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Artsimovich Memorial Lecture

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1. Introduction

After half a century of work, mastering on earth thermonuclear fusion to produce energy is becoming a realistic challenge : despite its scientific and technological complexity, considerable progress has been obtained without encountering insurmountable roadblocks.

Such progress is due for a great part to all the pioneers, as Academician Lev Andreevich Artsimovich, who, with their talents and a visionary mind, internationally promoted the civil use of thermonuclear fusion, a source which could help to face the long term energy demand.

To honour their faith and their investment in this challenge which would solve humankind energy needs on a millenary scale, I will try in this Artsimovich Memorial Lecture to : situate the fusion contribution in the future energy mix contemplated today ; survey the state of the art of fusion physics and technology fields, giving some examples ; underline the next priority, to study a burning plasma, launching the construction of the International Thermonuclear Experimental Reactor (ITER) as soon as possible.

2. Energy consumption, resources and needs

Mankind is confronted with a continually rising energy demand, because both the world population and the average world power consumption per capita rise. Our energy future depends on a number of uncertainties of technological, environmental and political nature. Our present primary energy consumption is of the order of 9 Gtoe, most of which is produced by burning fossil fuels (≈ 87 %). However, proved fossil fuels reserves will not last for very long. Oil and natural gas are expected to last several decades at the current rate of consumption, and coal a few hundred years. Moreover, the massive use of fossil fuels has serious consequences for our environment, since large quantities of CO_2 (> 10^{10} ton/year) are inevitably released into the atmosphere and, indeed, measurements show a very sharp increase of the CO_2 atmosphere content during the last few decades. Higher CO_2 concentrations in the atmosphere will lead to increased absorption of the infrared radiation re-emitted by the earth. There is general agreement among specialists that this will cause the earth average temperature to rise, but the consequences to the climate of this increase is a hotly debated issue. Moreover, it must not be forgotten that CO_2 removal from the atmosphere is a slow process : it takes over 100 years through slow carbon exchange between surface water and deep ocean.

Consequently, limited fossil resources and negative side effects for the environment may force us to introduce other energy sources as soon as possible. However, the number of conceivable non-fossil candidates which in the long term could substantially contribute to energy production is limited : renewables, nuclear fission and nuclear fusion.

Renewable sources (solar, wind, bio-products) are large and inexhaustible, but they suffer from low energy density and/or fluctuations in time. As an example, solar energy, using photovoltaic panels with an efficiency of 10 %, requires a surface of approximately 100 km^2

in western Europe to produce 1 GWe (the typical output of one single modern electric power plant). Renewables cannot therefore be an alternative solution for our future energy needs ; they can only be a complement to other energy sources.

Fission is a well developed energy source : 17 % of the present world electric energy is produced by nuclear reactors. To be a long term source it will need to switch from the present generation of water reactors to breeder reactors (Fig. 1). However, it presently suffers from a low level of acceptance by the general public, mainly because it produces highly radioactive, long-lived waste (but only a rather low volume) for which a definitive solution has not yet been clearly indicated. Calculations of the energy needs for the XXIst century are another hotly debated issue, since they strongly depend on the hypothesis on the rate of increase of the world population and their per capita consumption. However, all scenarii show that a strong increase of nuclear energy will be necessary before the middle of the century.

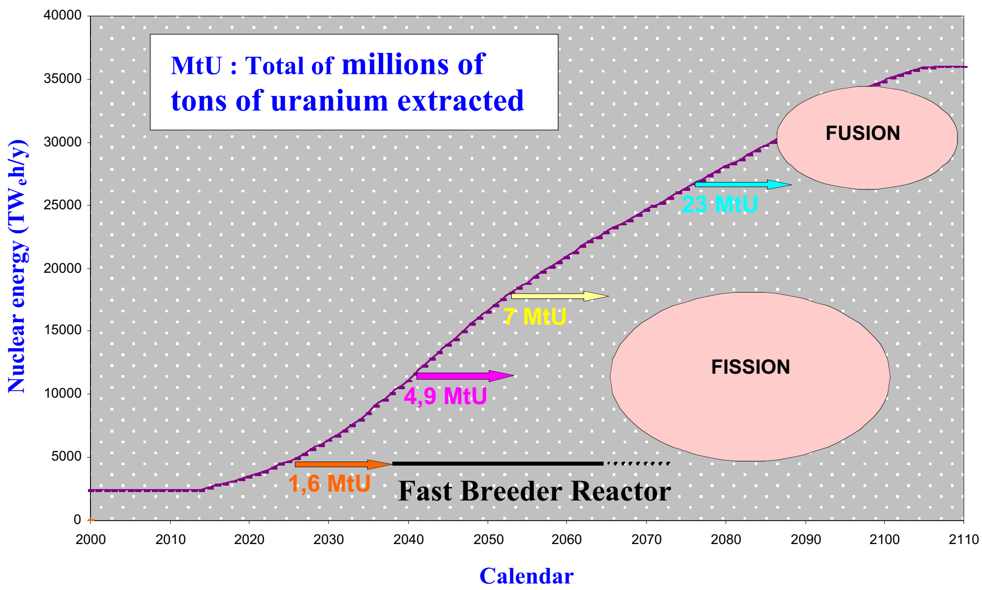

Figure 1 : Fission and fusion energy contribution to future world needs, for a given amount of uranium extracted. Fast Breeder Reactors would be used to maintain the annual fission energy produced (courtesy A. Simon).

Fusion is the least developed of the three non-fossil alternative energy sources, but has particularly valuable environmental and safety advantages : inherent and passive safety ; primary fuels not radioactive and not polluting ; radiotoxicity quickly becoming lower even than that of coal plants ; disposal of virtually inexhaustible deuterium and lithium resources. Calculations of the direct costs of fusion generated electricity indicate that, given only modest optimisation of fusion physics and use of anticipated near-term structural materials, it would be competitive. Moreover, fusion external costs are low. It is thought that fusion could contribute to the electricity supply by the end of the century, mainly constrained by the assumed rate at which it could be deployed (Fig. 1).

The development of nuclear fusion as an energy source is of course a complex scientific and technical task, and it will probably need at least another half century. Two approaches to the problem co-exist : magnetic fusion and inertial fusion.

3. Magnetic confinement

Magnetic fusion uses magnetic fields to confine the reacting particles. The more advanced configuration is the tokamak, but other alternative configurations are still investigated, especially stellarators. Tremendous progress has been obtained over the last thirty years, which have seen three tokamak generations, each one with a doubling of the characteristic dimensions : the fusion triple product (ion temperature times density times confinement time) has increased by a factor of approximately 10^4, and up to 16 MW of fusion power have been obtained in deuterium-tritium experiments in JET and TFTR. This corresponds to a Q value (ratio of fusion power to heating power) of 0.7, very near breakeven (Q=1). Although the theoretical understanding of transport is not yet complete, consistent confinement scaling has been found on many tokamaks, implying a common underlying transport physics. This has allowed empirical scaling laws for the confinement to be deduced, on which extrapolations to the next tokamak generation can be confidently based. On the experimental side, operational control of confinement and instabilities (large scale magneto-hydrodynamical and microscopic) , has been demonstrated : H-mode ; better confinement and decreased Edge Localised Modes by increasing the plasma triangularity ; internal barriers ; active feedback of neoclassical tearing modes with electron cyclotron heating ; control of the ideal kink mode by wall stabilisation ; increase of the beta limits with low aspect ratio (Fig. 2) ; plasma purity controlled by axi-symmetric divertors ; …

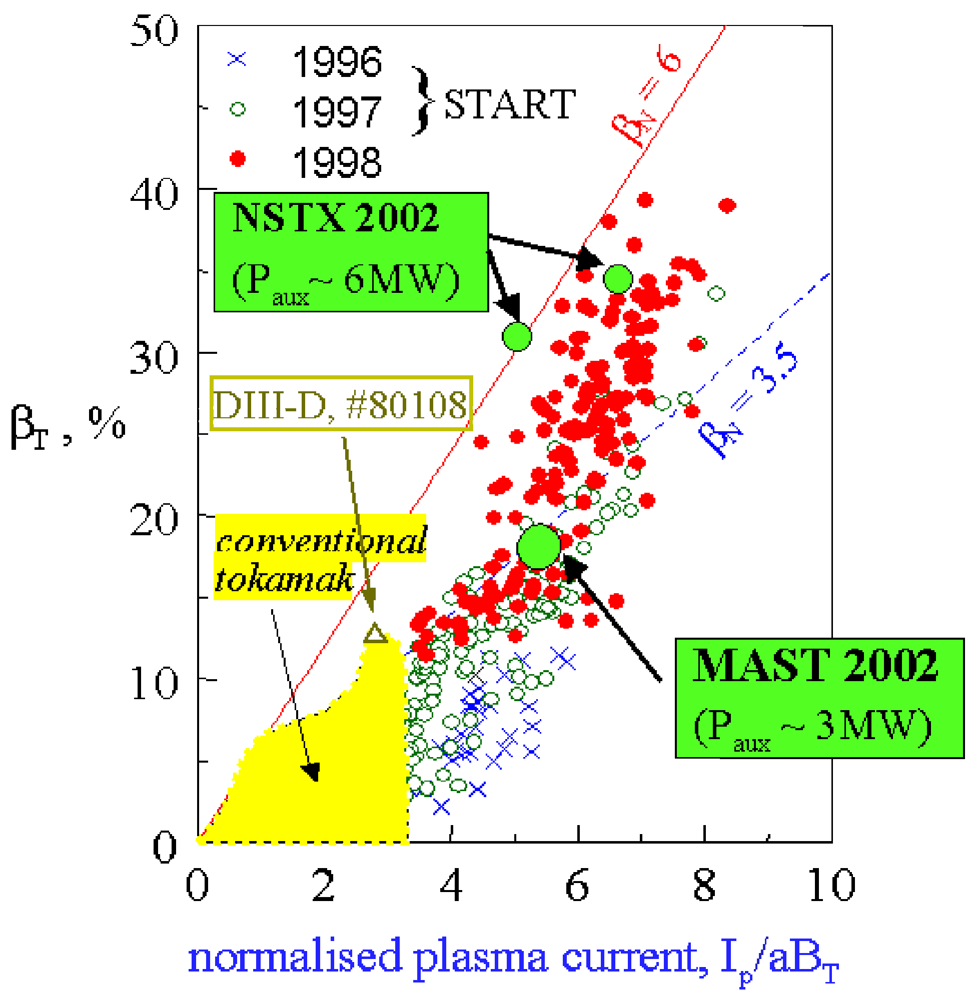

Figure 2 : β_T versus normalised plasma current for conventional and spherical tokamaks (courtesy A. Sykes).

The tokamak operation is intrinsically pulsed, since it relies on the plasma current (generally inductive) to realise the magnetic configuration, but efforts are being made towards long pulse operation and steady-state. This introduces new challenges, both in the physics and technology : superconducting magnets ; effective current drive, including bootstrap ; fuelling and pumping of the discharge ; injection and exhaust of the heating and current drive powers ; active control of the profiles. One of the most challenging aspects is the heat exhaust (Fig. 3) : actively cooled plasma facing components must completely cover the interior of the vacuum vessel, and this is a challenging industrial issue, as shown by the record of 740 MJ recently injected and exhausted on Tore Supra. Great hope is put on the "advanced tokamak" mode of operation, with a large bootstrap current fraction and active profile control.

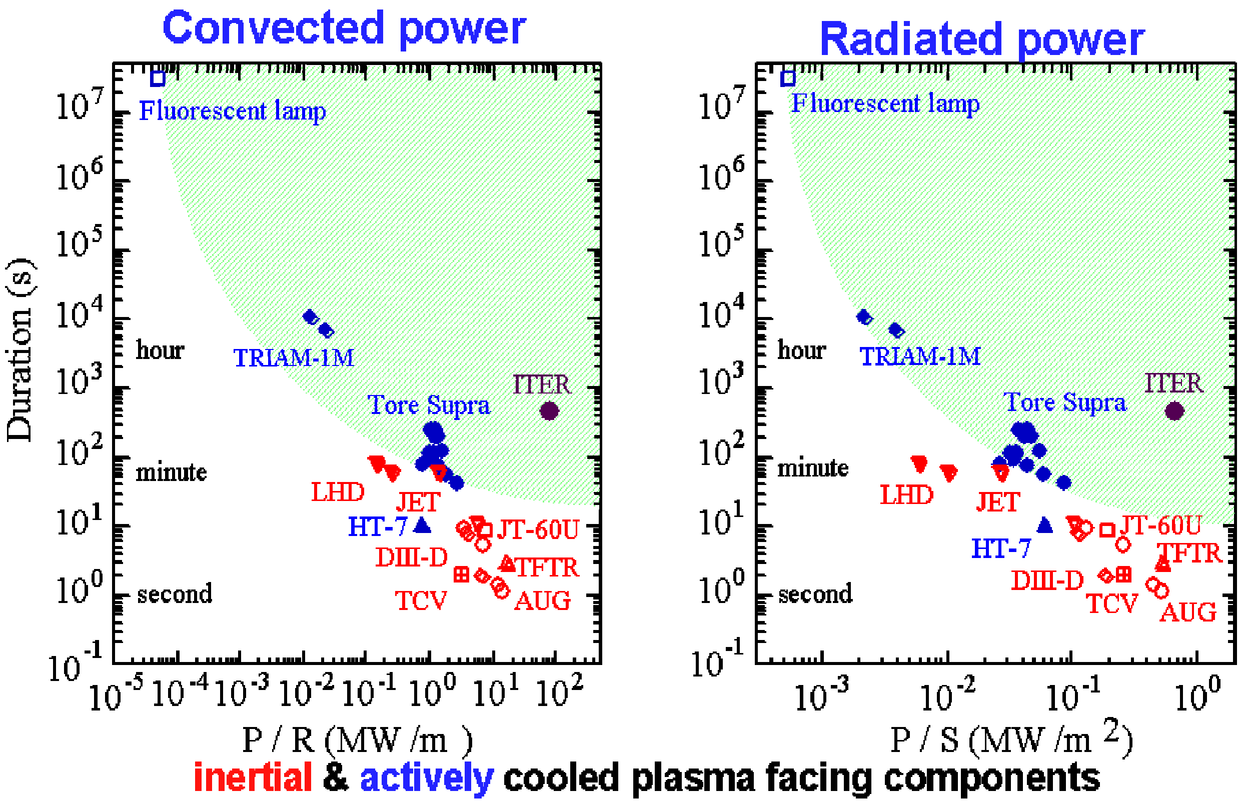

Figure 3 : Comparison of the performances of many tokamaks in terms of duration versus convected and radiated power (courtesy B. Saoutic).

Among the alternative magnetic confinement configurations, the stellarator is the most actively pursued. Since its magnetic configuration is realised only by external coils, it is intrinsically steady-state, and does not have current-driven instabilities. Although stellarators lag one generation behind tokamaks, their performances are comparable to those of tokamaks of similar size (Fig. 4), and have the advantage of high density operation and of showing quiescent behaviour at the operational limits. Stellarators based on the "quasi-symmetry" optimisation concept overcome the inherent stellarator disadvantages : high neo-classical losses and low beta. However, the design of their magnetic coils is technically much more difficult than in tokamaks.

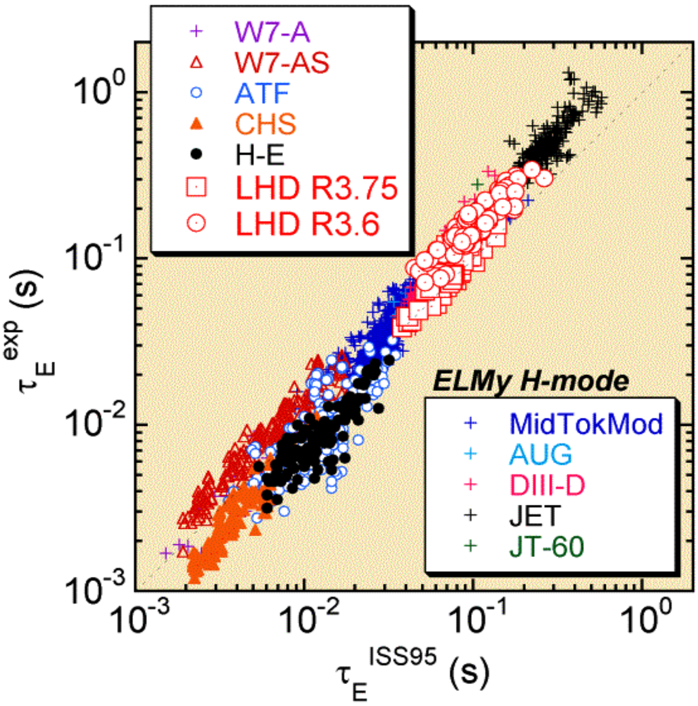

Figure 4 : Comparison of theoretical τ_E^{ISS95} and experimental τ_E^{exp} confinement times of tokamaks and stellarators (courtesy F. Wagner).

4. Inertial Confinement Fusion

Inertial confinement fusion (ICF) is based on the implosion of cryogenic DT capsules: a driver provides the energy necessary to concentrate the fuel so that it can sustain the propagation of a combustion wave ; a hot spot at a very high temperature, of the order of 60 keV, is necessary to ignite this wave.

Until now lasers are the drivers most studied through two scenarii : direct drive, where the capsule is directly irradiated by the laser, and indirect drive, where the laser light is first converted into X-rays confined in a « hohlraum ». Indirect drive seems to be more complex but has very useful features, such as ablation efficiency and irradiation uniformity. The new investigation area of the last decade is « Fast Ignition » : unlike the standard central hot spot approach, the hot spot is made at an edge of the compression region by very short duration and powerful petawatt beams ; this third scenario has been recently very challenging for many research teams in the world. On a lower scale, some work is also done on Pulsed Power and Heavy Ions drivers ; their use is close to the indirect drive laser scenario.

Let us see what has been mastered in laser ICF. The first neutrons from a laser shot were observed in 1968; several laboratories in France, Japan, Russia and US subsequently worked on ICF. Some of their important results can be underlined : high ablation compression, densities reaching values of 100 to 600 times the DT liquid density ; plasma instabilities control techniques using laser third harmonic and beam smoothing ; symmetry and stability implosion improvements ; technology progress such as cryogenic targets realisation and development of megajoule lasers.

Two main issues are to be solved to ignite the DT and to obtain energy gains closed to 10 : to control laser-plasma instabilities at a megajoule scale, avoiding energy backscattering ; to master implosion hydrodynamical instabilities which could destroy the imploding capsule or quench the hot spot.

Today, the major ICF investments are made by the US and France, which are respectively building the National Ignition Facility (NIF) at Livermore and the Laser Megajoule (LMJ) at Bordeaux, to achieve ignition at the beginning of the next decade (Fig. 5).

NIF building
March 2000

LIL building
2000

Figure 5 : View of the sites of the NIF and of the Ligne d'Intégration Laser (LIL) which is a prototype of the LMJ.

5. The road to the Reactor : ITER

From the last half century work, a well established fusion energy basis allows today to enlarge the research field to burning plasma studies in order to progress on the reactor road, going through its physics, technology and socio-economics interlinked steps.

After more than 15 years of international co-operation, the ITER project is now considered by the great majority of the scientific community as the most appropriate to produce a thermonuclear plasma where heating is mainly due to ✔ particles from DT fusion reactions and to control it on a long duration. Its major objective is "to demonstrate the scientific and technological feasibility of fusion energy". Two confinement modes are being contemplated :

- The inductive ELMy H-mode with an energy amplification Q of 10 (70% of the plasma heating coming from the ✔ energy deposition) during a time of the order of 400s.

- The so called "advanced tokamak" mode, to generate a steady-state discharge using non-inductive current drive, a Q value of 5 being expected.

Preliminary tests of the components of a future reactor are also foreseen, such as tritium breeding blanket modules submitted to neutron flux and neutron fluence respectively of the order of 0.5 $MW.m^{-2}$ and 0.3 MW am^{-2}. The main issues to reach such results appear to be : control of the current and the plasma pressure profiles in a ✔ dominated discharge ; divertor lifetime with large ELMs for the inductive mode ; tritium retention in the divertor. Nevertheless, using the existing facilities and in particular JET (the device closest to the ITER operational domain; Fig. 6), a better knowledge of the planned ITER operation is progressively acquired, increasing the confidence in the projected performances.

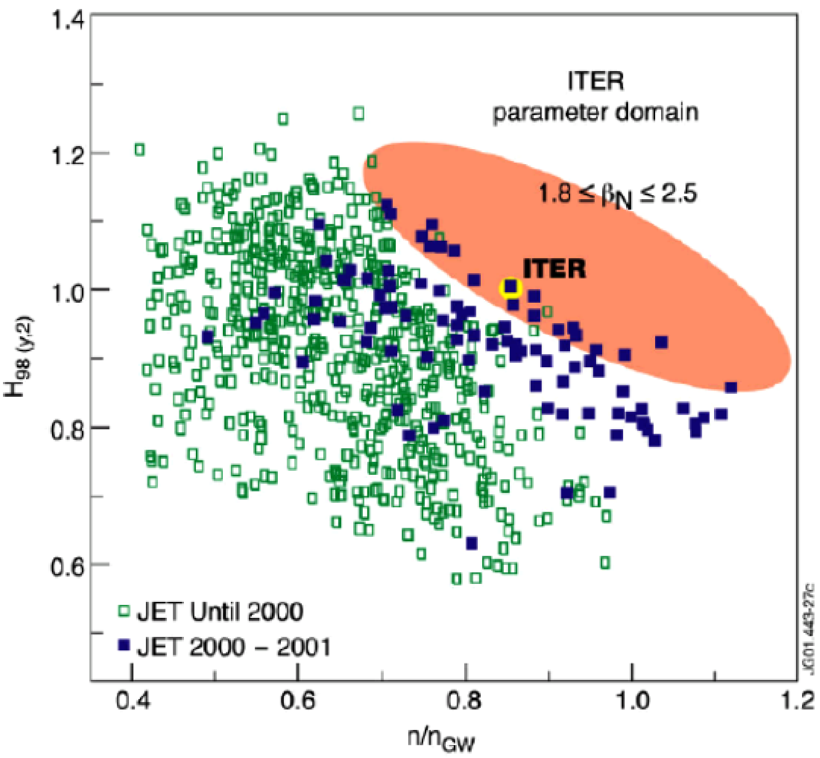

Figure 6 : JET and expected ITER operating density-confinement space (courtesy K. Lackner).

ITER, the first priority on the reactor road, requires a 4.6 billions of euros investment and its construction will need 10 years, followed by operation and decommissioning periods respectively of 20 years and 15 years. Started in November 2001, ITER negotiations between Canada, European Union (EU), Japan and Russian Federation, are progressing, with the possible future US and China participation. They deal with status, site and financial participations tightly linked, licensing, management, … and could be achieved mid-2003 if a site would be chosen in time among the four offers : Clarington in Canada ; Cadarache in France and Vandellos in Spain as EU offers ; Rokkasho in Japan. If concluded mid-2003, these negotiations would allow a construction start around 2005.

What could be the strategy towards the reactor, with the goal of a commercial reactor for the end of this century ?

First, to reach the ITER objectifs and on the long term to select the optimised reactor configuration, it is necessary to develop an appropriate “accompanying programme”. In particular, superconducting facilities, tokamaks and stellarators, could efficiently contribute to the study of steady-state discharges, such as the following facilities in construction, HT-U in China, KSTAR in Korea and W7-X in EU.

Second, technology and economics reactor issues have also to be progressively solved, having in mind that this next step, ITER, would be followed by other steps, as in the EU strategy: net electricity production with DEMO and economically competitive electricity generation with PROTO. In particular, the development of low activation and radiation resistant structural materials and of tritium breeding blankets has to be properly phased in time with these steps ; the required material neutron irradiations could be done with neutron sources (as the International Fusion Materials Irradiation Facility project) and on these future facilities.

At last, at a pace depending on the scientific and technological results and on the investments allowed for fusion energy, it could be foreseen to progress somewhat faster along the reactor road, the recently introduced Fast Track concept envisioning a commercial reactor for the 2050 horizon.

6. Conclusion

The past 50 years fusion work has established a well founded physics and technology basis : high fusion performances have been realized, reaching 16 MW of peak power and 20 MJ of energy with the Joint European Torus (JET).

Today, the demonstration of a sustained burning plasma is the next goal which will open the route towards the reactor. To reach this goal, we have to launch the construction of the International Thermonuclear Experimental Reactor (ITER) as soon as possible, choosing a site and concluding its negotiations.

At last, we must strengthen the international broad-based collaboration in order to harness the benefits of fusion for mankind.

Acknowledgements

I would like to acknowledge the fruitful exchanges I had with our fusion Community on progress done and on the burning plasma challenge. I thank all of those who helped me to prepare this Artsimovich Memorial Lecture, in particular Claudio de Michelis and the CEA Département de Recherche sur la Fusion Contrôlée, Pascal Lallia, Serge Païdassi, Alain Simon, Alan Sykes, Jacques Tassart, Friedrich Wagner and Jean-Paul Watteau who co-ordinated the preparation of this lecture.

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