THE EUROPEAN FUSION PROGRAMME

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ABSTRACT

The long-term objective of the European fusion programme is the harnessing of the power of fusion to help meet mankind's future energy needs.

This paper describes the current research programme, the unique organisational character of the fusion programme, and European and world-wide co-operation. The future evolution of the programme as part of the European Research Area and the developments currently taking place in preparation for the possible construction of ITER, the next major step towards the realisation of fusion power, are discussed.

I. INTRODUCTION

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

Fusion R&D has been part of the Community research programme since the inception of the Euratom Treaty (in 1957), which lists it as one of the areas of research to be supported by the Community. It has also been included in all six Research and Technological Development Framework Programmes. The Council Decision concerning fusion activities within the Sixth Framework Programme (FP6) [1] maintains the same overall long-term objective as previous Programmes, namely the development of fusion reactor prototype s safe, environmentally friendly and economically viable. In FP6 the objective is to make further progress towards demonstrating the scientific and technological feasibility of fusion energy. This is being done through a programme which involves primarily the preparation for the decision for the construction of ITER, based on a sound scientific-technical basis which, in Europe, has been developed through direct participation in the ITER design, the exploitation of the JET facilities, and a strong physics and technology effort in the associated fusion laboratories and industry, both in support of ITER and with a longer term perspective.

II. ORGANISATION OF FUSION R&D IN EUROPE

All the EU member states, plus Switzerland (since 1979) and the EU candidate countries associated to FP6-Euratom (Bulgaria, the Czech Republic, Hungary, Latvia, Romania, the Slovak Republic and Slovenia), currently participate in the European fusion programme. After the enlargement of the EU in 2004, participation will be open to all the new EU members. The principal mechanism of participation in the 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 within the overall Work Programme for fusion in FP6, promotes mutual access to major facilities, and provides the mechanism for funding from Euratom. During the previous Framework Programme, new Contracts of Association were signed with the Czech Republic, Hungary, Latvia and Romania, bringing them fully into the Community fusion programme. For countries without Association, contracts of limited duration for specific purposes are subscribed. 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 encourage the smaller Associations to participate in the larger experiments, for example by developing, installing and exploiting auxiliary hardware. Collaboration is further promoted by financial support to assist the exchange of personnel. Training and mobility of young researchers is also supported by a Euratom Fellowship scheme.

The Commission, with the advice of the Consultative Committee for the Euratom specific research and training programme in the field of nuclear energy (Fusion), the "CCE-FU", is responsible for implementing the fusion programme within FP6 and co-ordinating the activities of the Associations. All the countries participating in the fusion programme are represented in the CCE-FU.

In 1999 a new agreement was established to accommodate the evolving requirements of fusion R&D: the European Fusion Development Agreement (EFDA), which is a framework contract between Euratom and its usual partners in fusion (the Associates). It includes three activities: (i) technology activities carried out by the Associations and by European industry; (ii) the collective use of the Joint European Torus (JET) facilities; and (iii) European contributions to international collaborations such as ITER.

The planning and supervision of the activities carried out under EFDA is the responsibility of the EFDA Steering Committee in which all parties are represented. It appoints the EFDA Leader and Associate Leaders for Technology and for JET, upon proposal by the Commission. The EFDA Leader and the Associate Leaders are assisted by Close Support Units (CSUs), presently hosted by IPP-Garching (Technology) and the UKAEA–Culham (use of JET facilities). The EFDA Steering Committee and the CCE-FU share two sub-committees which provide them with specialist advice. These are the Science and Technology Advisory Committee (STAC) and the Administration and Finance Advisory Committee (AFAC), with membership drawn from experts in the Associations.

EFDA provides for the possibility of concluding separate Implementing Agreements relating to activities in specific areas. The JET Implementing Agreement serves as a single framework agreement between Euratom and its Associates for all the scientific and technical tasks carried out with regard to JET by the Associates. The exploitation of the JET facilities by the Associates is organised in a campaign-oriented manner. The facilities are operated by the UKAEA under a contract with Euratom, the JET Operation Contract.

JET has operated in this way under EFDA since the beginning of 2000. In addition to the small number of CSU staff and the operational staff provided by the UKAEA, the Associations provided a total of about 80 scientists for the experimental programme during each of the campaigns. The services of these latter staff are covered by a mobility scheme. A smaller number of physicists and engineers involved in operational activities are seconded to the UKAEA for longer periods.

In FP6, current expenditure by the Associations and under contracts of limited duration is generally supported by the Community at a uniform rate of about 20%. After consulting the CCE-FU, the Commission may also finance specific technology items at an additional 20% and the capital costs of projects which have been awarded priority status at a uniform rate of 40%. Specifically defined activities (such as the use of the JET facilities) are supported at a maximum rate of 75%, and contracts with industry at a maximum rate of 100%. The total effort in the Community fusion programme is close to 2000 professionals and expenditure from all sources is about 450 million euro per year. The Community contribution will total about 750 million euro from the FP6 budget over the four year duration of the Programme.

A further sub-committee, the Committee on Fusion-Industry, advises the Commission, through the CCE-FU, on Fusion-Industry matters. Its membership is made up of persons from relevant European industries and utilities (acting in a personal capacity), and from the European fusion programme.

This structure of Associations and the related committees has resulted in fusion research being fully integrated at the European level. This ensures that the research activities in the various member states are co-ordinated and complementary, and makes it possible to undertake projects that would be too large in scale for any individual member.

III. SUMMARY OF R&D ACTIVITY IN FP6

III.A. Programme in the Associations

The programme of the Associations gives priority to multilateral actions focussed on common projects such as the exploitation of JET and preparations for ITER. The mobility and training of scientific and technical personnel, the dissemination of results and the diffusion of information to the public are also an integral part of the activities carried out. The fusion physics devices in the EU are making a major contribution to the refinement of the physics basis for ITER. Among these devices, JET plays a unique role because it is closest in scale and parameters to ITER. The technology activities, under the supervision of EFDA, are performed in the Associations, the associated candidate countries and by industry. Table 1 gives a list of fusion devices in the European fusion programme. There is also a number of devices devoted in whole or in part to the technology aspects of the programme. The largest of these include: a neutral beam test bed, MANTIS, and thermal fatigue test facility, FE200, (CEA); a test facility for superconductor and joint samples, SULTAN, (CRPP); divertor test and refurbishment platforms (ENEA); the TOSKA facility for testing large superconducting coils (FZK); the tritium laboratory (FZK); and the Active Gas Handling System at JET.

The programme of the Associations is divided into three broad areas:

R&D in fusion physics and plasma engineering are focused on the preparation of ITER operation, the study and evaluation of toroidal magnetic devices (in particular continuation of the construction of the Wendelstein 7-X stellarator), and operation of the existing installations in the Associations.

The further consolidation of the scientific basis of ITER operation includes enhanced demonstrations of stability, confinement, power and particle exhaust, and control of plasmas under stationary conditions. There is also emphasis on operation in advanced regimes, such as those with internal transport barriers, and exploration of the control of modes appearing in burning plasmas. These tasks are being undertaken on both a single and multi-machine basis. The further development of advanced diagnostics, heating and current drive techniques, modelling and theory is an important ingredient of the programme, particularly in view of application on ITER.

A further objective is the evaluation of magnetic confinement formulas with the long-term aim of improving the economic competitiveness of a magnetic fusion reactor. The improvement of the basic concepts of fusion devices is undertaken by the small and medium-sized tokamaks in the European fusion programme (ASDEX Upgrade, CASTOR, FTU, ISTTOK, MAST, TCV, TEXTOR-94 and TORE SUPRA) as well as the stellarators (TJ-II) and the Reversed Field Pinches (RFX and EXTRAP-T2). These devices encompass an adequate range of configurations, size, shape, aspect ratio and heating systems, as well as being able to exploit a variety of operational scenarios. They provide a well-developed base for the examination of possible concept improvements. The stellarators have an intrinsic potential of for steady state operation. Reversed Field Pinches contribute to a better understanding of the physics of confinement in toroidal systems and the novel spherical tokamaks explore an extended parameter range of the tokamak and the potential of operation at significantly higher plasma beta than conventional tokamaks.

Structured R&D activities in fusion technology include the essential range of fusion technologies, in particular research on fusion materials.

The overall aim is to meet the needs of ITER and to develop longer term technologies. The work for ITER technology, carried out within the framework of EFDA, includes the further development and validation of key technologies such as superconducting magnets, vacuum vessel, blanket and shielding, heating and current drive systems, fuel cycle, and diagnostics.

The long-term technology is concerned with R&D related to the DEMO and the prototype reactor. Materials R&D aims at the development and qualification of structural materials with high radiation resistance and low activation. It covers three main areas: reduced activation steels, composites and advanced alloys and nuclear databases. Development of ceramic composites based on silicon carbide has continued with the characterisation a SiC/SiC composite from industry. For the future qualification of materials, calibration and benchmarking the engineering and validation of a 14MeV neutron irradiation facility is being taken up within an international cooperation, under the umbrella of the IEA, called IFMIF, the International Fusion Materials Irradiation Facility.

Another main area of investigation is dedicated to breeding blankets and materials development. Testing of blankets is planned as an activity for ITER.

Investigations of socio-economic aspects are focused on the evaluation of economic costs and social acceptability of fusion energy, in complement to the further studies of safety and environmental aspects; the dissemination of results; the diffusion of information to the public; and mobility and training. Given the reactor orientation of the programme, these wider issues need to be investigated in order to demonstrate the credibility of fusion as a future large-scale energy source.

There is also an activity to keep-in-touch with the Member States' civil research activities on inertial confinement and possible alternative concepts.

III.B. Exploitation of the JET facilities

The JET facilities continue to be exploited in the framework of EFDA, with a view to preparing for the ITER operation by completing the exploitation of the performance enhancements currently under way. With its divertor configuration, plasma size, heating, current drive and diagnostic systems, Tritium, Beryllium and remote handling capabilities, the JET device can access a wide range of operating regimes in experimental conditions closest to those of a burning plasma experiment.

The performance enhancements which have been made to JET, or are still in progress, allow it to make a major contribution to the consolidation of the scientific basis of ITER, in parallel with the work on the devices in the laboratories of the Associations. The scope of the work on JET, which is the only fusion device capable of operating with deuterium and tritium, encompasses confinement, heating, fuelling, exhaust physics and plasma control as well as associated technologies.

Recently, there has been significant progress in the understanding of the ELMy H-mode (the reference scenario for ITER operation) and the extrapolation of ELM size to ITER has been re-evaluated. Neoclassical Tearing Modes have been shown to be meta-stable in JET. Their beta limits have been increased by destabilisation (modification) of sawtooth by ICRH. Alpha simulation experiments with ICRH accelerated injected ^{4}He beam ions have provided a new tool for fast particle and MHD studies, with up to 80_90% of plasma heating by fast ^{4}He ions. With or without impurity seeding, quasi-steady state high confinement, high density and high beta ELMy H-mode has been achieved by operating near the ITER triangularity (~ 0.40_0.5) and safety factor (q_{95} ~ 3), at Z_{eff} ~ 1.5_2.

The ultimate goal of Advanced Tokamak research is to provide steady-state operational regimes with possibly improved fusion performance. These modes are candidate for the steady-state operation of ITER. In JET Advanced Tokamak scenarios, internal transport barriers (ITBs) are now characterised in real time with a new criterion, the normalised Larmor radius ρ^*_T. Tailoring of the current profile in these discharges with LHCD provides reliable access to a variety of q profiles, lowering access power for barrier formation. Rational q surfaces appear to be associated with ITB formation. Plasmas with 'current holes' have been observed and modelled. Transient high confinement Advanced Tokamak regimes with have been achieved with reversed magnetic shear. Quasi-stationary internal transport barriers are being developed with full non-inductive current drive, including ~50% bootstrap current. Record duration of ITBs, up to 11 s, has been achieved. For the first time, pressure and current profiles of Advanced Tokamak regimes are controlled by a real time feedback system, in separate experiments.

III.C. Next Step / ITER activities

In addition to the physics and technology R&D activities in the Associations which have supported the ITER design process and laid the foundations for the construction and operation of the machine, the EU has also been a leading player within ITER itself. This includes design activities, construction of prototypes of major components, and, most recently, participation in the negotiations with the other partners on the joint implementation of the project.

The original Engineering Design Activities (EDA) phase of ITER commenced in 1992 and expired in July 1998. It was followed by a three year extension in which three of the parties (EU, Japan, Russia) participated. The US committed itself unilaterally to a 1 year continuation only.

While the ITER Parties agreed that the original design (completed in 1998) showed the necessary quality and feasibility, and that it stayed within the original outline cost estimate, it was considered unlikely that approval for construction of such a device would be obtained, given the changed financial circumstances. The major task of the EDA extension was therefore an adaptation of the ITER design, aimed at reducing the direct capital cost of construction to about 50% of the original design, while maintaining the overall programmatic objectives of the original ITER mandate: "to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes". The Final Design Report for this machine [2] was presented to the Parties for their assessment before the end of the EDA in July 2001. These assessments were favourable, and led to the start of negotiations on a possible legal framework, in preparation for a possible decision to proceed with construction.

Recently there have been significant steps forward in the preparations for such a decision. A working document by the Commission for the Council of Ministers on the cost to Europe of implementing ITER was received with interest when it was presented in March 2002. The negotiating directives granted to the Commission by the Council of Ministers were broadened in May 2002 to include site and cost sharing aspects. The Commission then submitted formal offers by the French and Spanish governments to host ITER on their territories. Extensive technical evaluations of these have being undertaken, and have demonstrated that both sites meet the ITER technical requirements.

During the first half of 2003 the USA re-joined ITER and the People’s Republic of China and the Republic of Korea also joined and are now participating fully in the negotiations. The siting and cost sharing issues are now being discussed between the Parties at high level. The European Parliament and the Council are fully supporting to host the ITER project in Europe. A decision is expected soon about which of the two site offers (Cadarache or Vandellòs) to retain for the international site negotiations. The European Commissioner responsible for research, Philippe Busquin, said recently: “Europe's fusion research has a solid foundation, with firmly established networks of excellence. We must give ourselves the best chance to build ITER in Europe."

III.D. Fusion as an energy system

A wide range of investigations related to the safety of fusion, both in the context of a Next Step experiment and with a long term view, have already been undertaken. Particular emphasis is placed on the development, validation and application of EU fusion safety analysis codes to obtain licensing quality. Benchmarks, definition and performance of small-scale validation experiments, failure rate database and calculation of relevant accident sequences are included. The EU has also contributed to ITER Safety Reports, including the assessment of the ITER design and safety documentation, modelling of loss of coolant accident transients and analysis of the behaviour of tritium and activation products in the environment.

Safety and environmental issues for the longer term have been examined in the SEAFP (“Safety and Environment Aspects of Fusion Power”) studies. These have confirmed the attractive safety and environmental characteristics of fusion power. The “Safety and Environmental Impact of Fusion” (SEIF) study has integrated and extended all the previous work. It concludes that: any power excursions of the plasma in a future fusion power station are self-limited to low levels by inherent processes; the fuel inventory in the plasma chamber at any time is sufficient only for about one minute of operation; power densities are moderate in normal operation and very small after burn termination; and that the activated waste produced by the operation of fusion power stations will not be a burden for future generations.

A programme of Socio-Economic Research on Fusion (SERF) has been undertaken to respond to the questions related to the expected direct costs of electricity production by nuclear fusion; the associated "external" costs (mainly environmental) as compared to those of other energy supply technologies; fusion's potential share of the future electricity market; and the social acceptability of fusion experiments and power plants. The broad conclusions are that power generation by fusion can become a cost-effective method to satisfy European demands for electric power in this century, if the need to stabilise the CO2 content of the atmosphere is properly recognised. The financial aspects depend strongly on the assumptions made about economic development and CO2 stabilisation targets, and the external costs of the fusion power cycle are comparable to those of the best-performing renewables.

A Power Plant Conceptual Study (PPCS) has focused on three activities: clarification of the physics assumptions and evaluation of their impact on the design; exploration of remote maintenance concepts aiming for high reactor availability; and studying the sensitivity of achieving the safety and economic objectives to assumptions made about other issues in technology. Further work on the conceptual design of several models of commercial fusion power plants and their safety, plus an environmental and economic assessment is being initiated.

III.E. European and International Collaboration

Collaborations between Associations are a key element of the integrated European fusion programme. There are also extensive collaborations with laboratories world-wide.

All the Euratom Associations participate in collaborations which range from exchanges of personnel, through supply and operation of ancillary equipment (such as diagnostics) by one Association for an experimental device at another, to "clustering" in which several Associations take joint responsibility for an experimental device or programme of work. Under the EFDA umbrella, the Associations participate in two large scale collaborations: the exploitation of the JET facilities and contributions to the ITER design. The fusion programme is a genuine Europe-wide research area, with large and small laboratories working towards a common programmatic objective. In addition to ITER activities (under the auspices of the International Atomic Energy Agency) bilateral or multilateral agreements which provide an umbrella for collaborations between European and non-European laboratories, have facilitated the exchange of information, common developments and the definition of complementary scientific investigations. Eight Implementing Agreements in the frame of the International Energy Agency have continued to serve as the frame for collaborations to pool expertise and joint scientific interests. There are bilateral agreements with the USA, Russia, Japan, Ukraine and Canada.

III.F. Education, Training and the Promotion of the Public Understanding of Fusion

Education and training of young researchers is an important part of the work of the Associations. Many professional staff from the Associations have teaching responsibilities in academic institutions, mainly universities, and a considerable number of PhD students (currently around 250) perform their research within the Association laboratories. Several Associations hold summer schools in fusion and plasma physics for graduate students and young researchers.

Attention is also being devoted to the promotion of public understanding of fusion. Besides the Commission activities, all the Associations have activities in their own countries, coordinated in a network managed by EFDA. On top, there are actions organised in the frame of EFDA, such as the creation of an itinerant exhibition about fusion, currently managed by the Association Euratom-ENEA (Padova). Since its inception ten years ago, this "fusion-expo" has typically been visited by 3000-5000 people at each of its about 5 presentations per year and has been shown in almost all Member States and a number of other countries. Websites have been set-up and multi-language CD-ROMs have received wide distribution. EFDA is also member of EIROforum, a collaboration between seven European intergovernmental scientific research organisations.

IV. FUTURE DIRECTIONS

Fusion research in Europe has acquired a strong international role based on the joint European fusion programme as an important element of European energy research. A key feature of the current Framework Programme is to encourage the creation of the European Research Area with a strong partnership between the various actors, with an intensive integration of research efforts and focus on R&D of relevance to Europe. Indeed, the fusion programme is a successful example of a European Research Area where all relevant European actors work together and where joint actions can be undertaken which could not be achieved by individual Member States. Europe's strong role in ITER is clearly a manifestation of the outstanding added value of a European Research Area.

With the ITER negotiations approaching their final stage it is hoped that international consensus on the site will soon be reached. Internationally, it is hoped that the formal basis for committing to ITER construction becomes available during 2004. Once the formal ITER agreement would be established, the setting up of the ITER organisation and the start of the construction could be addressed. For handling the EU's contribution to ITER (participation to construction will be largely by in kind contributions) a European Legal Entity will be set up.

ITER is the necessary next step in the strategy of the European fusion programme. Long-pulse burning plasmas with significant power amplification in ITER shall demonstrate the scientific feasibility of magnetic confinement fusion power.

When embarking into ITER, Europe needs to have a strong accompanying programme in order to be able to have a key impact on ITER and its scientific-technical orientation and to be able to harness effectively the ITER experimental and technological output for the benefit of the subsequent DEMO / Prototype reactor development. A leading role of Europe in fusion R&D should be maintained in the period ahead, where fusion energy is coming closer to its ultimate goal of providing useful electricity for society.

V. REFERENCES

[1] Council Decision of 30/09/02 (2002/837/Euratom) concerning the FP6-Euratom programme for research and training activities (2003 to 2006)

[2] "Final Report of the ITER Engineering Design Activities", IAEA Vienna (2001). Information can also be obtained from: http://www.iter.org/

Table 1: Major Plasma Devices in the European Fusion Programme (I_p and B_{tor} are the maximum for the device)

Device	Type	Association	Location	Main Contributions to the Fusion Programme	R_0 (m)	I_p (MA)	B_{tor} (T)	Start Year (Upgrade)
ASDEX Upgrade	Tokamak	IPP	Garching (DE)	ITER-relevant divertor, H-mode, SOL, wall interaction, concept improvements, advanced scenarios	1.62	2.0	3.9	1991
CASTOR	Tokamak	IPP.CR	Prague (CZ)	Lower Hybrid Current Drive, fluctuations, diagnostic development, edge plasma polarisation	0.4	0.03	1.5	1977
EXTRAP-T2	RFP	NFR	Stockholm (SE)	Stabilisation, shell studies, fluctuations, scenarios	1.25	0.26	-	1994
FTU	Tokamak	ENEA	Frascati (IT)	Confinement at high density and high current, optimised shear studies, Electron Cyclotron Heating	0.93	1.6	8.0	1990
ISTTOK	Tokamak	IST	Lisbon (PT)	MHD activity, AC operation	0.46	0.01	0.5	1992
JET	Tokamak	EFDA (Prog) & UKAEA (Op)	Abingdon (UK)	Integrated high performance operation, divertor development, ITER-relevant operating scenarios, tritium and remote handling, DT operation	2.96	5-7	3.8	1983 (1992)
MAST	Spherical Tokamak	UKAEA	Culham (UK)	Tight aspect ratio scaling, spherical Tokamak physics at high temperature	0.7	>1	0.6 3	1999
RFX	RFP	ENEA	Padova (IT)	Reversed Field Pinch physics, toroidal confinement and transport, performance prospects	2.0	<2.0	-	1991
TCV	Tokamak	Conf. Suisse (CRPP)	Lausanne (CH)	Physics of strongly shaped plasma cross-section, Electron Cyclotron Current Drive	0.88	<1.2	1.4	1992
TEXTOR-94	Tokamak	FZJ / FOM / Etat Belge	Jülich (DE)	Wall interaction, edge plasma, Dynamic Ergodic Divertor, confinement with additional heating	1.75	0.8	2.8	1981 (1994)
TJ-II	Stellarator	CIEMAT	Madrid (ES)	Confinement and high-beta studies in a highly flexible device with helical magnetic axis	1.5	-	1.0	1997
TORE SUPRA	Tokamak	CEA	Cadarache (FR)	Long-pulse operation in Next Step relevant conditions of wall heat load, fuelling and current drive	2.4	1.7	4.5	1988 (2000)
Wendelstein 7-X	Stellarator	IPP	Greifswald (DE)	Physics and engineering of plasmas in an advanced (Helias) Stellarator, demonstrate reactor relevance	5.5	-	3.0	Scheduled for 2006