50 YEARS OF CONTROLLED NUCLEAR FUSION IN THE EUROPEAN UNION

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Rather soon after nuclear fission was discovered in 1938 – when its peaceful application as a terrestrial energy resource became recognized – a world-wide dynamic development was set in motion after World War II for its exploitation, with the result that the principal objectives of fission technology were achieved astoundingly quickly. A characteristic feature of this process was the first Conference on the Peaceful Uses of Atomic Energy held in Geneva in 1955, where information on such fission technology became declassified and was exchanged on a world-wide scale. Another feature of this development, in 1957, was the foundation of the International Atomic Energy Agency IAEA with their headquarters in Vienna, which from its very beginning also became a strong supporter of fusion R&D.

Stimulated by these early successes and their spirit of optimism, first concepts for the peaceful use of fusion energy likewise emerged well over fifty years ago, though also classified in their early stages (but fully declassified in 1957 when it became clear that they had no military implications). While at that time some countries already had fusion weapons technology (the hydrogen bomb), the move towards the peaceful use of fusion energy with their huge fuel resources and promising features appeared very attractive and challenging, though extremely difficult and protracted.

Two statements from that period make this particularly clear and typify the tension recognized early on between high expectations and the most intractable physical and technical difficulties. The first is from H. J. Bhabha in his opening speech to the first Conference on the Peaceful Uses of Atomic Energy held in Geneva in 1955: *"I venture to predict that a method will be found for liberating fusion energy in a controlled manner within the next two decades."* Conversely, in the first general article on the fusion issue published 1956 by a scientist from the USA[1], R.F. Post wrote: *"However, the technical problems to be solved seem great indeed. When made aware of these, some physicists would not hesitate to pronounce the problem impossible of solution".*

Despite the latter statement, but well aware of it, a world-wide R&D campaign was initiated with the aim of exploring and developing possible concepts which eventually might lead to a machine (reactor) delivering useful energy from controlled fusion processes. Results from these early years of fusion R&D were reported, among others, at the second Conference on the Peaceful Uses of Atomic Energy held in Geneva in 1958.

In retrospect it is surprising – and this has to be acknowledged – that the basics of those concepts, which nowadays are considered to be the most successful and promising, had already been published at that time, albeit of course without all the plasma physics knowledge, techniques and insights needed for test and proper scale demonstration.

The aim of controlled fusion is presently to build a reactor in which the fusion reaction is the least difficult one to accomplish on earth: ${}^{2}_{1}D+{}^{3}_{1}T\rightarrow{}^{4}_{2}He(3.6MeV)+{}^{1}_{0}n(14MeV)$ in a plasma at a temperature of ~ 150 million K. Initially, however, due to their attractive features concerning neutrons and fuel breeding, the $D+D$, and over some period even the $D+{}^{3}He$ reactions were considered.

From 1958 until 1980

After the Treaty establishing the European Coal and Steel Community (ECSC - 1951), the Treaty of Rome (1957) established both the Common Market (the European Economic Community - EEC) and the European Atomic Energy Community (EURATOM) of which the development of controlled nuclear fusion has become a major component.

How did this evolve? The Directorate for Fusion in the European Commission was established in 1958 in the wake of the 1958 Geneva conference. The first association between the Euratom Commission and an EU Member State was established in 1959 with the French CEA, soon to be followed by associations with the Italian ENEA, the German laboratories of the Max Planck Institute for Plasma Physics in Garching (Munich) and the Institute for Plasma Physics of the KFA (now FZJ) in

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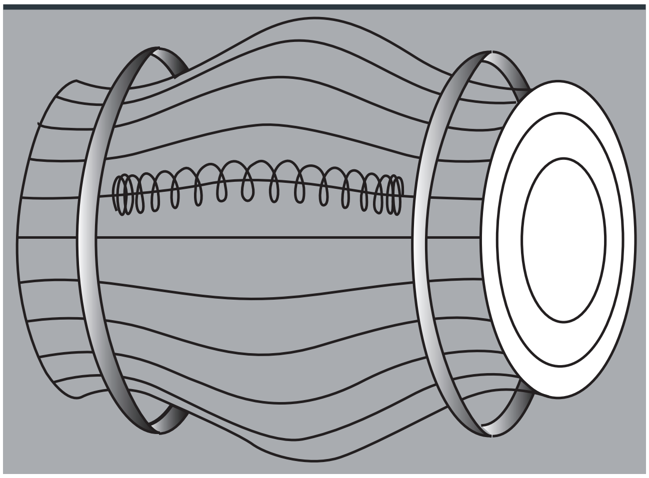
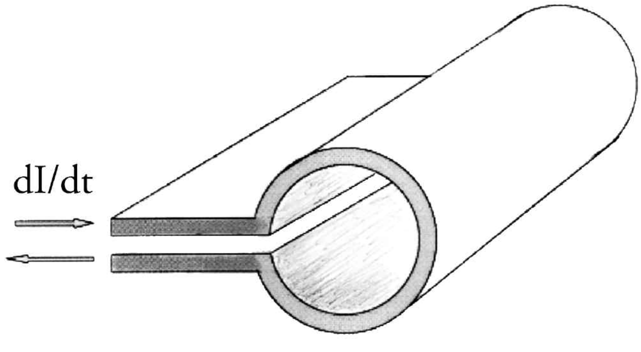
▼ **FIG. 1:** The plasma is trapped between the magnetic mirrors created by a set of two Helmholtz coils. Since the magnetic moment $^{1}/_{2}mv_{\perp}^{2}/B$ is an adiabatic constant of motion of each charged particle together with the constant sum $^{1}/_{2}mv^{2}$ of the parallel $^{1}/_{2}mv_{//}^{2}$ and perpendicular $^{1}/_{2}mv_{\perp}^{2}$ kinetic energies, it is clear that particles having at the central plane O, $v_{0\perp}^{2}/v_{0}^{2}-v_{0\perp}^{2} < B_{min}/B_{max}$ will escape with a non-zero $^{1}/_{2}mv_{//}^{2}$ through the bottleneck of the magnetic field. The remaining trapped particles are characterised by an asymmetric velocity distribution.





▲ **FIG. 2:** **Scheme of a linear theta-pinch coil. A fast inductance one-loop coil is used for creating a fast (µ sec) rising strong magnetic field – maintained at peak value – to compress, heat and transiently confine a hot and dense plasma, whose pressure approaches the pressure of the magnetic field.**

••• Jülich, and the Dutch FOM. The Belgian State founded a Euratom association in 1968. The 1970s witnessed the further birth of new associations in the UK and, through special treaties with the EU, in Switzerland and in Sweden. 1972 saw the beginning of the planning of the at present still largest machine in the world, namely the Joint European Torus (JET), as a Joint Undertaking of all Euratom countries, with construction decided in 1977. Since then, together with the gradual extension of the EU, many other Euratom associations were formed and in 2007 we have 26.

While describing the EU fusion situation, we must of course stress that the progress in fusion research occurred on a worldwide scale. Initially, cooperation and exchange of personnel between the individual European laboratories and both the leading US laboratories and the UKAEA Culham laboratory prevailed because of the advanced status of the latter. The role of Europe has become increasingly prominent over the decades and this has finally led to the forthcoming international research fusion reactor ITER being built in Europe (Cadarache, France).

What was the picture of world-controlled fusion research at the inception of the Euratom programme? The initial excitement caused by the Geneva conference and by the premature announcement in 1959 of the production of thermonuclear neutrons on ZETA (UK) gave way gradually to more sober views as was already apparent in the Salzburg IAEA Conference in 1961. The world-wide research remained in a broad exploratory phase in the 1960s. While originally colliding beams, beam-target reactions and even the acceleration of micro-pellets had also been considered, and while the concepts of inertial fusion were mostly not yet considered promising because of missing driver technologies, it had soon become clear that only the use of magnetic fields and of suitable magnetic field configurations could solve the task of sufficiently confining the required hot plasmas. Thus the main emphasis was on trying to understand the physics of magnetic mirrors, pinches of several kinds and of different toroidal configurations.

Let us briefly characterise a magnetic mirror machine, one version of pinches, a tokamak and a stellarator. In each device the hot electrons and ions are confined in a magnetic configuration with a characteristic confinement time τ_E for the energy.

1. A simple linear device is the magnetic mirror (Fig. 1).
2. The Theta pinch (Fig. 2), for which a huge, low inductance capacitor bank is discharged within microseconds into a broad one-loop coil and short-circuited *(crow-bar)* at peak-current.

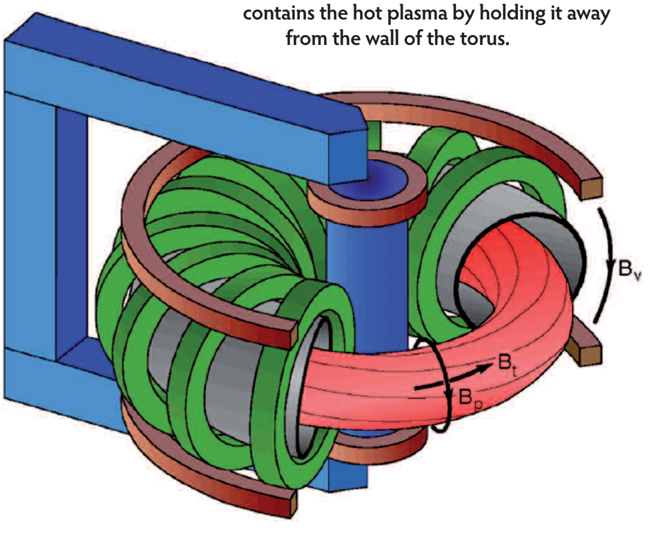
There are two main toroidal devices:

3. The tokamak (Fig. 3) in which the toroidal magnetic field is created by outer magnetic coils while the poloidal magnetic field is created by an induced toroidal current in the plasma, which has a very high conductivity. A key feature is its basic toroidal symmetry.
4. The stellarator (Fig. 4) does not depend on an induced toroidal plasma current. Both the toroidal and poloidal magnetic fields are created by appropriately shaped external coils. This means, however, that toroidal symmetry cannot be maintained.

Let us first address pinches. Due to their straightforward technology, a large part of the worldwide effort of that time was devoted to the study of pinches of several kinds (including plasma focus machines as a special type). Energy stored in capacitor banks (up to the MJ-scale!) was released and focused into a relatively small volume via collectors to build up high magnetic fields in a time scale smaller than microseconds; hot and dense plasmas were created by shock-heating and magnetic compression. While most pinch-types suffered strongly from hydro-magnetic instabilities, the so-called Theta-Pinch turned out to be the least vulnerable in that respect: at the end of the 1960s, very high temperatures had been reached. Despite their success in creating and studying hot plasmas, heat conduction to and outflow through the ends provided, however, no chance to even slightly come close to the desired plasma confinement time.

Also the attempts to avoid the ends and develop toroidal concepts based on pinch-type discharges were not successful and abandoned during the 1970s, though one principle provided an

▼ **FIG. 3:** **Schematic diagram of a tokamak. An axial toroidal magnetic field B_t is created by the green coils. The primary of the large transformer induces an axial toroidal current in the plasma acting as the secondary of the transformer. This plasma current creates a poloidal magnetic field B_p perpendicular to it. The combination of the axial toroidal and poloidal magnetic fields is a helical toroidal field which contains the hot plasma by holding it away from the wall of the torus.**



essential element for the present advanced Stellarator configuration. Only one special branch of this family, the so-called Reversed Field Pinch (RFP), evolving from a quiescent plasma phase of the abovementioned ZETA-experiment, appeared promising enough to be still studied today.

How did the mirrors fare? The basic magneto-hydrodynamic instability of the early devices was overcome by abandoning the rotational symmetry. Although very high temperatures have been reached, their main problem is the end-losses, because Coulomb-collisions and other processes destroy the required anisotropy of the ion-population. Despite worldwide efforts to invent ever more sophisticated types of end-plugs, this approach was considered, in the EU, as not promising enough and dropped around the mid 70s.

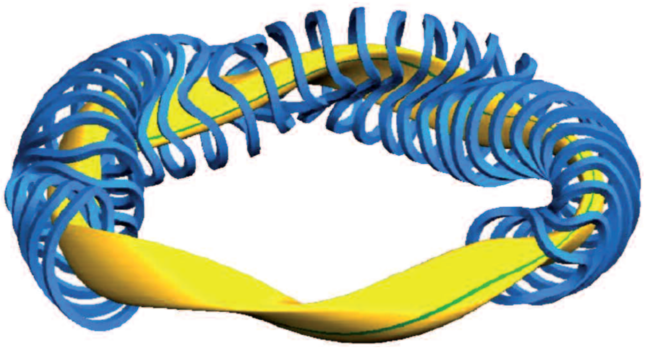
Apart from many insights into the behaviour of relevant high-temperature plasma physics and apart from the development of magnet technology, the above work is an important part of the necessary and continuing learning process on the way to an extremely demanding goal.

Let us now address the fate of the remaining two toroidal concepts. Until 1965, with the Princeton C-Stellarator being the flag-ship, the observed energy and particle confinement were Bohm-like [2]. It was during the 1965 Culham conference that the first results indicating energy confinement times τ_E better than Bohm were reported in some machines but they were met with considerable scepticism.

It was therefore a big surprise when at the 1968 Novosibirsk conference the Kurchatov team of the tokamak T3 reported an energy confinement time τ_E greater by a factor of 50 than that resulting from Bohm-diffusion and an electron temperature T_e of 1000 eV [3]. Artsimovitch, proposed an empirical scaling law $\tau_E \propto na^2T^{3/2}$ indicating that it was not Bohm-like at all. Some other machines also reported a better than Bohm behaviour. In 1969 the Thomson scattering measurements of T_e on T3 by the Culham team lifted the remaining doubts concerning the achieved electron temperature and, together with Artsimovitch's visit to Western Europe and the USA, led to a reassessment of toroidal confinement in the western world.

The ensuing reappraisal took a couple of years; fusion research then became gradually centred on tokamaks (immediately 3 medium-sized ones in Germany, France and Italy and about 100 machines of different sizes were built in the world over three decades). Record temperatures were obtained in the mid-1970s on the French TFR. The Stellarator activity continued on a smaller scale as a generic line on a few machines in Garching, Culham, Japan, USSR and Madison and is now undergoing, since the 90s, a revival linked to significant conceptual progress.

The 1960s and 1970s saw considerable progress in fusion theory (the Pfirsch-Schlüter diffusion, neoclassical theory, magneto-hydrodynamic phenomena – MHD, *etc.*) but, as we know today, the basically anomalous transport – though lower than the originally reported Bohm-level – has not yet been satisfactorily explained, though it is mainly attributed to turbulent processes. It has to be accepted that transport in a fluid as complex as a strongly turbulent magnetized plasma with its long-range electric and magnetic forces is not yet completely understood after decades of intense research. Though the theoretical description of fusion plasma turbulence has made tremendous progress, it has so far been unable to quantitatively predict the performances of fusion plasma machines on general grounds. Thus one has to rely on increasingly more sophisticated and experimentally underpinned empirical scaling laws, and on specialized theoretical and empirical models in order to extrapolate towards the performances of new and larger machines.



▲ FIG. 4: Schematic representation of the plasma and of the outer magnetic coils of the stellarator W7-X being built at the Greifswald site of the Max Planck Institute for Plasma Physics.

As soon as the first confirmations of the promise of tokamaks were being obtained on western tokamaks, further proposals emerged and decisions to accelerate the development were taken. More importantly, the fusion-community felt that time had come to take more daring steps: decisions were taken to build 3 very large tokamaks (TFTR, Princeton 1974; JET, Culham-Oxford 1977; JT60, Tokai 1977). These devices were commissioned in 1982, 1983 and 1985, respectively. When TFTR was closed in 1997, D-III-D in San Diego became the USA's largest tokamak. The EU machine JET (the Joint European Torus, Fig. 5) was built as a Euratom Joint Undertaking, which brought together all the European Associations including the Swiss one. The aim was to approach the $Q = P_{fusion}/P_{heating} = 1$ landmark, *i.e.* a breakeven between the produced fusion power and the invested heating power of a D-T plasma. This is generally considered as a benchmark for the scientific feasibility of controlled magnetic fusion. JET is the largest in the world, and the first machine with a D-shaped cross-section and a flexibility which has enabled a set of significant up grades. It has brought and is still bringing a wealth of important results which were essential for the design of ITER and its future operation. Among these can be highlighted the first controlled D-T production of fusion energy in 1991 and in 1997 of 16 MW corresponding to a Q near to 1.

The fact that the European planning of JET had started in the early 1970s is a proof of the strong ties which have been established between the different national Euratom Associations. These resulted from both the creative and coordinated efforts – in a spirit of competition and cooperation – of a large community of researchers and the enlightened leadership from 1958 until 1986 of the then EU director of Fusion, Prof. Donato •••

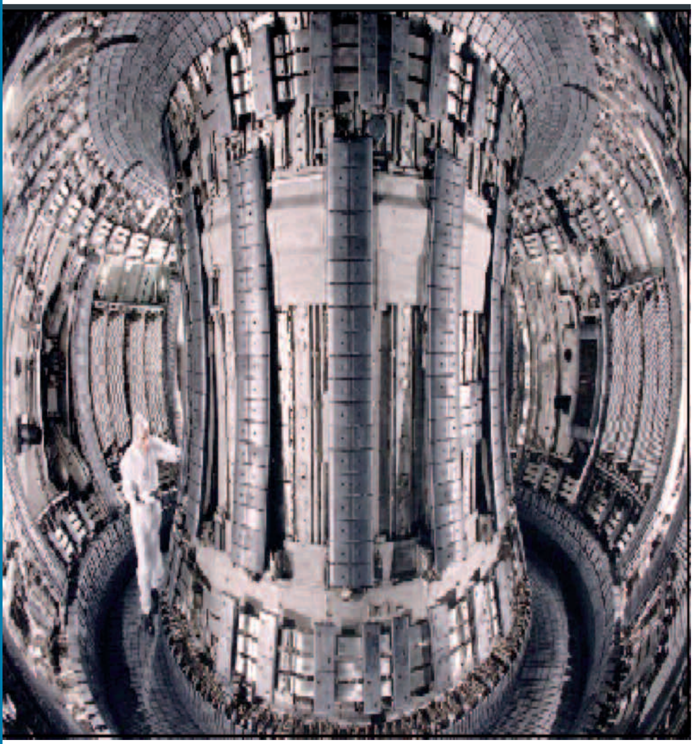
··· Palumbo, the father figure of European fusion. The strength of EU fusion, already apparent in the 1970s, is thus the result of the fact that it formed a coherent European research programme with a long-term strategy relying on the steady national and EU financing embodied in successive four or five years programmes. Up to 2007, the EU provided about 40% of the financial resources (the balance coming from national contributions). The long term strategy leading to the demonstration prototype fusion reactor is summarized in Fig. 6.

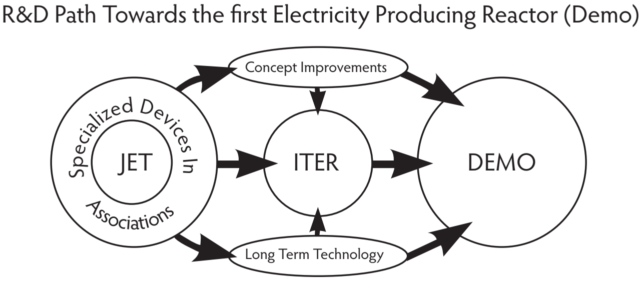
From 1980 onwards

Up to the end of the seventies the tokamak plasma was solely heated by the Ohm resistance of the plasma current. However this only brings the temperature up to 20 to 30 million K because the resistivity of the plasma decreases when T increases and the hope to boost Ohmic-heating by using high-field tokamaks has led to disappointment.

This is why strong “additional” or “auxiliary” heating in the MW range became required. Several methods exist: (i) Neutral beam heating in which ions accelerated up to ~ 140 keV are neutralized before entering the machine where the neutral atoms collide with the plasma, are ionised and impart their energy to the ions and electrons; (ii) Radio-frequency heating at approximately the characteristic ion cyclotron frequency (ICR) or at the electron cyclotron frequency (ECR), or at the hybrid electron-ion frequency (LH). Many European laboratories are among those that developed these demanding and very sophisticated methods for heating hot non-uniform magnetised plasmas. From the end of the 1970s onwards, these auxiliary heating methods were progressively applied and are still being considerably improved.

▼ **FIG. 5:** **The Joint European Torus (JET)**





R&D Path Towards the first Electricity Producing Reactor (Demo)

▲ **FIG. 6:** **Schematic representation of the scientific strategy of the controlled fusion programme of the European Union in going from the present situation to the demonstration reactor.**

However, in 1980, a degradation of confinement was observed with increasing heating power and resulted again in serious disappointment. Instead of the encouraging simple scaling law $\tau_E \propto na^2$ valid for ohmically heated plasmas – up to a certain range of $\overline{n}$ (where $\overline{n}$ is the average density and a is the minor radius of the plasma torus) – much more sophisticated scaling laws have now emerged encompassing large data bases (with very different machine sizes, magnetic fields, currents, heating powers, temperatures, etc.). These showed that very large-sized machines would be required to reach the burning process of a fusion plasma.

In addition to the heating and confinement issue, one well-known question was how to cope with the exhaust of power and particles and their interaction with the wall. While so far mainly metal limiters had been used for delineating the outer boundary of the plasma torus, the idea – first implemented in the C-Stellarator – of using a “magnetic divertor” for the exhaust of particles, led, among others, to the design of the Garching ASDEX (axis-symmetric-divertor) tokamak. On this machine, a new confinement regime was discovered in 1982 when the heating reached a certain threshold. This new H-mode is characterised by the establishment of a confinement barrier at the edge zone of the plasma leading to an improved confinement by about a factor two; other more inner modes have been discovered since.

The above indicates how different the physical picture of fusion had become between 1978 and 1988 when – following the preceding European studies on the “Next European Torus” (NET) – the ITER concept was launched as a result of a political initiative of Gorbachev, Mitterand and Reagan. The International Thermonuclear Experimental Reactor (ITER) is an experimental reactor aimed at demonstrating the feasibility of fusion power. It is designed up to its detailed engineering phase (including prototypes of its main components) and its building preparation phase has started in Europe (Cadarache, France) in 2006. A more in depth analysis of ITER is given below. The impressive progress of tokamaks performance is shown (Fig. 7) where the figure of merit $nT\tau_E$ (n: density, T: temperature) product of plasma pressure and confinement time, expressed in atm-s, is displayed as a function of T. Between 1968 and 1991, this figure of merit was increased by ~ 25 000 and is now only a factor of 6 away from that required for reactor operation. In parallel, not evident from this figure, even greater progress has been made in the achieved lifetime[4] of the plasmas. While in the early 1960s, with the pinches, the lifetime was limited to microseconds, fusion plasmas now exist for seconds to many minutes, with some parameters approaching steady state operation! Finally, we also have to underline the importance of many discoveries, findings and experiments made on smaller machines of the balanced Euratom programme, which were then successfully applied to the largest machines of the world programme. These range from important physical effects and the development of new diagnostic techniques to the appropriate treatment and material choice of the inner wall of the toroidal chamber and developments in engineering plasma physics. In particular, the huge progress in auxiliary heating and diagnostics needs to be emphasized, the latter being for measurements of ion and electron temperatures, density, impurities, fluxes, inner magnetic fields and islands, pressure, etc.

ITER

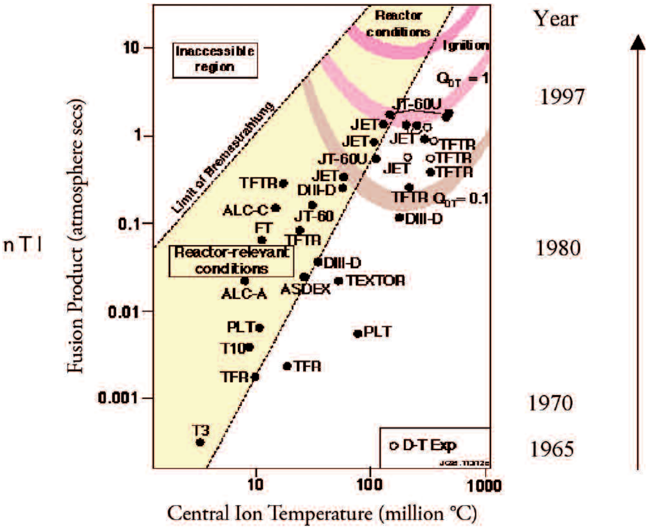
As indicated above, the EU launched in 1983 the studies of an ambitious machine, NET (Next European Torus), which led in 1988 to a possible fusion power-producing machine with dimensions, magnetic field and plasma current rather close to those of the final ITER adopted in 2001. But this remained a reserve option for Europe because the conceptual design activity (CDA) of ITER was launched in 1988 by the EU, Japan, USA and USSR. ITER initially meant the International Tokamak Experimental Reactor but now designates the “way” (to fusion) in Latin.

The CDA was completed in December 1990. The auspices of the International Atomic Energy Agency (IAEA) offered the opportunity of pooling the scientific experience and technological expertise of the world’s leading fusion programmes with the following mission for ITER:

1. demonstrate the feasibility of controlled ignition and extended burn in D-T plasmas with steady state as the ultimate goal;
2. demonstrate technologies essential to a reactor in an integrated system (superconducting magnets, remote-handling, etc.);
3. have integrated testing of high heat flux and nuclear components required to utilize fusion power for practical purposes.

The six-year long Engineering Design Activities (EDA) started in July 1992. The Parties produced a detailed, complete and fully integrated design together with all technical data necessary for the construction of a 1.5 GW ITER. The ITER Final Design Report, Cost Review and Safety Analysis were approved by the ITER Council in June 1998. Although the estimated cost for this ITER remained within the initially foreseen financial envelop, the political and financial situation led the Parties to investigate whether, with reduced technical aims and margins but keeping the same strategic aims, it was possible to bring down the cost by approximately 50 %. So, within another 3 years, a detailed engineering design of this reduced-cost ITER was produced.

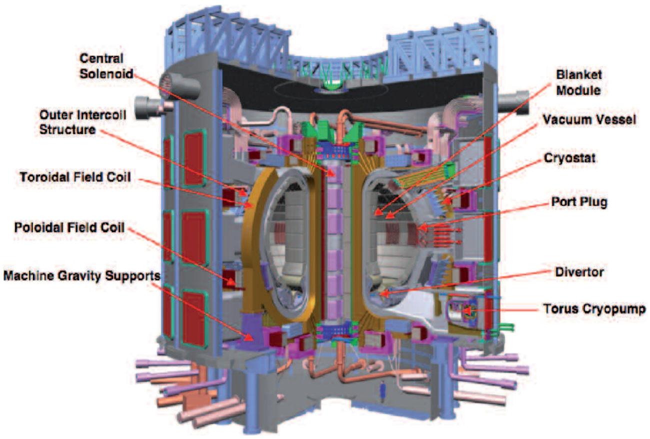
However, for the present smaller ITER the task remains to be the single step before building a demonstration fusion reactor (DEMO) producing electricity. But the decrease in neutron flux and neutron fluence leads to a reduction of the technical potential of the device (e.g. for materials and component testing). This makes it even more mandatory to start the engineering design phase of the International Fusion Materials Irradiation Facility (IFMIF) in order to have a neutron source with a suitable fusion energy spectrum and neutron flux to allow the necessary material tests.



▲ **FIG. 7:** The product $nT\tau_E$ versus temperature T (an energy of 1keV corresponds roughly to 10^7 °C) shown as a function of the time of achievement.

As the USA had temporarily withdrawn from the extended EDA in 1999, the revised Final Design Report (of the 500 MW ITER) was approved by the remaining parties in July 2001. The estimated construction cost is 4.6 G€ at December 2001 prices. The nominal design parameters are : plasma current 15 MA, major radius 6.2 m, minor radius 2.0 m, on-axis toroidal field 5.3 T, plasma elongation at the separatrix 1.85. The whole design is the result of nine years of effort, based on the scientific input from the world-wide fusion programme. The related R&D was mainly centred on seven large R&D projects addressing the key technologies needed. These are: the central solenoid model coil, the toroidal field coil, the vacuum vessel sector, the blanket module, the blanket module remote handling, the divertor cassette and the divertor remote handling. The successful completion of these key test modules gives great confidence in the success of building the whole machine. Fig. 8 displays a cutaway view of ITER.

The resulting negotiations for the building of ITER started in 2001 with Canada as a new member and addressed many aspects such as site, management structure, staff, procurement system and allocation, financial regulations, decommissioning, intellectual property rights and other aspects such as the proper management of the risks.



▲ **FIG. 8:** Cutaway of the ITER Tokamak inside the cryostat/biological shield. The dimensions of the cryostat are 24m. x 28m.

In 2003, the USA decided to rejoin the ITER process, China and South Korea to join and Canada to leave. Two sites, Rokkasho in Japan and Cadarache in Europe (France) remained as candidate sites for ITER. After an agreement between the EU and Japan on a broader approach to fusion, Cadarache was selected as the ITER site in June 2005. The broader approach agreement implies that Japan will be supported in three domains: (1) on the JT60 super upgrade tokamak, (2) in the preparatory work in Rokkasho of the IFMIF and (3) a fusion computer centre in Rokkasho.

The ITER International Fusion Energy Organisation (IIFEO) agreement (see Fig. 9) on ITER was reached in December 2005 and signed in November 2006 by the above stated parties (EU, China, Japan, Russia, South Korea and USA) plus India, the last and seventh partner; this represents more than half of mankind. The financial burden of the construction of ITER is borne by the EU at a level of 45.4 % and by each other partner at a level of 9.1 %.

The different components of ITER are distributed into ~ 85 important packages having each an agreed a priori value. Most of the contributions (~ 85 to 90 %) of the Parties will be "in-kind" and consist in delivering a certain number of these packages, the content of which having been very carefully contractually specified by the IIFEO Central Team.

The nominee Director General of ITER, Dr IKEDA (Japan) was chosen in 2006 together with the nominee Principal Deputy Director General, Dr HOLTKAMP (Germany). The appointment of the key staff and the building up of highly competent and skilled teams is underway. Before issuing the first contracts, a general review of the whole project was finalized at the end of 2007. Extending the phase of negotiations has now put the date of the first plasma around 2017, if no unexpected problems arise. The first phase of operation will be with hydrogen while the D-T operation will be launched some years later.

EU fusion has from the beginning played a major role in the ITER endeavour by providing its international director until 2004, the largest share of manpower and R&D funds, especially during the critical 1995-2001 period, and finally by shouldering nearly half of the construction cost at the European site of Cadarache. Thus one can say that ITER is for the EU a major achievement in its consistent long-term strategy (see Fig. 6) towards harnessing fusion energy as repeated in the preamble to each EU framework programme. Structure and content of the EU fusion programme are addressed in the next section.

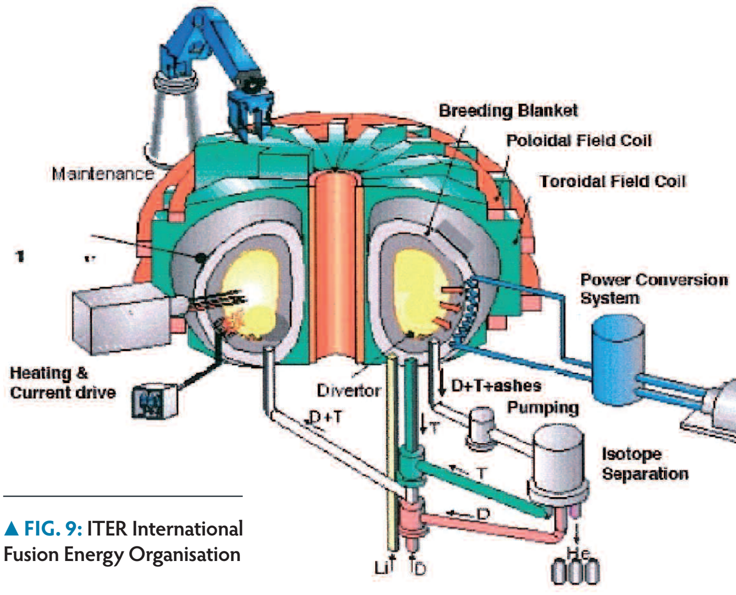
Implementation of the EU Fusion Programme

The principal mechanism used to implement the participation of member states in the European fusion programme is the "Contract of Association". Each state, or organisation within a state, concludes a contract with EURATOM, creating a "Euratom Association". This contract specifies the programme of work to be undertaken by the Association, promotes mutual access to major facilities, and provides the mechanism for funding by EURATOM. For those participants not having concluded a contract of Association, contracts of limited duration for specific purposes are installed. In addition a number of technological developments are pursued through contracts with European industry.

Some of the Associations have large-scale experimental facilities, while the smaller Associations generally have more limited facilities. The rules for awarding preferential support [5] encourage the smaller Associations to participate in the larger experiments, for example by developing, installing and exploiting auxiliary instrumentation. Collaboration is further promoted by financial support to assist the exchange of personnel. Training and mobility of young researchers is also supported by EU Fellowships.

The active collaboration between the European Commission and the Member states and Associations is ensured through the Euratom Consultative Committee for fusion and a set of relevant agreements and committees.

The total effort in the Community fusion programme is equivalent to about 2000 professionals and expenditure from all sources is about 450-500 M€ per year. Of this, about 190



▲ **FIG. 9:** ITER International Fusion Energy Organisation

M€ per year come from the EU Euratom budget (750 M€ in total over 4 years from the FP 6 budget plus a small supplement for the candidate EU States). Since the inception of FP 7 (2007-2011) and the start of the building of ITER, the EU fusion budget has risen to 1 947 M€ of which at least 900 M€ are for the Associations and JET.

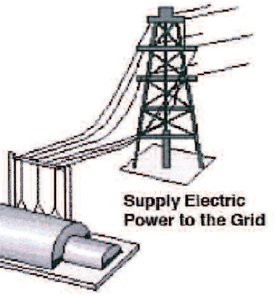
Towards fusion energy and final remarks

When in the early 1950s, the first ideas for the peaceful use of fusion energy emerged, society was already well aware of the finite nature of fossil fuel resources, and both fission and fusion development were supported in view of a future with dwindling resources. During the following decades, however, no public awareness existed yet about the greenhouse effect and its consequences on the global climate, and cheap oil – despite the first 1973 oil crisis – postponed the looming energy problem into the far future. In that situation, not only was the use of fission energy challenged (and in some countries still is) but also the continuation of the fusion programme with its very long perspective was questioned, not the least because of its so-called everlasting “50-years-horizon” as critics used to point out. Yet the stamina of the fusion community and the wise outcome of the political dispute bridged the crisis: we need to acknowledge the political support required for the decision to construct ITER.

The time has come when energy and climate are now at the top of the world political agenda. Society seems to have gained a deep-rooted understanding of the seriousness of these problems. Scenarios exist which demonstrate the huge supply gap to be expected towards the end of this century. It is obvious now that fusion energy must be developed with the necessary impact to gain its place in the world’s energy mix as soon as possible.

In Europe, the Council of Ministers has approved in 2003 the concept of a fast-track approach which envisages the start of the building of the DEMO-Proto reactor around 2025 and, extremely ambitiously, the operation of the first commercial fusion reactors around 2040-2050. Such an agenda will require much determination and effort.

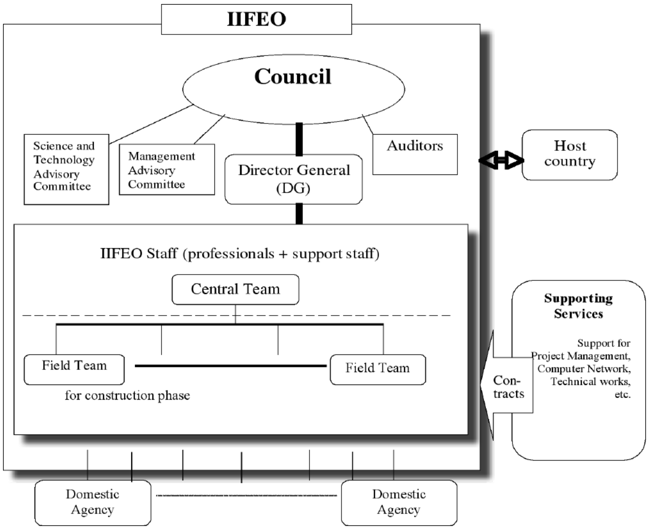
Can this ambitious time-table be achieved? To gauge its feasibility, let us look back at the history of fusion. In 1988, when ITER was launched, Europe was designing its next machine namely NET, the main parameters of which were rather close to the present ones of ITER. Had this machine been built, it would now be operating. Of course, the present ITER embodies the significant advances in physics and technological improvements made since then; it is therefore a better and more modern machine but it is clear that had we had NET, world fusion would be more advanced and we would have won years on the roadmap to fusion energy. Decision makers will therefore have to move faster and provide the necessary means if we want to achieve such a time-table.



In the domain of fusion materials and technology, the preparatory work on IFMIF has started and its construction is foreseen. The development of tritium breeding blankets is underway. Building more than one DEMO-Proto reactor would have a very beneficial influence in trying to keep such a time-table.

What about the price of such a programme? The cost of the construction of ITER is roughly 5 G€ (2001) over 10 years. Yes, this is a large sum, but remains small when compared to our energy bill: ITER is worth less than one day of the world’s present oil bill, even if – as might be foreseen – the construction of ITER would reveal unexpected difficulties and the need for more money.

Power-plant conceptual studies of a Tokamak-type fusion reactor (see fig. 10) have been completed by the European fusion programme in 2004 with a team which included economists and nuclear fission engineers. It assessed the safety and environmental impacts together with the economics of a fusion plant. It examined four models ranging from a water-cooled plant using steel (A) to a helium-cooled plant (D) using silicon carbide to allow higher coolant temperatures of up to 1000°C in order to increase the plant efficiency. The costs ranged from 0.05 to 0.09 € per kWh (depending on the maturity of the technology) for A down to 0.03 - 0.05 € for D and this without taking a carbon tax into account. To us, this appears quite acceptable even if it were underestimated. An obvious advantage of fusion is that the “external costs”, *i.e.* the impact on health, climate and environment, are essentially zero.



▲ **FIG. 10:** Sketch of a tokamak-type fusion reactor

Let us recall what Bhaba had said in 1955. He was right, because the JET design was presented less than 20 years later, and JET has demonstrated what Bhabha had foreseen. But Post was also right: while physics will also play a very important role in the future, mainly concerning the burn process and basic improvements, the main emphasis – and costs – will be gradually shifted to technology and engineering issues. And it will have taken a century from the start in fusion research until fusion electricity will be fed into the grid on a commercial basis.

Indeed, this will still be an arduous task with many uncertainties to overcome and it requires continuous political support.

Reality is also that the progress achieved in raising the fusion energy multiplication factor Q (Q = Fusion power/External heating power) — from 1/100 000 at the end of the 1960's to the present value of nearly 1 — is truly impressive (and comparable to Moore's celebrated law for the rapid progress of the number of transistors on a chip). ITER will have a Q of the order of 10 or more and thus confirm the scientific and technological feasibility of fusion. Although years would have been gained by more earlier support and less procrastination, the fusion power station is now in 2008 on the horizon.

The seriousness of the energy and climate issue requires that, within the portfolio of energy measures and solutions to be implemented, controlled nuclear fusion must have a distinct place within a proper mix of sustainable energy sources. It is the only one for which the basically inexhaustible fuel (deuterium and lithium) is evenly distributed on earth and thus able to ensure a safe, sustainable, environmentally friendly energy supply. ■

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We wish to thank Professor Fritz Wagner (Max-Planck Institute, Greifswald, Germany) for his constructive remarks and suggestions.

NOTES

1. *Rev. Mod. Phys.* **28**, 338 (1956).
2. Classical radial diffusion in magnetized (B) cylindrical plasma is characterized by the diffusion coefficient $D \propto T/B^2$ while anomalous Bohm diffusion by $D \propto T/B$, where T is the temperature. Neoclassical diffusion describes classical diffusion corrected for the global effect due to an inhomogeneous curved magnetic field. The Bohm-physics and its consequences are not mentioned.
3. 1eV corresponds to a temperature of 11 000K
4. The lifetime is the time during which a plasma is sustained.
5. The basic general support by Euratom amounted to 25% until FP6 and has now been lowered to 20%. Preferential support is an additional financing of 20% of specially approved capital costs by Euratom.