# Thermonuclear Fusion Energy : Assessment and Next Step

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**Abstract**

*Fifty years of thermonuclear fusion work with no insurmountable road blocks have allowed to continuously progress towards the fusion reactor which stays a physics and technology ambitious challenge of high level of integration. Results from studies on confinement concepts, the tokamak of which is presently the most successful, and on plasma stability and transport, power and particle exhaust, steady state contemplated for reactor operation, …, constitute a well established basis for a next step which goal is to produce and master a Reactor Relevant Burning Plasma. Such an international endeavour is well advanced through the International Thermonuclear Experimental Reactor (ITER) programme, which has defined a 400MW – 400s burning plasma facility. This € 3.5 billion project of 30 year lifetime will be negotiated between the three ITER Parties, the European Union, Japan and the Russian Federation, in order to take a construction decision around 2003. This next step will contribute both to conclude these fifty years of fusion research and above all, to open the reactor route.*

## 1. Historical aspects of magnetic fusion

After the second world war, research activities on nuclear fusion in view of energetic applications were pursued on a confidential basis by several countries. It appeared very early that the extreme conditions required for reaching appropriate fusion reaction rates made it necessary to use intense magnetic field traps to confine the hot ionised mixture of hydrogen isotopes (deuterium and tritium plasma).

Multi-Tesla range magnetic configurations were built, among which, « open traps » where the magnetic field lines enter and leave the region where the plasma lays, and « closed traps » where the plasma occupies a toroidal magnetic field geometry. In the first class of devices, so called « mirror » machines and linear « pinches » are found where confinement is limited by end losses (hot ions escape along the field lines, out of the plasma region) or fast hydrodynamic instabilities. In closed trap configurations, the magnetic field forms nested tori, where hot particles are moving along the field lines until diffusion or convection processes expel them out. In this category fall so called stellarators and tokamaks (Figure 1). In the former, the magnetic configuration is entirely produced by external conductors, whereas in the latter, an intense current, carried by the plasma along the magnetic field, creates the main poloidal component of the overall magnetic field.

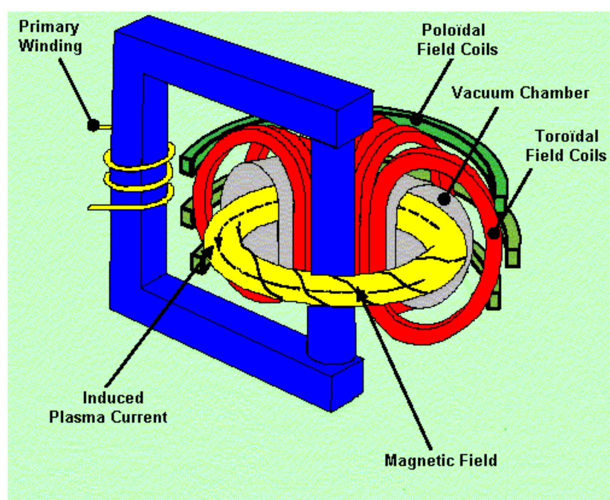



Figure 1 : Tokamak configuration

In view of the difficulty of the task, it was early decided to open broadly international collaboration on the subject and in 1957, during the cold war, the visit of Academician Igor Kurchatov at Harwell, where data on pinch experiments were exchanged, opened the way to the present international collaboration on peaceful applications of nuclear fusion. The Euratom treaty, which establishes the foundation of the European collaboration in nuclear energy research, was signed in 1959 and since that time, a wealth of European and world-wide collaboration has been growing up continuously.

A major event marked the late sixties, namely the remarkably large plasma temperature in the soviet T3 tokamak in 1965-68, which reached of order of 1keV (10 million degrees) for a duration of the order of some milliseconds, at relevant plasma densities (some $10^{19}$ particles per cubic meter).

This event was taken very seriously by the fusion community, and during the years seventies, some tens of tokamaks, of relatively small size (in or below the one cubic meter range plasma volume), were built throughout the world. In these devices, many experiments were conducted, to improve the understanding of the basic concepts. Major issues were:

- the understanding of plasma diffusion across the magnetic field, which limits the confinement time of the plasma heat and particles (and therefore fusion reactivity). It was shown that the natural diffusion due to charged particle collisions is much smaller than turbulence induced transport ;
- the development of original plasma heating methods, to reach the thermonuclear range of temperatures. High energy neutral beam injectors were developed (tens of amperes, tens to hundreds keV). Resonant plasma-wave coupling at the ion or electron gyro-motion frequency was investigated. All these methods led to efficient plasma heating, reaching in some cases the appropriate range for effective fusion burn;
- diagnostic developments to improve the experimental picture of the tokamak configuration properties, based on a broad range of original and specific methods among which : electromagnetic wave emission, transmission, reflection or diffusion, spectroscopy of multi-charged impurity ions, escaping particle detection (neutrons or atoms), magnetic measurements, etc.

Of particular importance was the observation that plasma performance (measured as the confinement time $\tau = E/P$: ratio of the plasma thermal energy $E=3nT$, i.e. density n times temperature T, to the external heating power P) improves with plasma size. A rough quadratic dependence was generally observed with large or small radius of the torus, based on analysis of the relatively narrow data base at that time. From this scaling law, the design of the Joint European Torus, JET, was undertaken by the European Union, a $100m^3$ device (large radius 3m and small radius > 1m) which started operation in 1983. More generally, the scaling law for the confinement time included dependencies with respect to plasma current $I_p$ and heating power P according to the law: $\tau \approx I_p.P^{-1/2}$. Therefore, a large elliptical plasma cross section was expected to give the best results, maximising the plasma current for a given current density.

Beside JET, other large tokamaks (some tens of $m^3$) were built in parallel : TFTR at Princeton in the USA (1982), JT60 at Naka in Japan (1985) and Tore Supra at Cadarache in France (1988). In contrast to others, the latter was designed with superconducting magnets to explore long duration discharges, and to experiment a technology required in the future for electricity production reactors. JET and TFTR have been equipped to use tritium as plasma fuel and JT60 has been redesigned in JT60-Upgrade (with a volume comparable to that of JET). Other medium size tokamaks (ASDEX in Germany, FTU in Italy, DIII-D in USA, JFT2-M in Japan,...) were and are still in activity, providing a wealth of specialised information that can be used subsequently on larger devices.

An example of the contribution of the world-wide collaboration is the most recent scaling law for energy confinement time based on the results of many machines, going from smallest to the largest which serves as a basis for extrapolating the performance of next step devices (Figure 2).

In JET, plasma parameters required for achieving deuterium-tritium fusion burn have been reached although separately and over short duration : temperatures above 10keV and densities in the range 5-10.$10^{19}m^{-3}$ corresponding to confinement times of order of some hundreds milliseconds to more than a second. In November 1997, JET produced 16MW of fusion power ($P_f$), during about a second, by using a deuterium-tritium mixture, while 23MW of input power (Pi) were used to heat up the plasma (Figure 3). For the first time in the history of magnetic fusion research, the balance of fusion to input energy was almost reached (the so-called « breakeven » : $Q=P_f/P_i=1$).

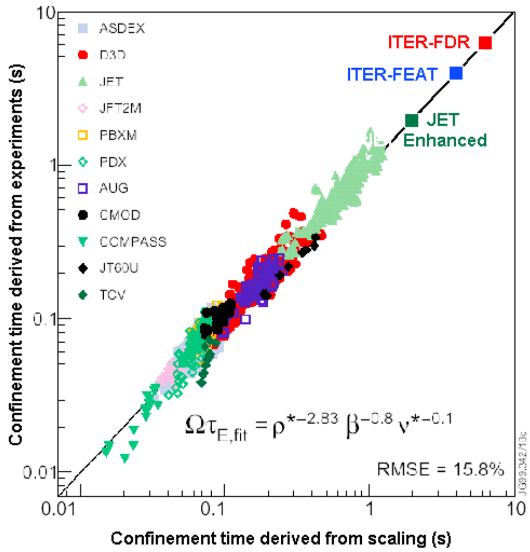



Figure 2 : Scaling law for energy confinement time

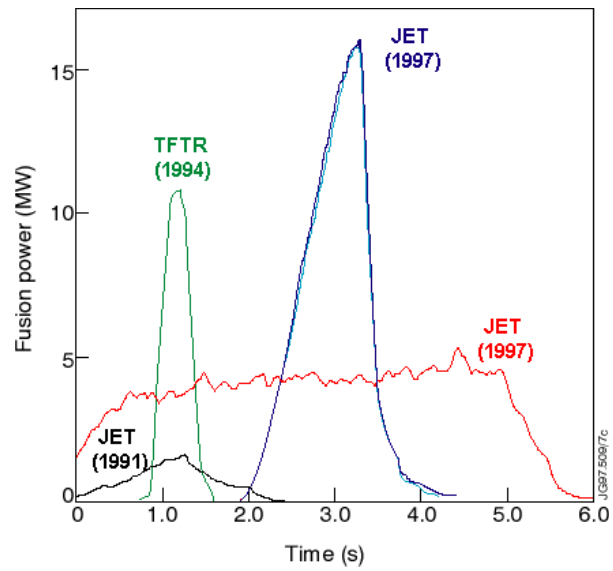



Figure 3 : JET and TFTR performance on D-T operation

## 2. Scientific and technical challenges in magnetic fusion

Considerable progress has been achieved in the understanding of underlying physics mechanisms although no complete theoretical description does exist today of thermonuclear magnetised plasmas. The perspective of building a next step fusion burner with long pulse duration has also motivated the development of technologies which will have to be available for this purpose and still need to be tested on present machines.

**2.1 Plasma transport**: core plasma temperature T and density n, and therefore fusion reactivity R, which behaves like $R \approx n^2T^2$, are determined by the balance between core plasma heating (by alpha particles in a fusion burner) and heat and particle transport across the magnetic field. The latter depends of small scale instabilities with wavelengths much smaller than the plasma radius. These instabilities are driven by free energy sources such as plasma pressure and magnetic energy.

The magnitude of the induced transport is function of the radial correlation length of the turbulence, i.e. the length over which it keeps a coherent structure. Stabilising mechanisms length of the turbulence. For example, radially sheared plasma rotation can reduce the radial correlation length, improving plasma confinement. A sheared current density profile in the plasma can also reduce the transport for similar reasons. These processes lead to confinement barrier formation inside the plasma, which have been experimentally observed.

One of the most important challenges for magnetic fusion research is to control plasma turbulence in order to optimise the size of a reactor.

**2.2 Plasma stability**: a plasma immersed in a magnetic field is subject to large scale instabilities described by magneto-hydrodynamics (MHD) theory. These instabilities can induce strong deformations of the plasma channel (so called "ideal" instabilities which occur in a perfectly conducting plasma) or a topological rearrangement of the magnetic configuration (so called resistive instabilities, because they involve finite plasma resistivity). A number of plasma parameters are limited by these instabilities.

This is the case of the plasma pressure $p \sim nT$, which can be limited by both types of instabilities. In a power plant, the thermonuclear reactivity R has to be large enough for economical reasons and plasma pressures have to be in the range of several atmospheres. This translates in terms of plasma pressure normalised to the magnetic pressure $\beta = p/(B^2/2\mu_0)$, B magnetic field, which has to be in the range of some percent. Although $\beta$ limits are usually observed, relevant values are reached in current experiments on tokamaks, stellarators or reversed field pinches (RFP).

In tokamaks, MHD induced limits are also observed on plasma current or density, triggered by ideal or resistive instabilities. When critical plasma current or density values are reached, a fast quench of the plasma thermal energy occurs (over typically a millisecond) followed by a quench of the plasma current (over typically 10 milliseconds). These two quenches produce large amounts of heat to the plasma facing components and large electromagnetic stresses on the mechanical structures. Such events, which do not exist in stellarators or RFP, will have to be properly considered in tokamak reactor design.

MHD theory and modelling have been extensively used to describe plasma behaviour in many experiments and to predict plasma stability in ITER.

**2.3 Power and particle control at the plasma boundary**: the control of intense steady state power and particle fluxes from the plasma to the wall is a major issue for magnetic fusion. In present machines, this control is achieved with a "divertor". In a divertor, the outermost field lines are spread outwards by means of appropriate windings, to channel the charged plasma particles toward plates, located further away from the plasma. In this way, the impurity source due to sputtering by plasma ions on the plates is expected to be effectively separated from the burning plasma, thus avoiding core plasma pollution.

A large fraction of the power has to be radiated in the plasma edge or within the divertor volume to minimise the fraction of this power carried by charged particles to the divertor plates. Indeed, the heat exhaust capability of the plates is limited ($<$ 5-10MW/m$^2$) and their lifetime, determined by the plates erosion induced by the impact of plasma ions, will have to be maximised.

Present experiments show that the physics in the divertor region and in the main plasma are not fully disconnected and that bulk confinement depends on the boundary conditions of the divertor. It was early shown (ASDEX) and subsequently confirmed on all divertor tokamaks, that the divertor configuration induces a confinement barrier at the plasma edge, the so-called H-mode, with improved plasma confinement. The counterpart of this favourable trend is the occurrence of periodic bursts of heat to the divertor due to a relaxation of the barrier height, connected to MHD processes.

**2.4 Long pulse requirements**: over the past twenty years, most of the tokamak experiments have been carried out over short duration (from a fraction of a second to some seconds). The main motivation was to demonstrate physics principles while minimising investment.

The only noticeable exception to this general trend is the tokamak Tore Supra at Cadarache, where some of the technologies required for long operation were included in the design from the origin : superconducting magnet (to relax the constraint of limited operation of copper magnets), actively cooled plasma facing components (to handle continuously several $MW/m^2$ of heat flux at the plasma boundary), real time feedback control of plasma parameters, actively cooled antennas for HF wave transmission to the plasma (heating), etc. In this configuration, discharge durations of two minutes could be performed where almost 300MJ of energy could be circulated in and out from the plasma (2.5MW of input power).

Future machines will have to use well developed technologies for long pulses and the physics and operational aspects related to processes taking place over long time constant will obviously come into consideration. Two examples of long time constant processes are: - the relaxation of the current profile in the plasma cross section at high temperature which may turn unstable when improperly controlled; - the interaction of the edge plasma with the wall, the latter being a reservoir of particles whose flow may be negative or positive, large or small, depending non linearly on plasma wall interaction.

**2.5 Advances towards a steady state tokamak:** during the last five to ten years, ideas have significantly evolved with regard to the concept of a steady state tokamak. In particular, it has been shown that plasma current could be self-generated effectively by the tokamak configuration itself, the so-called bootstrap current, when the plasma pressure is sufficiently large, i.e. in reactor conditions, relaxing the need for a strong steady state external source of current.

The radial distribution of this bootstrap current could also lead to good confinement conditions, provided it can be maintained stable with respect to the variety of magneto-hydrodynamic instabilities that may occur, via appropriate external current seeds. This concept of « advanced tokamak », whose features have been observed on present day machines, has to be demonstrated on long pulse devices due to the long relaxation time of the current profile.

**2.6 High magnetic field tokamak:** the use of high magnetic fields of the order of 10T increases safety margins with respect to MHD instabilities, allows to operate further away from pressure and density limits and to obtain high $nT\tau$ values with smaller plasma volumes. This approach was developed at the MIT in the seventies with the Alcator facility and pursued on Alcator C/C-Mod, and at Frascati with the FT/FTU tokamaks; high plasma density of $8.10^{20}m^{-3}$ and record value for the time being of the $n\tau$ product of $4.10^{19}m^{-3}.s$, with a temperature of about 1 keV, have been obtained in Alcator C experiments. To enlarge the tokamak basis towards high magnetic fields and to attempt to reach ignition, i.e. a state where the thermonuclear plasma is mainly maintained by its own fusion reactions, several projects are contemplated such as Ignitor and the US Fusion Ignition Research Experiment (FIRE). Ignitor, a 13T high density ($10^{21}m^{-3}$) tokamak using copper magnetic coils, was recently assessed by an international panel that I set up. Ohmically heated and using the cold radiating mantle concept to exhaust a great part of the power produced, Ignitor aims at exploring the ignition physics and to study alpha particle and burning issues.

Due to their high magnetic field and compactness, these copper devices are subjected to large mechanical stress and produce high exhaust power fluxes hardly compatible with existing materials. Reducing the field, increasing the volume and using a divertor to better appears appropriate to obtain high energy amplification factors. Such compact devices oriented towards ignition physics could be also contemplated as a useful next scientific step.

**2.7 Mastering the science and technology base :** looking back to the achievements and forward to the remaining issues, it can certainly be claimed that many of the physics problems are well in hands. This means that predictions for the performance of a next step device rely on an acceptably reliable database ensuring that the conditions for realising a stable burning plasma over a sufficiently long operation time can be met.

In such a next step device, still devoted primarily to the study of plasma physics properties, progress will be made on the understanding of alpha particles physics (confinement, stability and heating properties) as well as on burn control and steady state operation. The integration of several key technologies, directly connected to the realisation of this next step machine will also be a matter of immense progress: superconducting magnets, plasma facing components, fuelling, additional heating, etc.

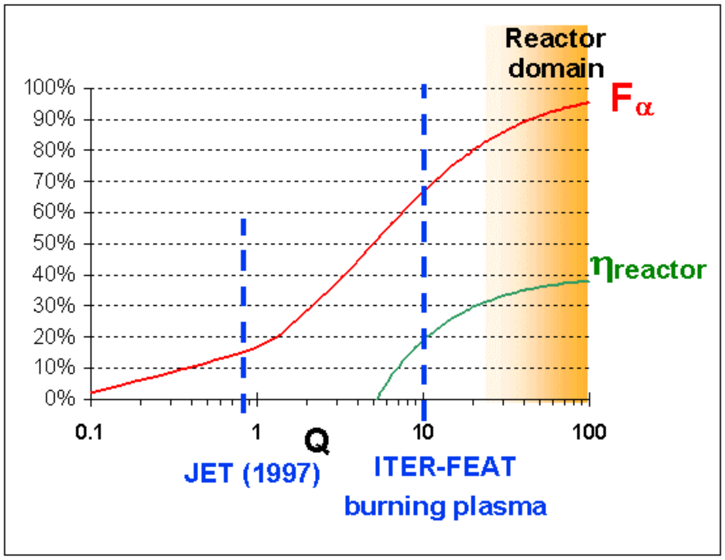
However, a number of issues will still require a further step before a prototype for a commercial reactor be built. These issues relate to the selection and appropriate qualification of neutron resistant and low activation materials, to the regeneration of tritium fuel in the reactor itself (breeding blanket), to remote handling technology (needed for repairs and decommissioning), to the development of proper safety principles and systems, to reliability of components and availability of the overall device. The next step will bring partial answers only to these questions which deserve the construction of a new generation device dedicated to a convincing demonstration of integrated solutions.

## 3. Strategy and Next Step

After this half a century fusion work, how to analyse the present situation and plan such a successful work for the next decades with an appropriate strategy ? Three main statements emerge from these past activities from which we gained experience in various fusion domains : fuelling, heating, confinement modes, energy and particle exhaust, steady state operation, …

Firstly, despite the non-linear and complex nature of the fusion field, continuous progress has been made without encountering any insurmountable roadblock towards the reactor. The $nT\tau$ product, which characterises facility performances, has been increased by six to seven orders of magnitude, reaching values within a factor of about 5 for net fusion energy production. Using deuterium-tritium and remote handling technologies the JET performance has exceeded the 10 MW – 1s fusion level, producing fusion peak power and energy respectively of 16 MW and 21 MJ.

Secondly, to conclude this 50-year past investment and above all, to open the reactor route, it is necessary to launch a Next Step, i.e. to produce and master a "Reactor Relevant Burning Plasma" of the several 100 MW – 100s class, where the alpha particles ($\alpha$) from the fusion reactions are the dominant heating source. Thermonuclear plasmas with a few 100s duration, larger than all their characteristic times, and with amplification factor Q of 10 for which 70% of the heating is due to $\alpha$ energy deposition, are contemplated (Figure 4).




$$\mathbf{Q} = \frac{\textit{Fusion Power}}{\textit{Injected Power}}$$

$$F_{\alpha} = \frac{\textit{Alpha Power}}{\textit{Alpha Power} + \textit{Injected Power}} = \frac{Q}{Q+5}$$

$$\eta_{reactor} = \frac{\textit{Electrical Power}}{\textit{Fusion Power}}$$

Figure 4 : Operating range of fusion reactor

Finally, the complex nature of the fusion field and the need of facilities of increasing size and cost make the international co-operation of first importance if one wants to progress efficiently, as well demonstrated by the positive results of the JET and the International Thermonuclear Experimental reactor (ITER) programme started in 1988.

Taking into account such statements, the strategy of the Euratom fusion programme has been oriented along the following guidelines :

- Promoting the international ITER programme and the decision of the construction of a long sustained burning plasma facility around 2003.
- Consolidating and enlarging the fusion physics and technology base using the existing devices and enhancing the deuterium-tritium Joint European Torus.
- Focusing technology in accordance with the two above guidelines.

The ITER Programme, a 1985 presidential summit initiative, is an ambitious long term international R&D venture the four Parties of which were the European Union (EU), Japan, the Russian Federation and the USA. Two phases of the programme have been successful : a 1988 – 1991 Conceptual Design Activities ; a 1992 – 1998 Engineering Design Activities (EDA). The USA withdrew from the ITER programme at the end of the EDA phase. But this phase has been extended by the three other Parties till July 2001 in order to define the ITER-FEAT device, a reduced performance and cost facility compared to the 1998 initial version.

ITER-FEAT is conceived to produce a Q = 10, 400 MW – 400s burning plasma and to study different operation modes such as a non-inductive steady state for which the plasma current is maintained by external sources (Figure 5). Its cost is today evaluated around € 3.5 billion and will be precised in one year after having fixed its final definition and conducted an international broad consultation of industrial firms.

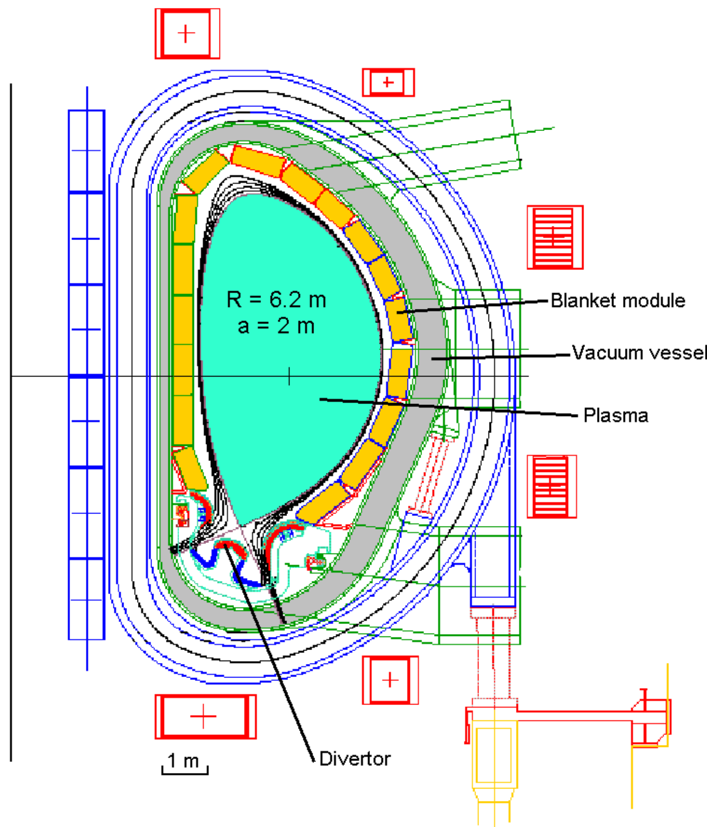



Figure 5 : ITER-FEAT cross section

To give a new momentum to the ITER programme and take a construction decision in 2003, a tentative ITER schedule has been elaborated taking into account the Party constraints and in particular those of the UE 6$^{th}$ Framework Programme preparation (Figure 6). An exploration phase starting soon, followed by a negotiation phase are planned to solve the main project issues :

- Setting a broad–based collaboration for the construction, the exploitation and the decommissioning of the facility assuring benefit and cost equity between the parties, as well as stability and flexibility during the 30 year project lifetime.
- Defining a corresponding legal entity compatible with hosting and non-hosting Party rights and obligations.
- Guaranteeing an efficient governance of the project with a clear organisation and clear responsibilities especially from the nuclear safety point of view.

From preliminary exchanges, harmonising the Party approaches dealing with legal framework, hosting and financial participation, which are tightly linked, appears to be the major exploration and negotiation task, Canada, Italy and Japan having expressed their interest to host ITER.

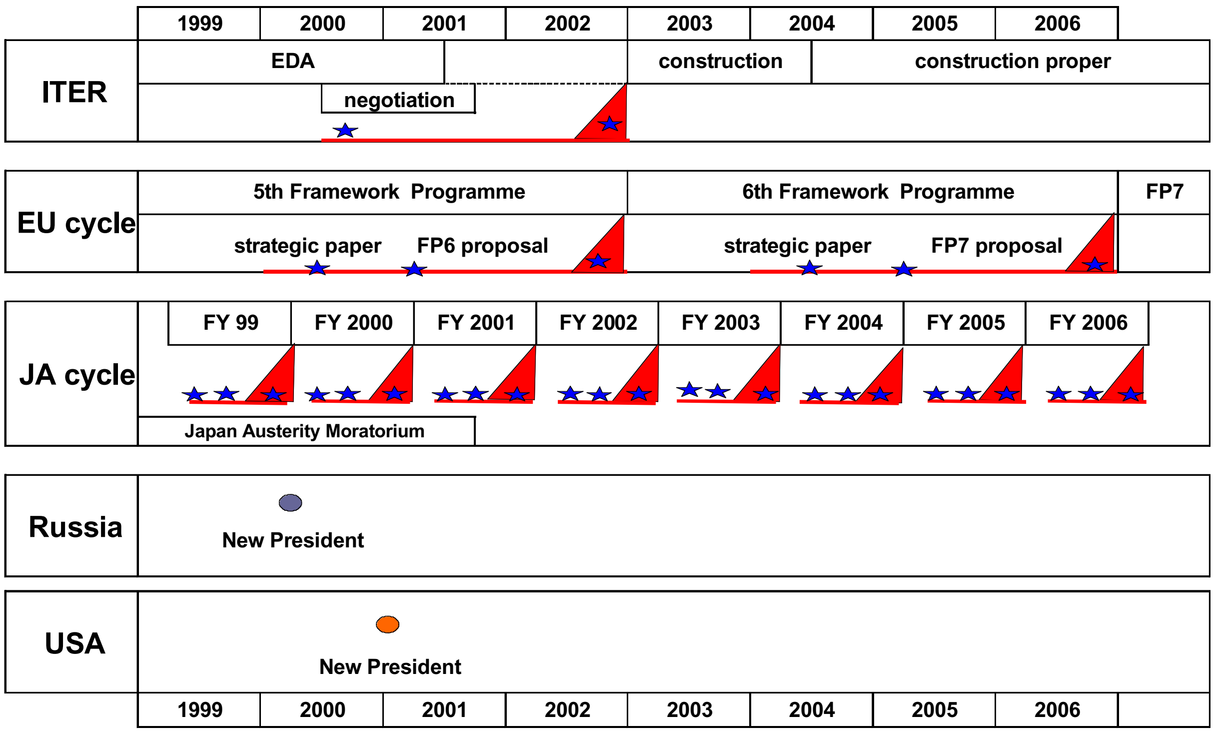



Figure 6 : Tentative ITER schedule

In order to consolidate the fusion base and assure the ITER-FEAT stated performances, each Party would have to reconsider its present fusion work and to settle an adequate accompanying programme depending on the chosen hosting location. To enlarge the base and in particular to better understand the tokamak operating conditions such as energy confinement time and pressure and density limits, EU considers to enhance the JET characteristics, doubling the heating power and increasing its plasma volume with the goal to reach a one to two Q amplification factor and 100 MJ of fusion energy.

Technology work is progressively recentered on the existing facilities and ITER-FEAT needs, but part of it is dedicated to long term activities, i.e. power plant conceptual studies and safety and environmental assessment of fusion power, in accordance with the reactor oriented Euratom fusion programme. Such long term activities will contribute, on one hand, to define an horizon for present and Next Step work, and on the other hand, to maximise the credibility of fusion energy as a technically feasible, economically viable and environmentally safe energy source.

## Conclusion

Fusion research has established a well funded physics and technology basis: physics and technology knowledges have been combined to demonstrate high fusion performances, reaching 16 MW of peak power and 21 MJ of energy.

Today, the demonstration of a sustained burning plasma is the goal which will open the route towards the reactor. To reach this goal, we have to consolidate the fusion scientific and technical basis by exploiting existing facilities with enhancements as required and to launch around 2003 the construction of the Next Step, the ITER-FEAT burning plasma tokamak.

Strengthening the international collaboration is the key for the success of such a challenge

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