and is consumed in the reaction. In addition, studies[37] indicate that the induced radioactivity can be reduced so that recycling could become possible after some decades to a century provided that an adequate choice of the reactor structure materials is made. For this purpose, it has been proposed to build the International Fusion Material Irradiation Facility (IFMIF)[35] jointly planned by Japan, the European Union, the United States and the Russian Federation under the direction of the IEA (International Energy Agency).

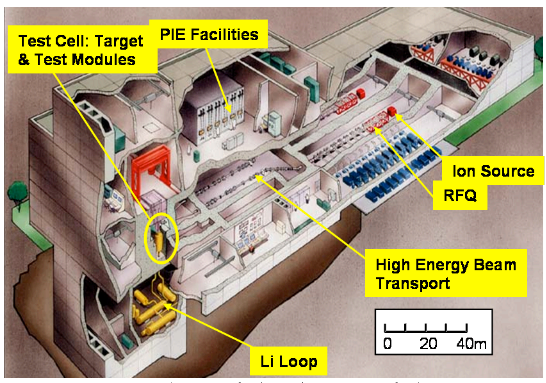

Figure 14 outline of the design of the proposed International Fusion Material Irradiation Facility (IFMIF)

IFMIF is an accelerator-based deuteron-lithium (d-Li) neutron source for producing an intense beam of high energy neutrons with the same spectrum as fusion neutrons. The main objective of this facility is to enable realistic testing of candidate materials and components to be used in fusion reactors up to full lifetime of their anticipated use. This will require a sufficiently large irradiation volume >0.5 L at equivalent fusion reactor irradiation conditions (10^{14} neutrons/(s cm^2)).

IFMIF will be composed by two deuteron beam produced by 175 MHz accelerators, with 125 mA and 40 MeV each. Acceleration is achieved by Radio Frequency Quadrupoles (RFQ) and Drift Tube Linacs (DTL). The research and development carried out by ITER, IFMIF and other complementary devices will lead to demonstration fusion reactors and power plant prototypes[36].

C. Power plant

The layout of a conceptual fusion power plant is similar to other conventional plants such as oil, coal or nuclear power plants, but with different fuel and furnace. The heat exchanger, steam generator, turbines and electricity generator are similar to those used in conventional plants. Similar plant auxiliaries such as water cooling systems will be used in fusion power plants. Therefore, fusion plants are expected to be similar in size to conventional power plants. The main difference is the replacement of the heat source: heat is generated by a fusion device such as the tokamak instead of a furnace for conventional fuels.

6. ENVIRONMENTAL, SAFETY AND ECONOMICAL ASPECTS OF FUSION POWER.

The main advantages of fusion power are the near inexhaustibility of the primary fuels (D and Li), the minimal amount of radioactivity generated and its safety aspects. The primary fuels and the direct end product (He) are not radioactive, do not pollute the atmosphere, and do not contribute to the greenhouse effect or the destruction of the ozone layer.

The fusion reaction can only continue with a continuous supply of D and T gas, and the amount of fuel available at each instant in the reactor volume only allows operation for a few seconds. Second, fusion reactions take place at extremely high temperatures and the fusion process is not based on a neutron multiplication reaction. With any malfunction of the operating system or incorrect handling the reactions will stop. An uncontrolled burn (nuclear runaway) of the fusion fuel is therefore excluded on physical grounds. Even in case of a total loss of active cooling, the low residual heating excludes melting of the reactor structure.

The total tritium inventory in the fusion power plant (internally closed) will be on the order of a few kg, of which only a 100g could be released in an accident. Special permeation barriers will have to be used to inhibit discharge into the environment of tritium diffusing through materials at high temperature. Studies indicate that even in the event of a major accident (direct exposure of the tritium available in the reactor to the air), the additional radioactivity at a radius of about 1 km around the reactor would be on the level of the natural background. As tritium is chemically equivalent to hydrogen, it can replace normal hydrogen in water and hydrocarbons. It could thus contaminate the food chain when released in the atmosphere. The absorption of tritium contaminated food and water by living organisms is a potential hazard. However, possible damage is reduced owing to the short biological half-life of tritium in the body of about 10 days.

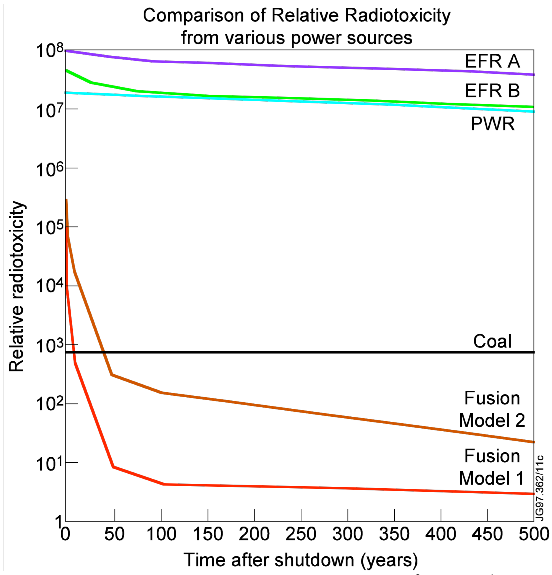

Figure 15 Comparison of relative radioactivity of materials from various power sources, including fission plants (European Fast Fission Reactor studies EFR A, EFR B, Pressurised Water Fission Reactor PWR), fusion and coal.

It is obviously difficult to estimate with any useful precision the cost of a system which will only be put into service several decades from now. In comparison with other energy sources, environmental and safety-related advantages and the virtual inexhaustibility of the fuel sources should be taken into account, as well as the evolution of the cost of electricity based on the present (exhaustible) resources. Recent studies, embodying many uncertainties, produce cost estimates, which are close to those of present power plants. Investment costs (reactor chamber, blanket, magnets, percentage of recirculating power) will probably be higher, but the fuel is cheap and abundant. Fusion is likely to be a centralised energy source. On the basis of present knowledge, technologically sophisticated power plants will probably have an electrical output larger than 1GW to be economic.

7. SUMMARY

Only a few options exist for large scale energy production in the second half of the 21st century: nuclear fission, fossil fuels (oil, gas, coal) and renewable energy sources (solar, wind). Use of fossil fuels poses a serious risk to the global environment due to the large quantities of greenhouse gases released in the atmosphere. With fission, care has to be taken regarding the long term waste. Renewable energies alone cannot provide a solution for the global energy problem due to the low energy density and intermittent availability. For the future a rational balance between all these options will have to be made, and new options need to be explored. A successful development of Fusion energy would provide a safe means for base load electricity production, with limited radioactive waste and no atmospheric pollution. Significant progress has been made regarding fusion energy research and 22 MJ of fusion energy with 5 MW of steady state fusion power (16 MW Fusion peak power) was achieved in JET duterium-tritium experiments in 1997. The next step fusion device, ITER would provide access to plasmas with adequate self heating (with a fraction of power delivered by alpha particles from the fusion reaction to be over 70%) and test essential technologies in reactor-relevant conditions. The main ITER components have been successfully tested such as the super-conducting magnets, heat load bearing divertor modules and remote handling test facility and ITER is ready to be built. In parallel, the IFMIF neutron source for producing an intense beam of high energy neutrons would enable realistic testing of candidate materials and components to be used in fusion reactors. The research and development carried out by ITER, IFMIF and other complementary devices will lead to demonstration fusion reactors and power plant prototypes.

The main advantage of fusion power lies in the energy available in relatively small amounts of fuel. One hundred milligram of Deuterium, reacting with the in situ produced Tritium can yield the same amount of energy as obtained by burning one ton of gasoline. The other main advantage of fusion energy is the radioactive impact, which is much smaller than conventional fission plants and is associated only with plant activation. In the long term the activation resulting from the operation of a fusion plant can be compared with the activation associated with coal power plants. On the other hand, controlled fusion conditions are very difficult to achieve. Fusion reactions occur only at very large temperatures, which require very complex and relatively expensive devices. These two leading factors will be ultimately reflected in the final price of the electricity produced using fusion power plants. Since, the fuel price is small, most of the cost is associated with plant construction, maintenance and decommissioning. Recent studies, suggest that the expected cost of fusion energy[38] will be comparable to that of conventional sources.

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