1 INTRODUCTION

1.1 The world-wide status of magnetic fusion in 1999

The general strategy for developing fusion as an energy source remains unchanged. ITER, even with Reduced Technical Objectives and hence at Reduced Cost, referred to as ITER-FEAT (for Fusion Energy Advanced Tokamak), is still intended to be the only step between the present size devices and a DEMO reactor.

ITER-FEAT is a scaled-down version of the original ITER design. In order to achieve a cost reduction of about 50%, some technical objectives had to be reduced, compared with the original ITER specifications. Reductions have been chosen in the power amplification factor Q (Q ~ 10 with a burn time of about 500s, Q ~ 5 in steady state), in the total fusion power (~ 500MW) and in the neutron fluence (≥0.3MWa/m^2). The EU, Japan and Russia are now collaborating in the EDA Extension Phase of ITER which will last until July 2001, with the aim of completing tests of critical components of the device as well as defining all the elements necessary for a political decision to build ITER.

Japan continues to maintain a strong commitment to fusion power. Its programme covers all the different aspects of fusion research, both in issues of physics and technology. On the physics side, the study of magnetic confinement is concentrated on the exploitation of the large tokamak JT-60U and the new large super-conducting LHD stellarator (Large Helical Device). The latter was successfully brought into operation in 1998. In parallel, all the required technologies are being developed for present day experiments as well as for a reactor. The support for fusion is widespread in government, economic circles, academic societies and also among the educated public. The Japanese government's commitment towards fusion is a continuation of a long-term view of the necessity of solving the critical issue of their energy dependence. Japan considers that ITER is affordable, that it should be the one step towards a DEMO fusion reactor and is actively pursuing detailed studies with the objective of hosting ITER in Japan.

In the US, there has been a phase during which strong doubts were expressed about the political and even the community commitment towards realising a fusion reactor such as ITER in the near term. However, recent developments indicate that a positive consensus is returning regarding the timeliness of starting a burning plasma experiment in an international context. This consensus presently being developed by the US fusion community is expected to have positive effects on both the overall American fusion programme and possible future US involvement on ITER. It has been stated by officials from the Department of Energy that the US should attempt to re-join the project if ITER goes forward to construction.

In the EU, the 5th Framework Programme (FP) was adopted in December 1998. The budget, 788 Million Euros, guarantees the continuation of all the European activities previously foreseen in the fields of physics, technology, participation in the ITER-EDA and the continuation of work on the JET facilities in the period 2000-2002. The EU Fusion Programme has become a "key action" of the EU thematic action "Preserving the Ecosystem". The goal of the Key Action Fusion is stated to be the development of the necessary basis for the possible construction of an experimental reactor with the objective of demonstrating the scientific and technological feasibility of fusion power production as well as its potential safety and environmental benefits. The physics programme encompasses activities for ITER, activities using the JET facilities and the supporting research in the Associations. The research priorities for ITER cover finalising the design and test of the large prototypes, adapting the design to specific potential host sites and consolidating the necessary scientific knowledge base. Discussions are underway to examine several potential European sites and to prepare the political context for a decision to construct ITER. A preliminary design of ITER-FEAT was presented to the ITER Technical Advisory Committee at the end of 1999 for discussion. Discussion on the European strategy and the role of ITER-FEAT has already been started to prepare of the 6th Framework Programme.

The JET Joint Undertaking ceased to exist at the end of 1999. JET reached record fusion power production during the 1997 D-T campaign and is now the unique facility with tritium capability in the world, following the completion of the TFTR project at Princeton. Scientific exploitation of the JET facilities is continuing in a campaign-oriented style driven by all the European Associations, including Switzerland. This requires a strong commitment from all the associated laboratories and will need co-ordination with the national programmes. However, success of the post-1999 exploitation of the JET facilities will have a major impact on the whole fusion programme. The present work-plan for the JET facilities foresees a major D-T campaign in 2002. Should major enhancements of the JET facilities be decided, this D-T campaign would be moved to a later date.

1.2 The CRPP in 1999

1999 was marked by the retirement of Professor Francis Troyon, Director of the CRPP since 1982. Under his leadership, the major scientific orientation for the laboratory was determined and its present largest experiment was built, TCV (Tokamak à Configuration Variable). Unification of the Swiss fusion physics and technology activities into a single institution was also accomplished during his tenure. It was with a deep feeling of gratitude and admiration that the members of the CRPP and a large representation from the international fusion community gathered for a farewell ceremony at the EPFL on March 30th 1999.

The long-standing strategy of the CRPP aims at excellence in certain carefully selected areas, based either on existing facilities capable of making a unique contribution to the field, or on solid scientific experience and expertise in the field. In the area of the physics of fusion plasmas, research at the CRPP has concentrated on the following:

- the exploitation of the TCV tokamak, which has a unique flexibility for producing and studying strongly shaped plasmas;
- the study of electron cyclotron heating and current drive, combining a high power and versatile additional heating scheme with the shape flexibility of TCV;
- the theoretical and numerical simulation of the equilibrium, stability and confinement of magnetically confined plasma, including the tokamak, stellarator and novel configurations;
- the development of high power high frequency sources for plasma heating and diagnostics;
- supporting the JET experiments and the ITER Engineering Design Activity.

The TCV tokamak is regularly upgraded and operation was interrupted according to plan during 1999 and successfully resumed in November. The installation of the Electron Cyclotron Heating and Current Drive system (ECH/ECCD) for TCV is progressing satisfactorily, considering the very tight situation regarding CRPP support personnel. During the 1999 shut-down the ECH system capability was increased to 3MW at the second harmonic (82.7GHz) in the extraordinary mode X2.

The TCV diagnostics are being continuously improved and new diagnostics are regularly added. Many of them are developed in collaboration with external research institutes in Europe, as well as in Russia and the US.

Following the start of ECH heating on TCV with 1.5MW of additional power, the scientific programme has broadened its scope to cover the physics of both Ohmic plasmas and additionally heated plasma. Some of the highlights of the TCV programme in 1999 are:

· fully non-inductive current drive using ECCD maintained a plasma current of 123kA for about 1.9s with no volt-second consumption;
· electron temperature record for TCV in excess of 10keV (100 million degrees) were measured during ECH heating with a significant counter-ECCD component;
· «H» modes (high confinement) have been obtained with ECH heating at a plasma density lower than the low density limit with Ohmic heating alone;
· the demonstration that the plasma elongation and shaping improve the energy confinement time by the "Shape Enhancement Factor" due to magnetic surface expansion of the shaped plasmas has been extended to strong ECH;
· plasma detachment was obtained with diverted plasmas, at low density and without the addition of impurities, a result not expected on the basis of results from other tokamaks.

The activities in gyrotron development have been streamlined and the expertise of the CRPP is integrated in the European effort aiming at the development of high power high frequency gyrotrons for existing or planned experiments. Only a very small effort is still being devoted to the development of a third harmonic quasi-optical gyrotron for diagnostic purposes. The 118GHz 0.5MW gyrotron for 3rd harmonic ECH on TCV and Tore Supra (France) has achieved a long pulse of 15.5s at 400kW, beating the world record in energy delivered by a high frequency gyrotron. A collaboration with the Association Euratom - Forschungzentrum Karlsruhe (FZK, Germany) is underway to design and test a 140GHz, 1MW CW gyrotron with a depressed collector for improving its efficiency. This gyrotron has been delivered to the FZK and its test is scheduled for 2000.

The theory and numerical simulation group has given support to various running and planned experiments, using existing codes, many of them developed at the CRPP. The synergy between theory and experiment has become highly beneficial for both, following the evolution of the TCV program in the direction of pressure and current profile control, intimately linked to the CRPP theory expertise in MHD. The extension of this synergy, both on JET and on TCV, will be strongly encouraged in the future. Computational models in the field of Alfvén eigenmodes have been compared with experimental results from JET, TFTR and DIII-D, showing that these models may now be used to make reliable predictions. Support for TCV has been provided by calculations of the MHD stability of strongly shaped plasmas and by impressive transport simulations and sawtooth modelling. In collaboration with the Keldysh and Kurchatov Institutes we have explored the potential of different 3D configurations with a view to a future experiment. Much progress has been made in kinetic modelling and several codes have reached the production phase. Using the massively parallel computer at the EPFL it was possible to study the physics governing the stability of ion-temperature-gradient (ITG) driven modes in tokamaks. The additional computing power of a Cray T3-E was made available through our collaboration with the Association Euratom-Max Planck Institut für Plasma Physik (Germany). We have thereby been able to assess the performance of non-linear kinetic ITG simulations of tokamak plasmas and to perform the first linear simulations of 3D configurations.

The CRPP provides an important contribution to the world fusion technology program in the field of superconductivity. The major asset of this work is the unique SUpraLeiter Test ANlage (SULTAN) which can test superconducting cables under realistic conditions of both the current carried and the externally applied fields. Work has concentrated recently on the test of the cable joint techniques to be used for ITER. SULTAN can also test the propagation of the energy which results from a “quench”, along very long cables, with the aim of validating thermo-hydraulic codes used for ITER design. In parallel, work is carried out on high temperature conductors for use in the current leads which cross the barrier between ambient and magnet temperatures, as well as on non-fusion applications for power transmission lines.

The fusion technology activities also include the study of materials suitable for fusion reactors. The environment of a fusion reactor is particularly difficult from the point of view of the material damage by high dose of neutrons during the life time of the components and the simultaneous production of impurities such as helium or hydrogen during the lifetime of a reactor. Developing and testing new materials capable of retaining their mechanical integrity in such an environment while not producing long lived radioactive elements are the main focus of our activity. This relies on the use a high energy proton beam irradiating small samples to simulate a fast neutron flux, in the world-wide absence of a high flux 14MeV neutron source. Post irradiation studies aim to understand the production and evolution of defects induced in the materials from the microscopic scale through to the scale at which major structural failure can occur.

It is important to acknowledge the continuous and strong support of the Paul Scherrer Institute, which hosts and provides technical support for both superconductivity and materials research carried out by the CRPP at Villigen.

Support for the EDA phase of ITER is one of the main priorities of the CRPP. Besides "Voluntary Physics" activities, we have contributed directly to the problems related to plasma control. Members of CRPP were nominated, ad personam, as Task Area Leader, European Expert or Member of various strategy defining and scientific committees of ITER.

The CRPP took an important part in the preparation of the scientific campaign of JET for the year 2000, through the involvement of its members, of whom one was the Task Force Leader in MHD.

All of the activities mentioned so far were performed within the framework of the Association Euratom-Confédération Suisse and have benefited from collaboration with all the Associations of the European Fusion Program. Bilateral collaborations have also been established with Eastern European institutions, Japan and the US in physics and diagnostic development. They include the exchange of personnel and equipment between the CRPP and these institutions. These scientific relationships have been extremely beneficial to the CRPP, especially in view of the very tight personnel situation in which the CRPP has found itself in the last two years.

The CRPP has developed a Plasma Processing group over several years, with the aim of transferring our know-how in basic plasma physics to industrial applications where different processes are frequently empirically optimised. This activity continues to expand with increasing interest from many industries. Considerable effort is now going into the development of novel diagnostic techniques to quantify the different processes occurring in the industrial plasmas in order to optimise both the speed and quality of the production. These techniques must be compatible with an industrial production environment.

1.3 Main fusion reactions and fuel

Research into controlled fusion aims to demonstrate that it is a valid option for generating power in the long term future in an environmentally, politically and economically acceptable way. Controlled fusion is a process in which light nuclei fuse together to form heavier ones: during this process a very large amount of energy is released. For a fusion reactor it is planned to use the two isotopes of hydrogen: deuterium (D) and tritium (T), which fuse together much more readily than any other combination of light nuclei according to the following reaction:

$$D^2 + T^3 \rightarrow He^4 + n + 17.6\mathrm{MeV}$$

The end products are helium and neutrons (n). The total energy liberated by fusing one gram of a 50:50% mixture of deuterium and tritium is 94000kWh, which is 10 million times more than from the same mass of oil. 80% of this energy is carried by the neutrons with an energy of 14MeV while the remaining 20% is carried by the helium nucleus. All this energy eventually becomes heat to be stored or converted by conventional means into electricity.

The reaction rate of all fusion reactions only start to become significant at temperatures above a few tens of millions of degrees. For the D-T reaction, the optimal temperature is of the order of 70-200 million degrees. At such temperatures the D-T fuel is in the plasma state.

Deuterium is very abundant on the earth and can be extracted from water (0.034g/l). Tritium does not occur naturally since its half-time is only 12.3 years but it can be regenerated from lithium using the neutrons produced by the D-T fusion reactions. The two isotopes of natural lithium contribute to this breeding of tritium according to the reactions:

$$Li^6 + n \rightarrow He^4 + T^3 + 4.8\mathrm{MeV}$$

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

The relative abundances of the two lithium isotopes Li^6 and Li^7 are 7.4% and 92.6%, respectively. The known geological resources of lithium in the earth are large enough to provide energy for several thousand years without counting the lithium in sea water.

1.4 Attractiveness of fusion as an energy source

The inherent advantages of fusion as an energy source are:

- The fuels are plentiful and their costs are negligible because of the enormous energy yield of the reaction;
- The end product of the reaction is helium, an inert gas;
- No chain reaction is possible; at any time only a very small amount of fuel is in the reacting chamber and any malfunction would cause an immediate drop of temperature and the reaction would stop.
- No after-heat problem can lead to thermal runaway;
- None of the materials required by a fusion power plant are subject to the provisions of the non-proliferation treaties.

Its further potential advantages are:

- Radioactivity of the reactor structure, caused by neutrons, can be minimised by careful selection of low-activation materials resulting in little long lived radioactive waste;
- The release of tritium in normal operation can be kept to a very low level. The inventory of tritium in the breeding section of the reactor and on the site can be sufficiently small so that the worst possible accident could not lead to a harmful release to the environment requiring evacuation of the nearby population.

1.5 The main research approaches

The main components of a fusion reactor are the reaction chamber in which the fuel reacts, the first wall which contains the reaction and absorbs the heat radiated or transported from the core and the breeding blanket which absorbs the neutron flux to produce more tritium fuel. Heat is extracted from the first wall and from the blanket and typically converted into electricity.

The key component is the core. Two very different concepts of reactor core are pursued today: the inertial confinement approach and the toroidal magnetic confinement approach.

In an inertial confinement reactor a small mass (a fraction of a gram) of solid D-T fuel is compressed and heated to the required temperature in a very short time (pico- to nano-seconds) by intense beams of energetic photons or particles. The pressure reaches about 10^{11} bar which leads to rapid disintegration (within nano-seconds) of the mass of fuel. The helium and unspent fuel are then removed and the process is repeated, ultimately about tentimes per second.

In magnetic confinement a volume of the order of $1000 m^3$ filled with a few grams of fuel at a pressure of a few bar due to its high temperature reacts at a steady rate. To keep the reaction going, helium must be constantly removed and replaced by fresh fuel. To ignite the reaction a heating system is needed to bring the temperature to the right range. This heating system can be turned off if the heat generated by the fusion reaction is sufficient to maintain the required temperature. Otherwise energy is released while maintaining the optimal conditions with external methods. The fuel is imbedded in a strong magnetic field which holds in the plasma pressure and slows down the heat flux to the vessel walls, confining the hot plasma. The difficulty is to insulate the required plasma well enough for the energy released by the fusion reactions to maintain the high temperature.

Magnetic confinement is the main line pursued throughout the world and the European programme is concentrated on this line. Only a watching brief is kept on inertial confinement. The ITER project is designed on the basis of magnetic confinement with the aim demonstrating long pulse energy production in a large plasma volume.