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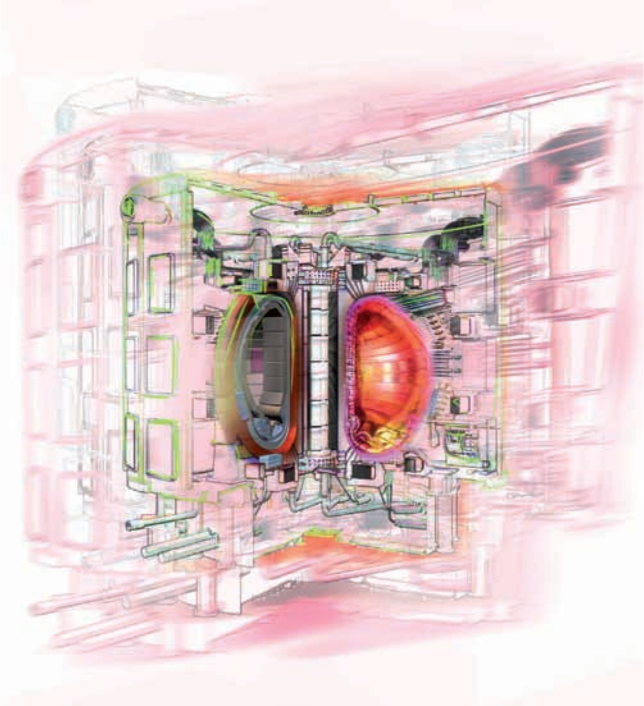
The Swiss Research Co-operation in the Field of Controlled Thermonuclear Fusion

27th report covering the years 2004 and 2005

ITER



Schweizerische Eidgenossenschaft
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27th report covering
the years 2004 and 2005

Content

Meilensteine

Auf internationaler Ebene:

20.05.2004: Der Europäische Fusionsexperimentalreaktor JET feiert 25 Jahre Betrieb.

28.06.2005: Die sechs ITER Parteien unterzeichnen ein Abkommen über den Bau von ITER in Cadarache, Frankreich.

28.06.2005: Die EU und Japan einigen sich auf zusätzliche Forschungs- und Entwicklungsarbeiten im Bereich der Fusionsenergie.

07.11.2005: Dr. Kaname Ikeda wird zum Generaldirektor von ITER ernannt.

06.12.2005: Das Umsetzungsabkommen zum Bau und Betrieb von ITER wird finalisiert.

06.12.2005: Indien wird als siebter Projektpartner in die ITER-Trägerschaft aufgenommen.

14.12.2005: Ein Informationsanlass mit dem Titel “Opportunities for European Industries” wird in Barcelona, Spanien, abgehalten.

15.12.2005: Der ITER Standort in Cadarache wird offiziell eingeweiht.

Auf nationaler Ebene:

23.06.2004: Der Bundesrat bewilligt eine Verlängerung des Assoziationsvertrage Schweiz - Euratom bis 31. Dezember 2005.

15.09.2004: Der Bundesrat bewilligt ein vereinfachtes Verfahren zur Verlängerung bestehender Vollzugsübereinkommen im Rahmen des Kooperationsabkommens von 1978.

22.09.2005: Das Departement des Innern bewilligt eine Verlängerung des Assoziationsvertrags Schweiz - Euratom bis 31. Dezember 2006. Die drei Ausführungsverträge EFDA, JET Implementing Agreement und Contract on Mobility werden ebenfalls um ein Jahr verlängert.

17.11.2005: CRPP und SBF organisieren in Bern einen nationalen Informationsanlass für die Schweizer Industrie über ITER und die zur Anwendung kommenden Beschaffungsverfahren.

30.12.2005: CRPP und SBF lancieren www.iter-industry.ch, eine Internet basierte Informationsplattform für die Schweizer Industrie.

Jalons de référence

Niveau international:

20.05.2004: JET, le réacteur expérimental de fusion européen fête ses 25 ans d'exploitation.

28.06.2005: Les six partenaires internationaux signent un accord sur la réalisation d'ITER à Cadarache, France.

28.06.2005: La Communauté Européenne et le Japon se mettent d'accord sur un effort bilatéral et supplémentaire afin de développer au plus vite l'énergie de fusion.

07.11.2005: Dr. Kaname Ikeda est designé comme Director General d'ITER.

06.12.2005: Finalisation de la négociation de l'accord d'implémentation pour la construction et l'exploitation d'ITER.

06.12.2005: L'Inde devient le septième partenaire du projet ITER.

14.12.2005: Un événement intitulé "Opportunities for European Industries" est organisé à Barcelone, Espagne.

15.12.2005: Le site d'ITER à Cadarache est inauguré.

Niveau national:

23.06.2004: Le Conseil fédéral autorise l'extension du Contrat d'Association Suisse - Euratom jusqu'au 31 décembre 2005.

15.09.2004: Le Conseil fédéral décide de simplifier la procédure de renouvellement d'accord d'exécution dans le cadre de l'accord de coopération de 1978.

22.09.2005: Le Départment de l'intérieur autorise la prolongation du Contrat d'Association Suisse - Euratom jusqu'au 31 décembre 2006. En même temps, les trois accords d'exécution EFDA, JET Implementing Agreement et le Contrat sur la mobilité sont aussi prolongés.

17.11.2005: Le CRPP et le SER organisent à Berne un événement d'information sur les possibilités de la participation industrielle dans la construction d'ITER.

30.12.2005: Le CRPP et le SER lancent www.iter-industry.ch, un site internet d'information pour l'industrie suisse interessée à prendre part dans la construction d'ITER.

Milestones

International:

20.05.2004: The Joint European Torus JET celebrates its 25th anniversary

28.06.2005: The six ITER Parties sign an agreement that will site the ITER reactor in Cadarache, France.

28.06.2005: The European Community and Japan agree to undertake further efforts to speed up the development of fusion to become an energy source

07.11.2005: Dr. Kaname Ikeda appointed as Director General of the ITER organization.

06.12.2005: Final negotiation on the joint implementation agreement of ITER concluded.

06.12.2005: India becomes the latest nation to join the ITER project.

14.12.2005: The workshop “Opportunities for European Industries” is held in Barcelona, Spain.

15.12.2005: The ITER Joint Work Site in Cadarache is inaugurated.

National:

23.06.2004: The Swiss Federal Council approves the extension of the Contract of Association between Switzerland and EURATOM until 31st December 2005.

15.09.2004: The Swiss Federal Council approves a simplification for renewing existing agreements between Switzerland and EURATOM.

22.09.2005: The Federal Department of Home Affairs approves the extension of the Contract of Association between Switzerland and EURATOM until 31 December 2006. Three other agreements are also extended, EFDA-agreement, JET Implementing agreement and Contract on Mobility.

17.11.2005: CRPP and SER organise an awareness and information event on ITER procurement and procedures for Swiss industry.

30.12.2005: CRPP and SER launch the Internet-based information platform for Swiss industry, www.iter-industry.ch, in order to foster the industrial sectors participation in fusion R&D.

Foreword

Since the late seventies, Switzerland's effort in fusion research has been paired, and coordinated, with the EURATOM fusion programme. The recognized competence of the Swiss scientific partners, combined with highly skilled Swiss industry, has enabled Switzerland to benefit from the joint activities. While Swiss science is one of the major pillars of European fusion research, business opportunities need to be better advertised to, and better addressed by, industry, particularly with regard to the decision to build ITER. Like particle physics and its machines, fusion research on the European level can be more and more compared with CERN and ESA activities. Although the ultimate goal or objective lies years ahead, the developments undertaken create medium- and even short-term benefits that can generate new business cases well outside the fusion community. Past technology transfers, and spinout business from fusion research, have generated not only new welding technologies, semiconductor production schemes, plasma screens, and other applications. Knowledge transfer from the fusion community has also contributed in a non-negligible part to the success of many public and privately run projects, including the Beagle 2 mission to Mars, increased production efficiency in the automotive sector, or the development of laser-based anemometers for wind turbines.

It is true that fusion power for everyday life is still some 30 to 50 years away. The intermediate step of building, and exploiting, the international thermonuclear fusion reactor ITER is, however, a unique opportunity to engage in science and technological innovation.

The present report covers the main activities of Swiss fusion research in 2004 and 2005. The first part summarises fusion research. It is addressed to the (as yet) uninitiated, but interested reader. The second part is more technical. It describes research undertaken at the Centre de Recherche en physique des plasmas CRPP, the Paul Scherrer Institute PSI, and the University of Basel Physics Department UniBS.

Chapter 2 reviews significant events in the world of fusion research in 2004/2005; it focuses on ITER and on the EURATOM fusion programme. Chapter 3 summarises the noteworthy events in Switzerland in 2004/2005. The report closes with links to further information and contacts for the interested reader.

For the benefit of those readers who have only episodic exposure to this field, an updated version of the executive summary of the previous overview is provided in Annex 1. Furthermore, two annexes have been added. Annex 2 gives an overview of the scientific and technical work performed in 2004/2005 at the CRPP of EPFL, whereas Annex 3 reports on findings obtained at the University of Basel Physics Department. Both annexes are for the benefit of the technically and scientifically versed reader; brief summaries of both documents are provided in the main body of the report (see Chapter 3).

The author is indebted to various scholars for providing a wealth of information, all of which contributes to the richness of the present report: Dr. Jean-François Conscience, former head of the SFOE Fusion Programme; Prof. Minh Quang Tran, Director of the Center for Research in Plasma Physics (CRPP), Swiss Federal Institute of Technology in Lausanne; Dr. Mark Siegrist (CRPP); Prof. Peter Oelhafen, University of Basel Physics Department.

Dr. Andreas Werthmueller
State Secretariat for Education and Research
Head of SFOE’s fusion programme

1 ITER, the milestone on the road to fusion electricity

1.1 Introduction

Since 1978 Swiss fusion activities have been closely linked with the European research programme, i.e. the EURATOM Framework programme on fusion. Switzerland participates in these efforts to develop knowledge on plasma physics and fusion technology in order to obtain an energy source with almost no limits. Fusion produces enormous yields of energy without CO^2 production. The fuel is available in huge quantities and well distributed all around the planet. A fusion reactor is intrinsically safe and its power can be transformed into heat, electricity or used for production of hydrogen. One hundred years after decommissioning, the activated material can almost entirely be recycled as non active. All these advantages have been and still are challenged by a major difficulty, which goes hand-in-hand with the already mentioned intrinsic safety: nuclear fusion requires extreme conditions in order to take place. It is therefore a physical as well as a technological challenge to make fusion happen. The European fusion research programme has concentrated from the very beginning on the development of fusion power. This strategy, which is nearly 40 years old has been tenaciously followed Europe, together and with with Switzerland, presently finds itself at the hub of knowledge in fusion energy. With the construction of the Joint European Torus JET, where Switzerland again participated as a full-fledged partner, Europe is well prepared for the next experimental fusion reactor ITER, which is the only remaining step between present day experiments and a demonstration plant DEMO producing electricity.

Back in 1985, the Russian President Mikhail Gorbachev proposed a project for an International Thermonuclear Research Reactor later called ITER. After 20 years of technical evaluation and a lot of politics, the project has found the support of six governments in addition to the European Union. With the EU (including Switzerland), Russia, China, South Korea, Japan, India and the United States of America, this represents more or less half of the world population. A lengthy and especially difficult negotiation phase on the future location of ITER stalled the project for almost three years. Finally, on 28 June 28th 2005, the project partners agreed to build ITER in Cadarache, France. The decision was accompanied by a bilateral agreement between the EU and Japan. The two partners also expressed their intention to investigate and develop technology for the step beyond ITER, i.e. the demonstration reactor DEMO. As a matter of fact, DEMO should follow ITER as the first fusion reactor producing electricity, thus giving proof of the economic viability of fusion power.

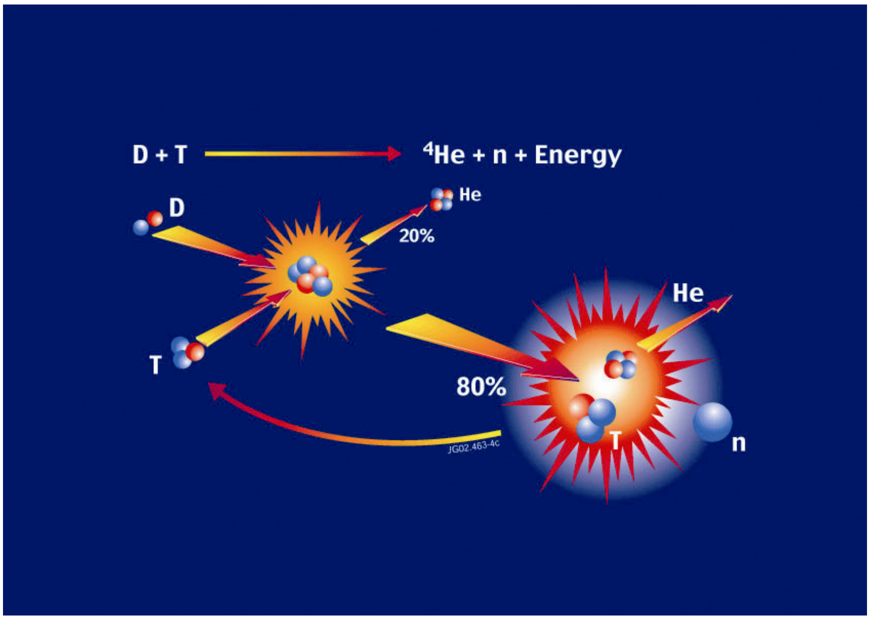


Fig 1: Schematic representation of the fusion reaction of deuterium and tritium, both hydrogen isotopes

1.2 Basic fusion physics

When light nuclei, such as the hydrogen isotopes deuterium and tritium, fuse together, the total mass of the resulting particles is slightly lower than that of the initial nuclei. According to Einstein's equation, the lost mass is converted into energy. As a matter of fact, the tiny mass losses in one fusion reaction generate a comparably huge amount of energy. This means that a given amount of fusion energy, compared to all other energy sources currently available could be produced with much less fuel. Fusing one gram of a deuterium/tritium mixture releases as much energy as burning eight tons of petroleum. Under these conditions, it is not surprising that one litre of seawater is equivalent, in terms of the fusion energy, to 300 litres of petroleum. As both deuterium (in water) and lithium (in rocks) are widespread and abundant on Earth, fusion power is in many ways an ideal solution to the world energy needs for the next 1,000 years or more.

However, nuclear fusion requires highly unusual physical conditions to take place. This is due to the strong electrostatic repulsion between positively charged atomic nuclei, which represents the ultimate barrier to fusion. Thus, achieving fusion on Earth is a formidable challenge. Two approaches are currently under investigation. In so-called inertial fusion, small pellets of deuterium and tritium are subjected to enormous pressures and high temperatures, using powerful laser beams or other sources of electromagnetic radiation. In another approach, atomic nuclei are heated to very high temperatures so that they overcome the electrostatic repulsion simply by kinetics. This principle is known as fusion by magnetic confinement.

As most fusion projects directed towards energy production, ITER is based on the magnetic confinement principle. The fusion of one nucleus of deuterium with one nucleus of tritium produces a nucleus of helium and a neutron. If the kinetic energy of the fusing nuclei is given a value of one unit for each, or two for both, the total kinetic energy of the products is 177 units, which corresponds to an energy gain of close to 200. Of the output energy, 37 units are carried away by the helium nucleus and 140 units by the neutron. The kinetic energy of the helium nuclei is dissipated through collisions with the other ions in the reaction chamber and contributes therefore to the heating of the plasma (so-called α particle heating). The energy of the neutrons is absorbed by the reactor walls as these particles get slowed down in the so-called "blanket" (see further down). The resulting heat can be collected with conventional heat exchanging technology and become available to the end user in form of heat, electricity, and, if the reactor is designed for such a purpose, hydrogen-gas for combustion or fuel cell applications or other uses.

For the fusion research community, the summit to achieve is the so-called "ignition", a situation when the plasma temperature is self-sustained by the α particle heating. However, ignition is not a prerequisite to harvest electricity from a fusion reactor. The reactor simply has to produce a large excess of energy, compared to the power that needs to be returned to the reactor for heating. The critical value here is the so-called Q ratio, that is the ratio between thermal fusion energy produced and external input heating. For a power plant, a Q of around 40 is needed. ITER, with a Q in the order of 10, will be a big advance in the direction of a fusion power plant.

1.3 Basic fusion technology

One of the greatest challenges in thermonuclear fusion is plasma confinement. Since temperature of the order of 100 million degrees is required, no direct contacts between plasma and material confinement is possible. In fact, even the slightest contact with the walls of the reaction chamber must be avoided, as it would immediately and drastically lower the plasma temperature and therefore prevent net excess from the fusion reactor. The solution to the problem is to build an immaterial reaction vessel through magnetic fields, the so-called magnetic confinement. Several ways to do this are being investigated, but the most advanced concept is that of the Tokamak. This Russian development is basically a doughnut shaped chamber (a torus) with a cross section profile similar to the letter D and equipped with two sets of magnets. Today's designs of Tokamak reactors use D-shaped cross sections, which is a major development from the Russian concept. The toroidal coils are wrapped vertically around the chamber at regular intervals along its circumference. They induce a constant magnetic field that is primarily responsible for confining the plasma. The poloidal coils encircle horizontally at various heights the whole reaction chamber. Together with a central solenoid coil (in the hole of the "doughnut"), they create variable magnetic fields, which are responsible for inducing a net electrical current in the plasma and for controlling its position.

The second major challenge in thermonuclear fusion is heating the plasma to the very high temperatures required for nuclear fusion to take place. Three approaches are used, often in combination. Firstly, the net electrical current induced by the poloidal magnetic field contributes to heating through a simple ohmic effect (conversion of electricity into heat as the current flow encounters resistance). Secondly, neutral particles (typically deuterium or tritium atoms), accelerated to very high velocities, are injected into the plasma; through collisions, they transmit their kinetic energy to the nuclear ions and, thus, raise the plasma temperature. Thirdly, by means of specially designed antennas, electromagnetic – also called RF (radio frequency) – waves can be injected into the plasma and, by selecting the appropriate resonance frequencies, used to heat either the electrons (100 - 200 GHz) or the nuclear ions (30-100 MHz); this is the so-called cyclotron resonance heating system. RF heating can also be performed using waves at another characteristic frequency of the plasma, the so-called “lower hybrid frequency” at around five to six GHz.

Last but not least, even with appropriate magnetic confinement the reactor material undergoes heavy stress from the fusion reaction. The intense neutron radiation, the main path of energy transportation from the plasma, is placing the reactor material under considerable load. First by the transportation of energy with temperature variation that can be considerable, and then by interfering with the atomic structure of the reactor’s material, causing problems related to structural integrity and radioactive protection. It is therefore a further challenge to develop adequate materials, which can withstand these conditions over long periods of time without major alteration of their physical properties and without being transmuted into long-lived radioactive isotopes. As the inside of the reactor will nevertheless be contaminated with activated material, shirtsleeve interventions inside the torus are out of the question. As an absolute prerequisite for a working power plant, remote handling is an additional technical challenge.

1.4 The design of ITER

Fig. 2 is a schematic representation of the torus section of the ITER Tokamak. The central torus has a radius of 6.2 m (measured at the centre of the vacuum or reaction chamber) and is braced by 18 toroidal coils to create a five Tesla magnetic field, which confines the plasma. Each of these magnets, together with its supporting structure, weighs 300 metric tons. In addition, six poloidal coils and a central solenoid coil induce a 15 millions A current in the plasma. All magnets are superconducting at liquid helium temperature (-270°C). For isolation purposes, the whole machine is enclosed in a cylindrical evacuated vessel. This so-called cryostat is 24 m high and 30 m in diameter. The total volume of the plasma is close to 850 m^3 but its weight is only about one gram since it has a density of only one millionth that of air. In other words, in the thermonuclear approach, fusion reactions take place in a vacuum with very little deuterium and tritium present in the reactor, and this in turn is an important safety feature of fusion reactors.

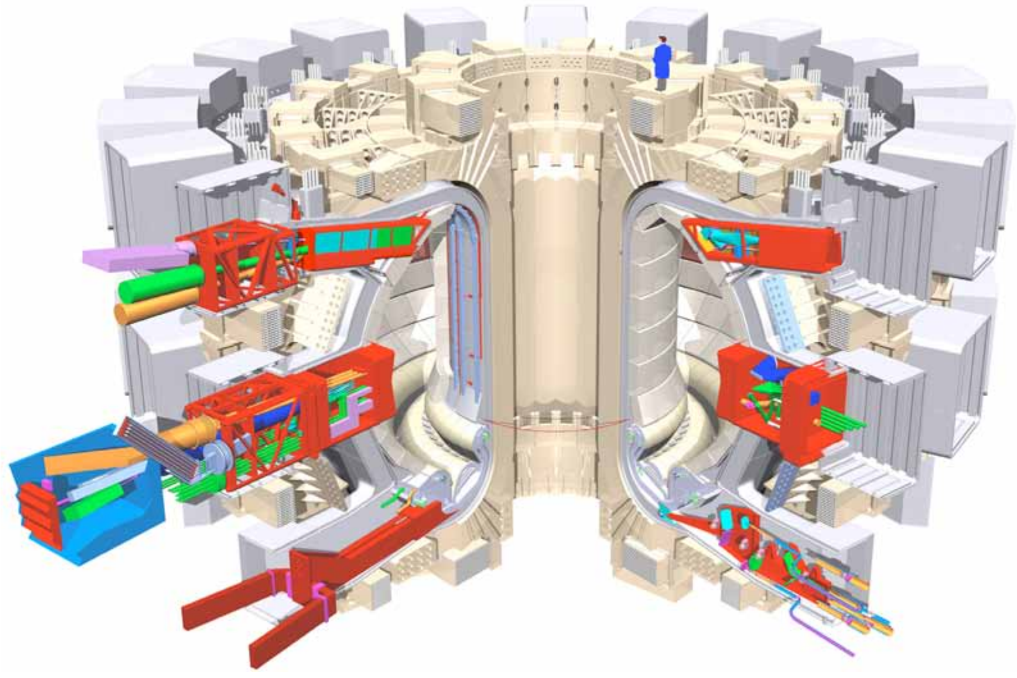


Fig 2: Cutaway of ITER showing some key plasma diagnostics

ITER will exploit all three approaches to heat the plasma: ohmic resistance, neutral particle injection and RF waves heating. In summary, ITER design can be regarded as a model for future Tokamak-based fusion power plants, with slightly reduced dimensions and lower power level, but with a wide operating flexibility in order to study operational modes of future reactors.

Therefore, diagnostic tools are an essential part of ITER design. They are aimed to assess three groups of parameters:

- basic machine operation and control (plasma shape and position, plasma current, gas pressure, electron density, fusion power, surface temperature, etc.),
- advanced control (electron temperature profile, ion temperature profile, radiation power profile, helium density profile, etc.),
- additional measurements for performance evaluation and physics.

The development of the corresponding technologies is not the least challenging part of ITER design and construction. The multiplicity of diagnostic tools is also one of the main reasons why access to the reaction chamber through remote handling is essential.

1.5 ITER performance and objectives

As already stated, ITER will produce about 500 MW of thermal power for sustained pulses of 300 to 500 seconds. This represents roughly a 10-fold excess over the heating power that will be supplied to the machine. Other operating modes with lower power outputs will result in steady-state operation conditions. In this way, ITER will meet its first objective to produce burning plasma of sustained duration. This will allow, in particular, the study of the heat exchange and tritium generation in the blanket, helium evacuation and fuel injection.

One of the fuel elements of fusion reactors is tritium. This radioactive isotope of hydrogen has a half-life of 12.5 years and is produced by neutron irradiation of lithium. Thus, the current concept of fusion reactors is to include lithium compounds in the inner wall of the reaction chamber (the so-called blanket), in which the energetic neutrons coming from the fusion reactions are being absorbed. In ITER, fusion reactions will be initiated primarily by injection of exogenous tritium, but the facility will be an ideal test bed for various blanket designs. Indeed, a second important objective of ITER is to allow a precise definition of the type of tritium - generating blanket in view of the first prototype power plant DEMO. Here, too, remote handling capability is essential in order to test different blanket modules inside the reaction chamber.

A third objective is to assess, in a power-plant-like situation, most of the required technologies, such as superconducting magnets of unusual size, heating systems, etc., in order to show that these technologies are mature enough to envisage the construction of fusion power plants.

Last but not least, ITER will also be an important test bed to assess safety-related aspects of fusion.

Since the successful series of JET experiments we know that controlled fusion can be generated on Earth. ITER will bring the final demonstration that its exploitation as an energy source is both scientifically and technically feasible in a safe way.

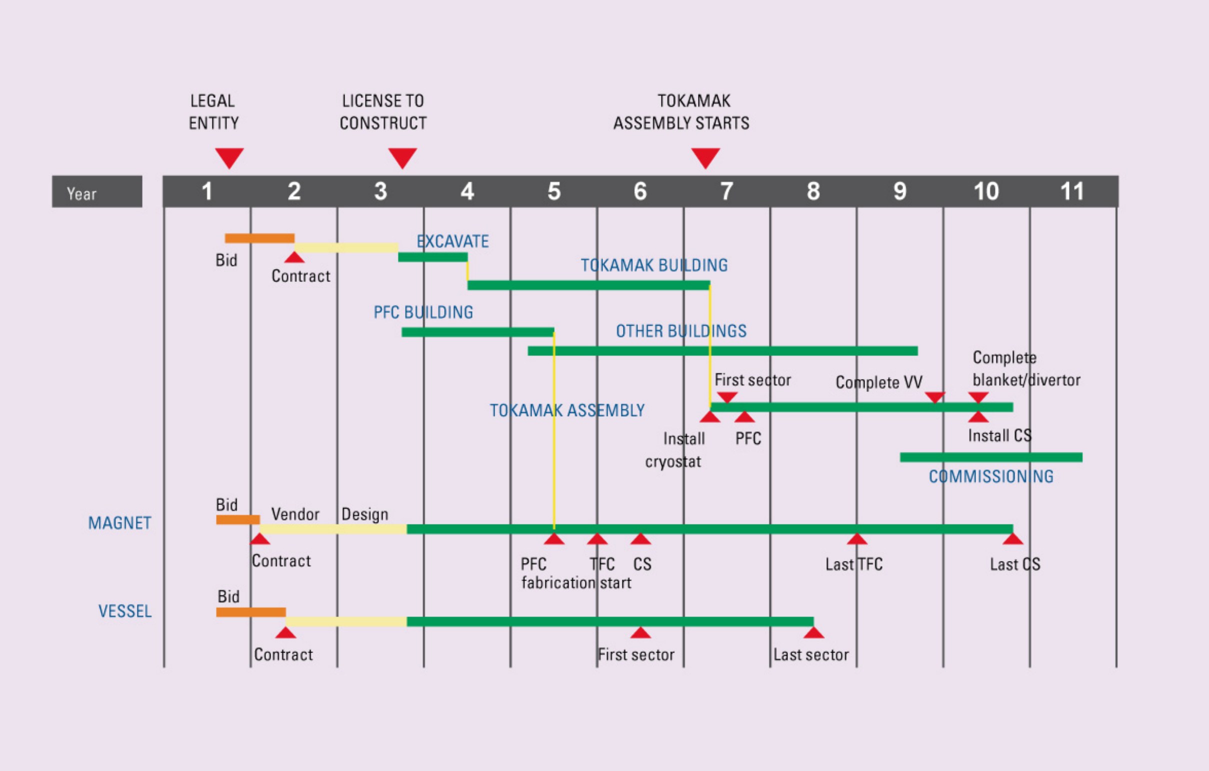
1.6 Costs and calendar

Current estimates put the ITER price tag at approximately 4’700 million € for construction and 5’000 million € for 20 years of operation. During early 2006 the Parties entered in their final negotiation round to define the cost sharing of construction, operation, deactivation and decommissioning. Concerning the construction phase, the Parties have agreed that EURATOM as the host party would bear 50% of the construction while each other party would provide 10%. For the phases of operation, deactivation and decommissioning it is foreseen that EURATOM will bear 34% of the total costs, Japan and the USA 13% each, and the other four Parties 10% each.

The resources for the construction phase will be provided predominantly by “in kind” contributions, including secondments of qualified persons as staff of the ITER Organization. The supply of ITER components has been divided into 90 procurement packages. These packages, items described with detailed specifications or build-to-print orders, are allocated to the prospective parties according to the “Common Understanding on Procurement Allocation”. The procurement of the parts, components or systems to be provided will be under the responsibility of the member providing the item, acting through its Domestic Agency. From this allocation procedure follows that there is a high degree of interdependency between the ITER Organization and its Members during the construction of ITER. In order to be able to assume its overall responsibility of the ITER Project, the ITER Organization will not only carry out its activities through its Headquarters in Cadarache but also establish Field Teams in the territory of each member. The Central Team will direct the project and assume responsibilities for the design, integration and assembly of the ITER Facilities and the preparation for their operation and exploitation. The Field Teams will oversee the procurements to be undertaken by the Member's Domestic Agencies. They will ensure quality assurance and manage in consultation with the Domestic Agencies scheduling changes and other necessary adaptations of the contributions in kind.

The so-called International Legal Entity ILE, will manage the ITER project. The European member in ILE will be the European Union, representing its member states as well as the countries associated with the EURATOM fusion programme. The European partners plan to organise their contribution in a so-called European Legal Entity ELE, which will coordinate ITER-related activities and contributions. It has been agreed among the European partners that the respective project shares will be delivered primarily through in-kind contributions as well, so that cash payments will be kept to a minimum.

Construction is expected to last about 10 years. Three years will be needed for machine testing in the presence of hydrogen, and another year in the presence of deuterium. It will then be possible to start with the critical experiments, using burning plasmas of deuterium and tritium. This key phase of ITER operation will last 3 years. In other words, it will take about 15 years from the beginning of ITER construction to have the answers needed to design and build the first prototype fusion power plant (DEMO). ITER will not become obsolete, though. Like JET today, it will remain a test bed for components, technologies, and operating concepts of future fusion reactors for many years.



1.7 Accompanying programme

Constructing and exploiting ITER will truly be a worldwide undertaking. Laboratories and industries of the seven Parties will design and build components. An example among many is to be found in Chapter 3 of the present report, which briefly describes the role of CRPP in the development of an electron cyclotron resonance heating system for ITER.

Clearly, ITER is the necessary next step on the road to harvesting fusion power and the current efforts aiming at its implementation are fully justified. However, it is important to realise that a coherent programme should be established to accompany ITER along the way, during both construction and exploitation. The content of this so-called "Accompanying Programme", which encompasses physics and technology, is briefly outlined below.

The priority placed on ITER should not preclude continuing studies on other reactor concepts. The current focalisation on a Tokamak design is fully justified by the advanced state of that particular technology, but nobody knows today what the final design of commercial fusion reactors will be. Other approaches, such as stellerators (see Chapter 2), are promising as well, and they should be continued, in combination with experimental and theoretical studies in basic plasma physics. This in no way diminishes the importance of ITER as the essential next step because many of the questions it will help resolve are critical for other reactor types as well. Thus, conceptual design and experimental work on future fusion reactors is an important chapter of the ITER Accompanying Programme.

The other chapter deals with materials studies. Although ITER will allow certain types of investigations in fusion materials to be undertaken, it is not a dedicated facility to study the alterations taking place in materials submitted to heavy neutron irradiation over extended periods of time. For that, another machine is needed, IFMIF (International Fusion Materials Irradiation Facility), a dedicated, high-flux neutron source. Designing and exploiting IFMIF, and, in the meantime, performing meaningful materials studies at other neutron sources, such as spallation sources, is the other important chapter of the ITER Accompanying Programme and a prerequisite for the successful realisation of a prototype fusion power plant.

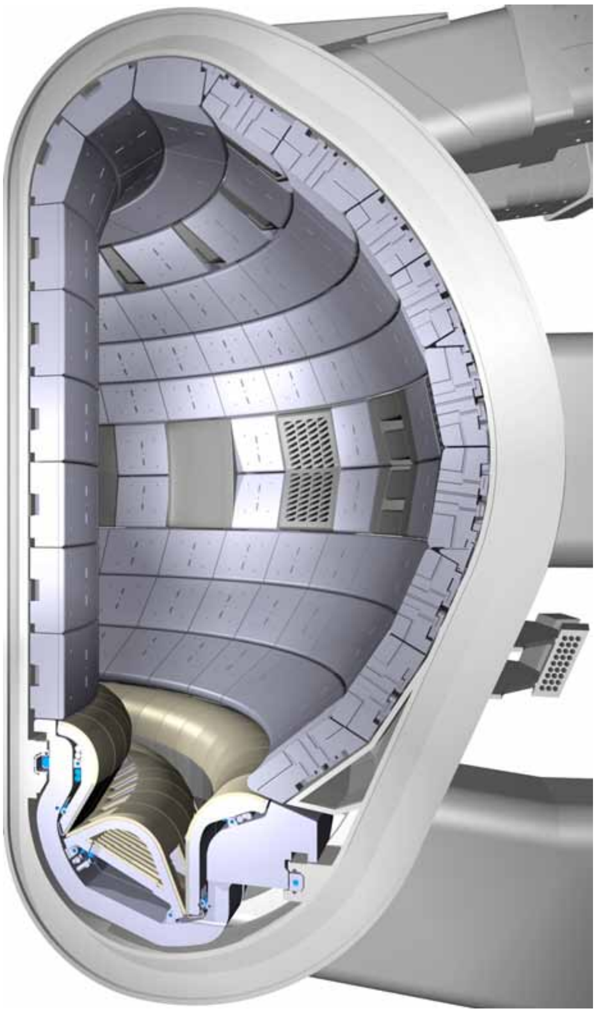


Fig 4: Cross-section of vessel and internal components

1.8 Risks and benefits of fusion research

By all criteria, there is no doubt that the road to fusion power is long and expensive. If and when fusion, one day, becomes a significant source of electricity, probably more money and time will have been spent to develop that form of energy than any other. Is it worth it? What are the risks that we may never get there? Is it producing spin-offs along the way that make it worthwhile even if the ultimate goal is not reached?

Undoubtedly, the attractive features of fusion energy weigh very heavily on the benefit side of the scale (see Annex 1). They include a plentiful, readily available and universally distributed fuel supply, the fact that fusion reactions produce neither CO^2 nor radioactive “waste” while releasing huge amounts of energy per unit weight of fuel, the inherent safety of power plant operation due to the very nature of the fusion reactions, and the relatively benign consequences for the environment of power plant refurbishment and decommissioning. Indeed, socio-economic analyses of future energy supply indicate that it will be extremely difficult to meet, in an environmentally acceptable way, the increasing demand of a developing world without fusion, even if the global consumption per inhabitant remains significantly lower than the current consumption of the industrialised nations.

Is there a risk that we might not get there? Despite the current confidence of fusion physicists, which rests firmly on the results obtained so far, it is fair to say that the risk of a significant scientific or technological stumbling block remains. Furthermore, even if the feasibility and practicability of harvesting fusion power is demonstrated, failure to develop appropriate materials for fusion power plants might never make it an economically acceptable source of energy. Indeed as in every human endeavour, there can be no certainty that the goal will eventually be reached.

So is fusion research producing results applicable to other fields in such a way that its spin-offs make it a worthwhile undertaking even if the ultimate aim is not reached? Yes, but only to a limited extent. The physics of hot plasma is a branch of modern physics and thus enriches basic knowledge. Fusion research has produced improved models in fluid dynamics and in diffusion phenomena that have found applicability in such diverse fields as wind energy and steel production. Basic research in plasma physics has applications in astrophysics and space physics, and has impacted upon the development of industrial applications of plasmas, and this in turn has led to improved manufacturing methods, for example, for solar panels. Materials developed for fusion can find other applications, i.e. in the field of high temperature. High-temperature superconductivity is undoubtedly attractive in other fields as well. Yet, these benefits are relatively few in number. It would be wrong, therefore, to overemphasise the spin-offs of fusion research in an attempt to justify it. It is the attractiveness of its ultimate goal, fusion electricity and energy production, which remain its main raison d'être.

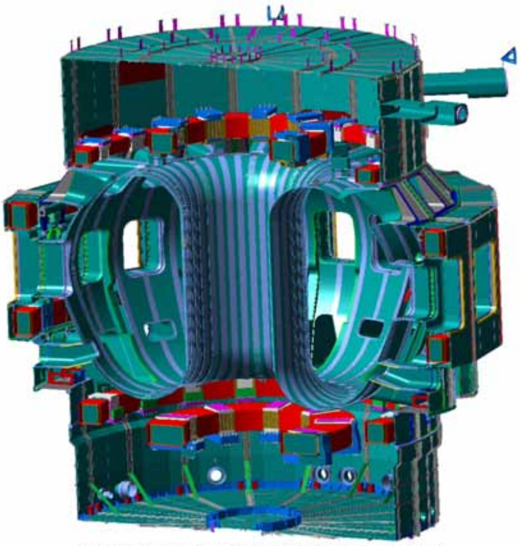


Fig 5: Thermal shield between coils and warm surfaces

2 Fusion research in the world

2.1 Introduction

Throughout the years, the interest in nuclear fusion as a credible energy option has continued to grow. In spite of the rather reserved funding schemes related especially to the long-term return of fusion research, the fusion community has made considerable advances. Also, the Governing Board of the International Energy Agency (IEA) endorsed in April 2003 a document entitled Energy Technology: Facing the Climate Challenge, in which fusion is included in a review of energy options for the future.

2.2 ITER

After the withdrawal of Canada and the extremely time-consuming negotiation on the future location of the ITER reactor, Brazil and especially India expressed their interest to join the ITER project. At the end of 2005, the ITER project involved seven partners: China, India, Japan, Russia, South Korea, the United States and the European Union. During the final ITER negotiations, good progress was made. By the end of 2005, there was a general agreement on almost every major issue. Therefore, there is good hope that the ITER International Legal Entity (ILE) will be instated by the end of 2006.

In particular, it was agreed that the ILE should be more than just an entity responsible for placing construction and operation contracts; indeed, it should also play a central role in managing the scientific exploitation of the facility. In parallel to the negotiations, detailed planning of ITER continued under the ITA (ITER Transitional Arrangements) and will continue until the ILE enters into force.

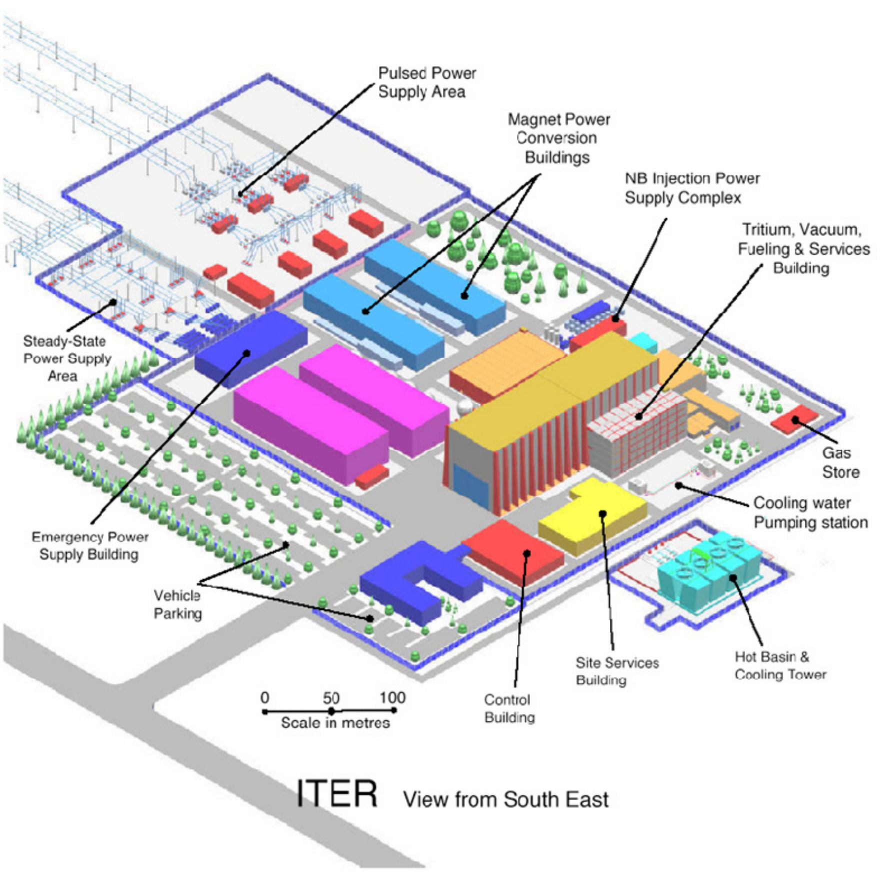


Fig 6: Diagram of the ITER site with the main building holding reactor pit and assembly hall

2.3 EURATOM fusion programme

Within the European Union, the European Atomic Energy Community (EURATOM) has been responsible for almost 50 years of research and development activities in the field of controlled thermonuclear fusion. Although the corresponding programme is now part of the framework programmes, it is still a separate chapter subjected to the rules of the EURATOM Treaty of 25 March 1957. This implies, for instance, that final decisions regarding programme content and funding are not taken by the European Parliament but by the Council of the European Union.

The European fusion programme includes the continuing exploitation of the European Tokamak JET in Culham (UK), the European participation in the design and planning of ITER, and a large fusion physics and technology section, including materials research and the investigation of magnetic confinement concepts other than Tokamaks.

Two main instruments are used to execute the programme: (1) the Contracts of Association between the European Union and about 20 national fusion research institutions (the so-called "Associations"; for the situation in Switzerland, see next chapter) and (2) the European Fusion Development Agreement (EFDA), which deals mainly with the centralised activities around JET, ITER and various other topics grouped under the subtitle "technology". These two instruments underline the peculiar situation of the EURATOM fusion programme that includes both joint activities managed centrally by the European Commission and the EFDA leadership, and decentralised projects carried out in the Associations with the financial support of the programme.

In addition to EFDA and the Contracts of Association, two other agreements help implement the EURATOM fusion programme. The JET Implementing Agreement (JIA) focuses on the use of the large European Tokamak and provides for a Joint Fund in which the participants to the programme contribute according to a scale, which is dependent upon their effective use of the facility. The JET Joint Fund covers slightly more than 25 % of the total cost of the facility; the rest is paid from the EURATOM fusion programme, and most of it is channelled through the JET Operation Contract (JOC) that the European Commission has concluded with UKAEA (United Kingdom Atomic Energy Agency), since the latter now owns JET and is responsible for operating it. Last but not least, the Mobility Agreement, which exists also in many other European programmes, encourages personnel mobility at all levels by granting travel and secondment allowances.

On these legal bases, activities were pursued under the 6th framework programme, which foresees for fusion a budget of 750 million €, including up to 200 million € for ITER. All Contracts of Association terminated at the end of 2005 and have been renewed for one year, until the end of 2006.

Fig 7: Euratom's fusion programme is driven by national research organisations and institutions called the Associations

2.4 EFDA and JET

EFDA activities are very much focused on ITER and reactor technologies, as well as on a whole range of supporting technologies (plasma heating systems, diagnostics, heat exchange, tritium generation, etc.). Another important aspect of EFDA activities is the exploitation of JET. Since the European Tokamak is based on the same concept as ITER, it has become an ideal test bed for ITER systems and components, and it has been widely used for that purpose. Indeed, some of the enhancements that were added to the machine did bring key ITER plasma parameters closer to JET's reach. In view of these developments, a continuation of JET exploitation throughout the period of ITER construction has been strongly advocated by some members of the fusion community, most notably (and not unexpectedly) by UKAEA.

Throughout the year, the machine operated with a very high degree of availability, in spite of a number of problems related to aging components. For the first time since the milestone experiments of 1997, which had set world records in fusion power production, tritium was again injected in trace amounts into the facility in order to study various aspects of particle transport in a fusion reactor. The current arrangement, whereby UKAEA is operating the machine and the European Associations, under EFDA and JIA, are using it, has worked smoothly and appears also to be cost effective.

Other activities under EFDA cover materials research, including the European participation in the design of the dedicated neutron source IFMIF (International Fusion Materials Irradiation Facility) (see below).

A replacement for the EFDA Leader, Karl Lackner, who resigned at the end of 2002, was found in 2003. On 24 June, the EFDA Steering Committee elected unanimously Prof. Minh Quang Tran of the EPFL/CRPP to the post. In November 2005, Prof. Tran announced his intentions to resign from his position as EFDA Leader. His motivation was basically the need to be able to devote all his time to prepare the future participation of CRPP, but also Swiss industry, for the upcoming ITER tasks and the future challenges in the field of fusion. The resignation took effect on 31 March, 2006.

Since 2002, EFDA-JET has been an active member of EIROFORUM (European Intergovernmental Research Organisations Forum: www.eiroforum.org), a loose association of the major European research organisations (CERN, ESO, ESA, EMBL, ESRF and ILL) that, among other activities, promotes public information. EFDA Associate Leader for JET, Jerome Pamela, has chaired this forum until June 2004.

2.5 IEA and IAEA

The International Energy Agency (IEA), an agency of OECD, plays an important role in coordinating various topics in fusion-related research worldwide via Implementing Agreements (IA's) between participating laboratories. Eight such agreements are currently in force and cover a broad range of fields including Tokamak physics, stellarators and other alternative concepts of magnetic confinement, plasma/wall interactions, socio-economic aspects, etc. (the site:www.iea.org/impagr/imporg/impagpub/listof.htm#5 gives a list and a short description of current IA's in the field of fusion). One of these IA's, devoted to fusion materials, is the incubator for IFMIF, the large neutron source that is needed to test materials under conditions similar to those in the interior of a fusion reactor, and whose construction costs are estimated at about 500 million €. A report entitled “IFMIF Comprehensive Design Report”, prepared by the IFMIF International Team, was published in early 2004. This report summarises all of the work performed in the IFMIF project since the beginning of the Conceptual Design Activities, with emphasis on the details of the design at the end of the Key Element technology Phase, giving the rationale and justification for the design arrived at by that point in the programme. The CDR also includes the users’ requirements and a cost assessment for the possible implementation of EVEDA (Engineering Validation and Engineering Design Activities) and of IFMIF construction, operation, and decommissioning. Although the financial investment of IEA in those activities is modest, usually limited to administrative support, the importance of its coordinating role cannot be overemphasized.

Besides providing administrative support to ITER, the International Atomic Energy Agency (IAEA), a specialised organisation of the United Nations, also has a number of activities related to nuclear fusion and steered by an advisory body, the International Fusion Research Council (IFRC). Following the positive reaction in 2003, Switzerland participated as an observer in IFRC. This was in response to a request by Prof. Minh Quang Tran but was also motivated by Switzerland's interest in hosting the Fusion Energy Conference (FEC), the major scientific event of IAEA in the field of fusion, in 2008 in Geneva. That year will be the 50th anniversary of the 2nd Geneva Conference on the Use of Atomic Energy for Peaceful Purposes. On that occasion, fusion research, previously buried in military secrecy, was presented for the first time to the public in the exhibit “Atoms for Peace”. Thus, 1958 is generally regarded as the starting point of fusion power research.

3 Fusion research in Switzerland

3.1 Introduction

Research in the field of controlled thermonuclear fusion is hardly possible without broad international co-operation, especially for smaller countries like Switzerland. Accordingly, the Swiss activities in this field are practically entirely integrated into the EURATOM fusion programme of which Switzerland has been an associate member since 1978. Furthermore, some research projects are carried out within the framework of Implementing Agreements of the International Energy Agency of the OECD and, finally, there are also a number of activities done within bilateral or multilateral collaborations with other fusion research laboratories. All this is financed by the Swiss Federal Institute of Technology in Lausanne (EPFL), the Paul Scherrer Institute (PSI), the Swiss National Science Foundation, the EURATOM fusion programme and, to a small extent, by the Swiss Federal Office of Energy (SFOE).

A major player is the Center for Research in Plasma Physics (CRPP) of the EPFL with its two sites in Lausanne and at the PSI in Villigen, near Zurich. At the EPFL, besides a strong theory group, the CRPP relies on its large facility, TCV (Tokamak à Configuration Variable), and on other facilities to study basic fusion plasma physics. In fusion technology, the centre has acquired international recognition notably for its expertise in heating systems using cyclotron-electronic waves. At the PSI, the interest of two CRPP groups lies in materials research and in superconductors with the worldwide unique test stand SULTAN. At the end of 2005, the EFDA also announced its decision to host a new facility for the test of the ITER superconductor near SULTAN. This facility, called the European Dipole, will allow Europe to undertake the qualification of industrial SC produced for ITER. It could also be used for future SC development in the frame of DEMO.

3.2 Coordination and funding on the national level

State Secretariat for Education and Research SER: The SER is the administrative unit responsible for coordinating Swiss fusion research. It cooperates closely with SFOE, which oversees, coordinates, and partly funds energy research in Switzerland.

Swiss Federal Office of Energy SFOE: With the financial support of SFOE, a unit of the University of Basel Physics Department has been co-operating for many years with the CRPP on studying surface changes resulting from exposure to hot plasmas. The group capitalises on the expertise it has acquired in photoelectron emission spectroscopy, and related techniques, to analyse graphite tiles from the inner wall of TCV; it has also continued its co-operation with the Forschungszentrum Jülich, Germany, and other EURATOM associates.

3.3 Agreements between Switzerland and EURATOM

The Cooperation Agreement in the Field of Controlled Thermonuclear Fusion and Plasma Physics between Switzerland and the European Atomic Energy Community (EURATOM) of 14 September 1978 remains the legal basis for an ongoing cooperation that has led to an almost total integration of Swiss fusion research activities into the European programme. It is a broad agreement of unlimited duration unless one of the two parties withdraws. The work programmes and the financial boundaries of the research activities carried out under the agreement are defined in implementing agreements of limited duration concluded between the executive branches of both parties, namely, the Federal Council for Switzerland and the European Commission for EURATOM. Currently, four such agreements are in force:

- The European Fusion Development Agreement (EFDA: see page 18);
- The Jet Implementing Agreement (JIA: see page 17);
- The Agreement on the Promotion of Staff Mobility in the Field of Controlled Thermonuclear Fusion (Mobility Agreement, see page 17);
- The Contract of Association which deals specifically with the bilateral co-operation between the CRPP and the EURATOM fusion programme; formally, the work programme is carried out by the so-called Association EURATOM-Confédération Suisse, which, de facto, means the CRPP.

The Contract of Association terminated at the end of 2005 and, following a decision of the Federal Departement of Home Affairs, was renewed for the 12th time, until the end of 2006.

Under these various implementing agreements, the two years 2004/2005 contribution of Switzerland to the EURATOM fusion programme – which is part of the EU framework programmes – amounted to approx. 15 million Swiss francs (incl. JET Joint Fund) and is likely to remain at a similar level for the last year of the 6th framework programme. Afterwards, the Swiss contribution will depend upon the final budget the EU grants to fusion in the 7th framework programme and upon the decisions concerning the financing of the ITER project.

3.4 The Association EURATOM - Confédération suisse

Except for a unit dealing with industrial applications of plasma physics (and whose activities are not reported here because they fall outside the scope of the Association), the work of CRPP is fully integrated within the EURATOM fusion programme and financed by the Swiss Federal Institute of Technology at Lausanne (EPFL), EURATOM, the Paul Scherrer Institute (PSI), the SER and the Swiss National Science Foundation. Research in fusion related fields is performed according to the work programme as defined in the Contract of Association. It foresees activities along the following broad lines:

- Physics of Tokamaks and, more generally, of fusion plasmas using mainly the large Tokamak TCV (Tokamak à configuration variable),
- Theory and modelling of fusion plasmas,
- Participation in the scientific exploitation of JET within the framework of EFDA,
- Technology activities, including research and development in the fields of electron cyclotron heating and current drive, of materials for fusion, of socio-economic studies, and of superconductivity, also within the framework of EFDA.

Most of these activities are carried out at the CRPP headquarters within the campus of the Swiss Federal Institute of Technology in Lausanne (EPFL). Activities in the fields of superconductivity and materials are partially supported by the Paul Scherrer Institute (PSI) in Villigen, near Zurich, where large, dedicated infrastructures (SULTAN, PIREX (now decommissioned), SINQ, hot cells and hot laboratories) are located and scientifically exploited under the supervision of CRPP. Finally, for socio-economics studies, cooperation was established with the Centre for Energy Policy and Economics (CEPE) and the Laboratoire des Systèmes Energétiques (LASEN) of EPFL.

As exemplified by the tight link with the EURATOM fusion programme, international collaboration is an important component of the activities of CRPP. Scientific and technical contacts are maintained and strengthened with international research institutions of the European fusion programme and within the framework of international agreements, such as the fusion-related Implementing Agreements of the International Energy Agency (IEA), as well as with industry.

Finally, in addition to the research duties, education and training of physicists and engineers is another important mission of CRPP. Besides its participation in the teaching of general physics, it offers a specialised graduate course for its Ph.D. students, covering all activities of CRPP.

Annex 2 summarizes for the specialist the scientific achievements and many exciting results obtained in the years 2004 and 2005. A more detailed account can be found in the Annual Reports, which can be ordered from CRPP (crppwww.epfl.ch). Only a brief executive summary is given below.

A worldwide unique feature of TCV is the possibility to produce magnetically confined plasmas of different shapes, and this turns out to be essential in order to verify numerical simulations and design geometrically optimised reaction chambers for future fusion power plants. Activities along this line of research in 2003 dealt with electron cyclotron resonance heating of plasma, edge effects and the influence of various disturbances on the behaviour of plasma, and the requirements to optimise magnetic confinement. These studies were supported by extensive refurbishment and upgrading of the facility and of diagnostic tools during shutdowns.

A new facility for plasma physics (TORPEX for Toroidal Plasma Experiment) came into operation in 2003 at CRPP, dedicated to the study of turbulence and abnormal transport phenomena in toroidal plasmas. Furthermore, the facility is ideally suited for training plasma physicists. Plasmas of argon and other rare gases can be reproducibly obtained in a 1 m diameter torus through electron cyclotron resonance heating at pressures of 10-4 to l0-5 mbar.

Different parameters can be adjusted in order to control density profiles and plasma temperature. Operation of TORPEX continued during 2004 and 2005 with optimised plasma production.

In superconductivity research, the SULTAN (Supraleiter-Testanlage) facility of CRPP, located at the PSI, can look back to a full year of testing superconductors for the magnets of future large fusion facilities. Most of the tests were performed on prototype cables for ITER made of NbTi and Nb3Sn, but samples for the stellerator[1] Wendelstein-7X (W-7X), currently under construction in Greifswald (Mecklenburg-Western Pomerania), were also tested. During fall 2005 the European Commission allocated a new test facility for ITER supraconducting components to the Swiss associate. The CRPP group at the PSI will therefore see SULTAN be complemented with a unique test stand for supraconductive joints.

The attractiveness and economics of future fusion power plants depend heavily upon the development of so-called low-activation materials. When submitted to the intense neutron flux generated by fusion reactions inside the reaction chamber, such materials do not transmute into radioactive isotopes with long half-lives and their mechanical properties remain essentially unaltered. Thus, materials research is an integral part of any fusion programme, and the CRPP materials group, also located at the PSI, vigorously pursued such studies. Investigations were also carried out using the locally available Swiss spallation neutron source SINQ. A special emphasis was placed on modelling studies. Indeed, such studies, combined with carefully selected experiments on SINQ, allow research on fusion materials to make progress, until IFMIF comes online and permits materials testing to be done under neutron irradiation conditions comparable to those present inside a fusion reactor.

CRPP's expertise in developing electron cyclotron heating systems is acknowledged worldwide. As a result, the centre is coordinating a collaboration of European laboratories in charge of developing a gyrotron for ITER (170 GHz, 2 MW). In 2004, after completion of the conceptual studies, construction of the device has started. In addition, a European test stand for the instrument is under construction at the CRPP premises.

Finally, CRPP has been involved in socio-economic studies in cooperation with two other institutions of the Swiss Federal Institutes of Technology. Together with CEPE, fusion related risk perception was studied in different geographical groups, in Europe (Switzerland, Belgium, France and Austria) and in the Cadarache area. Another institute, LASEN, investigated global energy scenarios for the year 2100 and assessed a possible role of fusion in that time frame. CEPE is presently involved in sociological studies about the acceptance of fusion and other novel energy sources.

Research done at the University of Basle

Within the physics department, the group of Prof. Peter Oelhafen has acquired considerable expertise in the use of photoelectron emission spectroscopy and related techniques, which are particularly well-suited to study surface phenomena. For many years, the group has been analysing graphite tiles coming from the inner wall of the TCV in order to characterise the surface changes caused by exposure to hot plasmas, indeed a critical question for designing future fusion reactors. Continuing contacts with the Forschungszentrum Jülich (FZJ) enabled investigations on surface changes in optical mirrors after exposure to plasma.

Such mirrors are foreseen in ITER diagnostic ports as components to measure plasma light radiation in a broad range of wavelengths. Information about their performance is still insufficient. In particular, the deterioration of the reflectivity due to particle impact is not yet characterised. Experiments in smaller machines are needed in order to develop strategies to investigate and control the interaction of the plasma with the mirror surfaces. In collaboration with the Institut für Plasmaphysik at FZJ, the Oelhafen group has investigated changes in optical properties of molybdenum mirrors after exposure to plasma in TEXTOR. As the presence of carbon and oxygen, and the resulting molybdenum carbides and oxides, strongly influence the optical properties of the surface, codepositions of Mo and C in the presence of O were carried out. The different phases present in the film were analysed by photoelectron spectroscopy (XPS and UPS). The optical constants were measured by ex-situ spectroscopic ellipsometry and photospectometry and were correlated with the chemical composition of the film. A full report of the current status of this work is given in Annex 3.

The Swiss Federal Office of Energy (SFOE) supports work of the Basle group financially. The long-standing contract between the group and SFOE ended in June 2006.

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[1] Stellerators represent another concept for magnetic confinement of plasmas; interesting and promising, too, they are however less advanced than Tokamaks

Annex 1: Where do we stand in fusion research?

The question is today of particular interest as the international community is being asked to invest 10 billion € in the International Thermonuclear Experimental Reactor (ITER), half for building it and half for exploiting it. Under the auspices of the International Atomic Energy Agency, the milestone project will be a joint venture of many countries with, as main partners, China, the European Union (EU) including Switzerland, Japan, the Russian Federation, South Korea, the USA. and India. The design of what will be the first fusion reactor producing significant amounts of energy was completed in June 2001.

The negotiations aiming at a decision on the ITER site took a long time, but progressed during 2004-2005. The deadlock between the European Union (EU) (wishing to construct ITER at the European site of Cadarache in France) and Japan (wishing to construct ITER at Rokkasho in the north of Japan) was resolved in June 2005 in an agreement in which the European candidate site was selected. The choice of European site of Cadarache as the ITER site was strongly supported by the Swiss government and the Swiss Association and we are convinced that the CRPP is well placed to take advantage of our proximity to the site.

The agreement reached with Japan includes an extremely important component, the inclusion of programmatic elements beyond ITER and aiming towards the fast realisation of fusion as an energy source. This programme, known as the “Broader Approach”, could for example include a computational centre for ITER data analysis, the construction of large Tokamak to optimise the operation of ITER (the satellite Tokamak), a centre to develop the step after ITER, namely a demonstration reactor (DEMO) as well as a facility to advance fusion material science and technology (the International Fusion Material Irradiation Facility IFMIF). The details of this Broader Approach are presently under negotiation between the EU and Japan.

In the agreement between the EU and Japan, the EU also conceded part of its own procurement packages to Japan. The Director General of the ITER Organisation was nominated in November 2005 and on 6 December of the same year India joined the ITER project.

The facts

Technical feasibility: Production of fusion energy has been demonstrated in experimental devices at levels of up to several megawatts for short time spans (up to five seconds). Scientific and technological know-how, leading to an agreed design, is now available for the construction of the first experimental reactor, ITER, in order to demonstrate that harvesting power from thermonuclear fusion is indeed scientifically and technically feasible. Thus, fusion energy generation on a commercial scale is not dependent upon further scientific breakthroughs; it is a matter of research and development to optimise existing concepts and technologies, and it requires both large international facilities and strong domestic programmes of supporting research. As materials with high irradiation resistance and low neutron-induced activation are of particular importance for highly performing, environmentally benign and economically attractive power plants, an International Fusion Materials Irradiation Facility is being designed to test materials for fusion.

Safety: Extensive studies have shown that fusion is inherently safe and environmentally friendly. Initiating and maintaining fusion reactions require a number of such highly uncommon physical conditions that failure of components or uncontrolled operation immediately leads to reactor shut down. Although a fusion reactor contains significant amounts of tritium – a radioactive isotope of hydrogen, which, together with non-radioactive deuterium, makes up the fusion fuel – the worst in-plant generated accident would result in limited hazards to the public. Similarly, the consequences of accidents caused by external events, such as a large earthquake, would be far less severe than those resulting from the event itself. Finally, fusion fuels and materials are not subject to non-proliferation treaties because none of them poses a security threat with respect to nuclear weapon development.

Environment: The fusion reactions produce no greenhouse gas and no radioactive or toxic products, but neutron-induced radioactivity of the inner reactor walls does occur. Almost all of the activated materials, however, can be disposed of as inert waste, recycled, or given shallow-land disposal about 100 years after the end of operation. Furthermore, it is reasonable to expect that future research on materials will optimise this aspect.

Security of fuel supply: Tritium is produced in the fusion reactor from lithium, an element that, like deuterium, is plentiful, widespread and available at low cost. It is recalled in this context that fusion reactions release huge amounts of energy: 0.1 ton of deuterium and four tons of lithium would be enough to fuel for one year a 1,000 megawatt electrical power plant requiring today 2.1 million tons of coal, or 10 million barrels of oil, or 100 tons of uranium.

Economics: The estimated costs of ITER have been validated by industry. Extrapolating from them, the final costs of fusion electricity can be estimated and will depend upon the extent to which fusion physics, technologies and materials are further optimised in the next few decades. Despite these uncertainties, current evaluations show that fusion electricity would be competitive in the future energy market. This is all the more so if emission mitigation costs such as carbon sequestration or external costs (e.g., environmental damage, adverse health impacts) are taken into account, and the significance of these costs is expected to grow in the future. Under these conditions, the projected cost of fusion electricity is comparable to that of other, environmentally friendly sources, thus ensuring it a significant share of the market by the end of the century.

Social acceptance: Ongoing social studies indicate that no specific public acceptance problems are expected for fusion if comprehensive information is available and if the public is actively involved in the decision process at an early stage.

The questions

« When will fusion power be available? » Despite significant progress, it is an acknowledged fact that the practicality and economical feasibility of harvesting fusion power remain to be demonstrated. ITER construction and operation are major steps toward that goal. The experimental reactor is designed to be a flexible test facility capable of producing a significant amount of thermal power (500 megawatts) under conditions mimicking those of a power plant. After about 10 years of construction, it will be exploited for some 20 years, and, combined with the materials development programme it will tell whether a demonstration power plant can be brought on line approximately 35 years from now. This would then lead to the first prototype commercial power plant toward the middle of the century. Stronger political will, leading to quicker decisions and heavier initial investments, could shorten markedly the development time ("fast track" scenario).

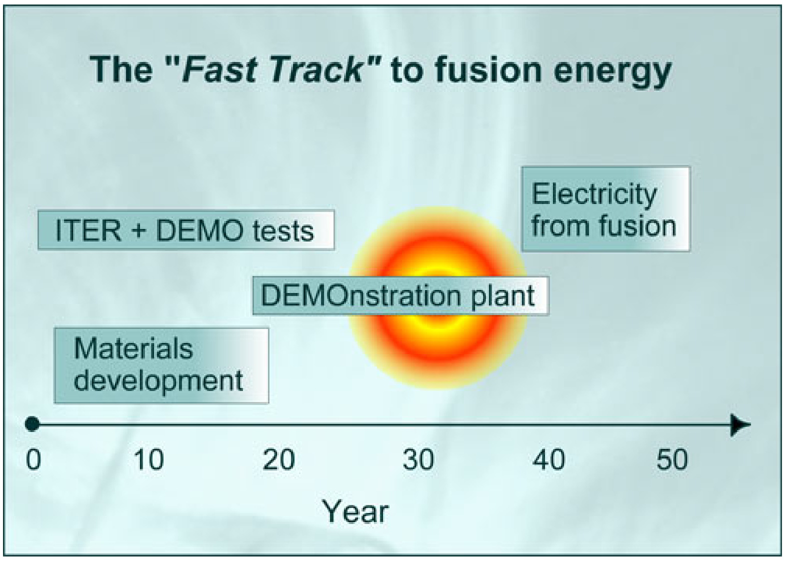

Fig. 8: With intensifield and coordinated use of existing research infrastructure fusion energy become reality in our lifetimes

«Why is it still so far away?» Since the 1960's, fusion research has often been perceived as an expensive, moving target, because the fusion community regularly had to revise its estimate of the time needed to bring the technology to maturity. With the benefit of hindsight, it is easy to understand why. The most important factor was the initial lack of knowledge in the state of matter to be reached in order to allow a fusion power plant to work. The construction of a series of experimental devices has enabled the building up of the necessary experimental data and the testing of theoretical models, which allow now to undertake with confidence the development of fusion as an energy source.

«Why invest in fusion?» The difficulties in solving the vital problem of providing energy for the future, with assurance of a secure supply while avoiding climate change, are universally recognised. No technological options can be ignored and, among these, fusion is a principal candidate for major contributions to the energy future, in particular for the centralised supply of base-load electricity. Indeed, socio-economic studies of long-term energy scenarios show that the cost, including externalities, of satisfying energy demand without fusion would be huge, dwarfing the cost of fusion development.

«How is fusion research coordinated?» Worldwide cooperation on fusion is established primarily within the framework of the International Atomic Energy Agency and of the International Energy Agency. The latter coordinates the activities of eight Implementing Agreements fostering international cooperation on many fusion-relevant topics. Several countries have national fusion research programmes that, in Europe, are largely integrated into the EURATOM fusion programme of the European Union.

Annex 2: Fusion research at EPFL/CRPP in the years 2004 and 2005

Research in the field described in this report is part of the integrated EURATOM Fusion Programme. Through its participation in the EURATOM programme, the Centre de Recherches en Physique des Plasmas (CRPP) benefits from collaboration with all the European Fusion Laboratories (also referred to as the Associations) and with laboratories outside Europe. The international fusion programme is aimed at the exploitation of fusion as an energy source. Two lines of research are followed in view of achieving this goal:

- Physics research aimed at understanding the phenomena in a "burning plasma" (i.e. in a high temperature plasma where fusion reactions generate a large fraction of the heat source).
- Technological developments to ensure the feasibility and environmental acceptability of a fusion reactor.

The CRPP research programme addresses these two lines. The technological axes are research into superconducting magnets and into suitable materials for a reactor. Both these lines of research are carried out in the CRPP laboratories at the Paul Scherrer Institute (PSI). The CRPP also has a vigorous industrial plasma group, financed independently of the fusion research programme.

Among the European fusion research facilities, TCV remains unique with respect to:

- Its capability of creating plasma with a very large variety of cross sections. With this flexibility it is possible to explore plasma with different shapes, contributing to the available database of Tokamak properties,
- Its additional heating properties. TCV has a 4.5MW electron cyclotron wave (ECW) heating system with three MW in the extraordinary second harmonic mode (X2) and 1.5 MW in the extraordinary third harmonic mode (X3). Combined with a launching system, which controls the spatial deposition of the beam, this system is still the most powerful ECW installed in a Tokamak worldwide.

In conjunction with a state of the art set of diagnostics and close collaboration with the CRPP Theory Group for data interpretation, significant contributions have been reported in various important fields of Tokamak physics, such as heating and current drive by ECW, plasma shaping and control, studies of internal transport barriers, of magnetohydrodynamics (MHD) phenomena and of plasma-wall interaction.

Theory and numerical simulations of hot magnetised plasma is a well-recognised field of expertise of the CRPP. Numerical modelling is possible through the availability of modern computing facilities at the EPFL (for example a cluster including about 100 PCs has been operational since 2003 and will be continuously upgraded and "Blue Gene", a cluster of up to 10,000 PCs), in Switzerland and in other Associations.

The research activities in this field are focused on:

- The simulation of important phenomena (such as ion temperature gradient mode) that influence transport;
- Exploration of novel 3D magnetic confinement structures;
- Support for the TCV and other experiments
- Participation in the activities of the European Integrated Tokamak Task Force.

The CRPP theory group collaborates with many other laboratories such as CEA Cadarache (F), IPP-Greifswald (D), LHD group (J).

Since 2000, the scientific exploitation of JET and the implementation of major improvements to its hardware are under the responsibility of European laboratories. The exploitation is organised in campaigns around "JET Task Forces".

The CRPP has also contributed to the following activities:

- A member of the CRPP is Task Force Leader in the field of plasma edge.
- The CRPP is responsible for a major novel diagnostic implemented on JET, an antenna for Alfvén wave (TAE diagnostic).
- Members of the CRPP have been participating in all JET campaigns, in spite of the heavy domestic load associated with the operation of the TCV.

- The TCV team is also engaged in specific projects on ASDEX-Upgrade, AUG, (D), Tore-Supra (F) and FTU (CNR-Milano and ENEA-Frascati (I)).

Scientific and technical contributions during the present phase of ITER are one of the main priorities of the CRPP. With the intention of making important contribution in its fields of expertise, namely the electron cyclotron wave (ECW) system, diagnostics, and plasma control, CRPP is also preparing the ITER construction.

In collaboration with other European Associations, the CRPP is currently participating in:

- The development of the 170GHz-2MW-CW gyrotron and of the ITER ECW upper launcher;
- The construction of the European gyrotron test stand. The test stand will be used for the development of the 170GHz-2MW-CW gyrotron and of the RF components of the ECW upper launcher in ITER operating conditions;
- The development of ITER diagnostics. The CRPP has expressed its wish to be responsible for the ITER magnetic diagnostics.
- In parallel, members of the CRPP serve as experts in the “International Tokamak Physics Activities” groups.

For more details you may consult the annual reports of CRPP which are published on the website crppwww.epfl.ch.

Publications

CRPP publications can be found on the webpage of the institute under the following link:
crppwww.epfl.ch/archives/

Scientific collaboration

National collaboration:

- Plasma-surface interaction, in collaboration with the University of Basel
- Socio-economic Studies Long Term Electricity Supply Scenarios Worldwide : Quantitative Assessment with a Least Cost Electricity System Planning Model (PLANELEC-PRO) (Work performed by the LASEN (EPFL) for the Association on behalf of EURATOM;
- Sociological studies related to fusion performed by CEPE (ETH-Z) for the Association on behalf of EURATOM: Ph. Mullhaupt, D. Bonvin, B. Srinivasen,
- Laboratoire d’Automatique, EPFL: S. Siegmann, Jong-Won Shin,
- EMPA Thun: P. Ott, S. Pavon,
- Laboratoire de Thermique Appliquée et Turbomachines, EPFL:
  Studies in materials for high temperature applications in collaboration with the PSI

International collaboration:

- A. Alfier, P. Nielsen, R. Pasqualotto, G. Manduchi: Consorzio RFX, Padova, Italy,
- J-F. Artaud, V. Basiuk, Association EURATOM-CEA, France, “Coupling of the DINA-CH and CRONOS codes to simulate the ITER hybrid scenario”
- F. Castejon, CIEMAT, Madrid, Spain; F. Volpe, Culham Laboratories, UK, “Electron Bernstein Wave Current Drive in Stellarators (and Tokamaks)”
- S. Cirant, F. Gandini, EURATOM-ENEA-CNR Association, Italy, "Electron transport studies on TCV via shear modulation experiments with ECCD"
- G. Conway, IPP, Garching, Germany, “Planning of a reflectometer diagnostic for TCV”

- A. della Corte, Association EURATOM-ENEA, Italy, D. Ciazynski, Association EURATOM-CEA, France, “Test in SULTAN of the ITER TFAS (Advanced Strand)”
- W. Fietz and R. Heller, Association EURATOM-FzK, Germany, A. della Corte, Association EURATOM-ENEA, Italy, J. Rifflet, Association EURATOM-CEA, France, F. Toral and J. Lucas, Association EURATOM-CIEMAT, Spain, “Conceptual design of 12.5 T EFDA Dipole”
- R. Heller, Association EURATOM-FzK, Germany, “EFDA task on design of high-temperature superconducting bus bars”
- Y. Ilyin and A. Nijhuis, University of Twente, The Netherlands, “Assessment of AC losses results from tests in SULTAN”
- H.P. Laqua, IPP Greifswald "Electron Bernstein Waves on TCV", Successful experimental determination of optimum ECRH injection angles for mode conversion from O- to X- and finally to Bernstein mode.
- D. Mazon, Association EURATOM-CEA, France, “Temporary loan of imaging hard-x-ray camera”
- Ph. Moreau, Association EURATOM-CEA, France, “Equilibrium diagnosis by modulation”
- S. Nowak, EURATOM-ENEA-CNR Association, Italy, “Modeling of X3 top-launch on TCV with beam-tracing code ECWGB”
- Y. Peysson, J. Decker, Association EURATOM-CEA, France, “Quasilinear Fokker-Planck simulations and modelling of hard X-ray emission in TCV”
- V. Piffl, IPP Prague, September-October. The aim of this collaboration is to study the carbon ionisation equilibrium using Charge Exchange Spectroscopy and to infer transport coefficients for carbon ions.
- A. Rodrigues, L.A. Pereira, C. Varandas, CFN Lisbon, “Advanced plasma control for TCV”. This project consists in upgrading the central analogue controller of the TCV plasma control system with a system based on an array of DSP boards connected together to provide about 32 inputs and 32 outputs.
- I. Tigelis, S. Mallios, Association EURATOM Hellenic Republic, "Modeling of the EM field distribution at 2.45GHz in the empty TORPEX torus"
- I. Tigelis, G. Latsas, Association EURATOM Hellenic Republic, "Instability calculations in the 170GHz coaxial-cavity-gyrotron beam-duct"
- G. Veres, HAS, Budapest on impurity transport using laser ablation. A first visit took place in March, which allowed the apparatus, supplied by KFKI in 1997, to be taken into service again. A follow-up visit will take place in October-November, with the aim of injecting Ti into eITB plasmas.
- F. Volpe, Association UKAEA Fusion, Culham, UK, “Electron Bernstein wave (EBW) modelling with the ART ray tracing code, planning of EBW experiments on TCV”
- M. Windridge, Association UKAEA Fusion, UK, “Non-linear modelling of MAST”
- J. Egedal, W.Fox, M.Porkolab, PFSC, MIT, USA, “Investigation of the physics of magnetic reconnection in the collisionless regime in a dedicated laboratory device, the Versatile Toroidal Facility"
- Dr. Debasi Chandra, IPR, Bhat, Gujarat, India, "Comparison of theoretical and experimental stability properties of resistive MHD modes with plasma shape"
- R. Gruber, EPF-Lausane, Switzerland, S.P. Hirshman, ORNL, USA, K.Y. Watanabe, H. Yamada, S. Okumara, Y. Narushima, S. Sakakibara, C. Suzuki, T. Yamaguchi, NIFS, Japan, K. Yamazaki, Nagoya Univ., Japan, “3D anistropic pressure equilibrium and fluid magnetohydrodynamic stability”
- R.W. Harvey, A.P. Smirnov, E. Nelson-Melby, CompX, San Diego, CA, USA, “Development of a fully relativistic ray tracing solver for study of mode conversion and electron Bernstein wave propagation in TCV”
- W. Heidbrink, H. Boehmer, UC Irvine, USA, "Sources for energetic ions for a simple magnetized torus"
- Y. Igithkhanov. T. Andreeva, C. Beidler, J. Kisslinger, H. Wobig, Max Planck Institut fuer Plasma Physik, Greifswald, Germany, "Bootstrap Current Effect on Stability in a 4-Period Helias Reactor"
- M.Yu. Isaev, Russian Research Centre Kurchatov Institute, Moscow, Russia “Development of the VENUS-df Code for Bootstrap Current and Neoclassical Transport in Stellarators”

- M.Yu. Isaev, Kurchatov Inst. Moscow, Russia, H. Maassberg, C. Beidler, J. Nuehrenberg, M. Schmidt, J. Geiger, IPP-Greifswald, Germany, A. Bergmann, IPP Garching, Germany, “Nontecarlo-delta_f neoclassical transport in 3D systems”
- K. Kim, KBSI, South Korea, K. Okuno, JAERI, Japan J. Minervini, PFSC, MIT, USA, V. Pantsyrny, ASRIIM, Russian Fed., and P. Weng, CAS, China, “Preparation of ITER conductor qualification samples”
- S.Yu. Medvedev, A.A. Martynov, A.A. Ivanov, Yu.Yu. Poshekhonov, Keldysh Institute of Applied Mathematics, Moscow, Russia, M.Yu. Isaev, V.D. Shafranov, A.A. Subbotin, RRC Kurchatov Institute, Moscow, Russia
- "Equilibrium and Stability of 2D and 3D plasma configurations"
- M. Mikhailov, A. Subbotin, V.D. Shafranov, M.Yu. Isaev, M. Samitov, Russian Research Centre Kurchatov Institute, Moscow, Russia; J. Nuehrenberg, Max Planck Institut fuer Plasma Physik, Greifswald "Optimisation of Advanced Stellarator Systems"
- G. Moritz, GSI Darmstadt, Germany, and V. Vysotsky, All-Russia Scientific Cable R&D Institute, Moscow, Russian Fed., “Research and development of Novel-Cable-In-Conduit Conductors (N-CICC) for use in the fast ramping superconducting accelerators”, INTAS Project 05-96-4889
- V. Naulin, Risoe, Denmark (with S. Mueller), “Adaptation of the ESEL fluid code for modelling of turbulence in the TORPEX device”
- J. Nührenberg, A. Koenies, V. Kornilov, A. Mishchenko, S. Sorge, IPP Greifswald, Germany, A. Bottino, A. Peeters, IPP Garching, Germany, R. Hatzky, Rechenzentrum MPG Garching, Germany
- “Linear and nonlinear gyrokinetic code developments and simulations“
- H.K.B. Pandya, Institute for Plasma Research, Bhat, Gandhinagar, India, “Design of a vertical ECE diagnostic for TCV”
- L. Rossi, CERN, Switzerland, N4 - CARE “ Coordination of studies and technical R&D for high energy high intensity hadron beams”
- P. Savrukhin, A. Sushkov, RRC Kurchatov Institute, Moscow, Russian Federation, “Planning of tangential X-ray measurements in TCV”
- V.D. Shafranov, M.Yu. Isaev, M. Mikhailov, A. Subbotin, Kurchatov Inst., Moscow, Russia, J. Nuehrenberg, IPP Greifswald, Germany, “Advanced stellarator optimisation”
- J. Snipes, R. Parker, M. Porkolab, J. Freidberg, J.Sears, PFSC, MIT, USA,
- “Fast particle physics, Alfven waves, and active MHD mode excitation on the Alcator C-Mod Tokamak plasma"
- A. Sushkov, Nuclear Fusion Institute, Kurchatov, Moscow, Russia: 1) “Electron heat transport at switch-off in sawtooth-less TCV discharges”, 2) “Development, commissioning and use of DMPX soft X-ray wire chamber towards Te measurements”
- E. Valeo, Princeton University, USA, and R. Berger, Lawrence Livermore National Laboratory, USA, “Development of numerical methods for Vlasov simulations”
- E. Zapretilina, Efremov Research Institute of Electrophysical Apparatus (NIIEFA), St. Petersburg, Russian Fed., “Assessment of scaling laws for AC losses in ITER conductors”
- Wendelstein Group, IPP Greifswald, Germany, “Test of conductor joint samples”
- K. Yamazaki, K. Y. Watanabe, S. Okamura, T. Yamaguchi, Y. Narushima, H. Yamada, S. Sakakibara, C. Suzuki, National Institute for Fusion Science, Toki, Japan; S.P. Hirshman, Oak Ridge National Laboratory, USA, "Model Anisotropic Pressure Equilibria in Stellarators with Tangential Neutral Beam Injection"
- J. Yu, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, P.R. China, ‘Effects of irradiation in SINQ on the Chinese Low Activation Martensitic steel (CLAM)’.

Annex 3: Fusion related surface investigations at the Physics Institute, Basle, in the years 2004 and 2005

Almost all optical diagnostics systems in ITER (International Thermonuclear Experimental Reactor) will make use of metallic first mirrors either as plasma viewing components or as light transmitter through the diagnostic ducts. The possible deterioration of their surface reflectivity as a result of erosion by charge-exchange neutrals and re-deposition of material eroded from the plasma facing components represents a serious concern for the reliability of spectroscopic signals. A concerted effort within the Tokamak community has been initiated to characterise these effects and seek mitigation methods. The Institute of Physics of the University of Basle (IPUB) is actively participating in the activities in this field through collaboration with groups from different Tokamaks. In TEXTOR, a comparative test of single crystal and polycrystalline mirrors in erosion conditions showed the better resistance to sputtering of reflectivity of single metal mirrors. Such mirrors may have a sufficiently long lifetime in case sputtering is the main damaging effect. In the laboratory, mirrors made from polycrystalline copper and stainless steel were exposed to low temperature deuterium plasma with controlled partial pressure of methane in the gas mixture. Under similar conditions markedly different erosion/deposition patterns are observed on the different materials, showing the influence the material itself plays in the erosion/deposition mechanisms. In the TCV, mirror samples prepared from different materials are installed on a specially designed manipulator allowing their insertion into the divertor floor region. The samples are recessed behind the front surfaces of the divertor tiles to avoid direct plasma contact. In experiments to date, very thin carbon layers have been found on the sample surfaces, but strong carbon accumulation has in some cases been found at the border between area open to the plasma and area protected by the sample head.

A spectrophotometer compatible with beryllium handling has been installed at JET. This system will be used for optical measurements on metallic mirrors to be exposed in the divertor and first wall regions of JET during operation in the coming 2005/2006 experimental campaigns.

Publications

- G. De Temmerman, M. Ley, J. Boudaden, and P. Oelhafen, Study of optical properties of MoxC1-x films, accepted for publication in Journal of Nuclear Materials.
- G. De Temmerman, M. Ley, J. Boudaden, and P. Oelhafen, Optical properties of co-deposited molybdenum carbide films, submitted for a contribution to the 16th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, May 24-28 2004, Portland, Maine, USA.

Scientific collaboration

National collaboration:

- Dr R.A. Pitts, Centre de Recherche en Physique des Plasmas (CRPP), Lausanne

International collaboration:

- Dr A. Litnovsky, Dr V. Philipps, Gruppe Plasma-Wand Wechselwirkung, Institut für Plasmaphysik, Forschungszentrum Jülich, Germany
- M. Lipa, Plasma-wall integration division, Tore Supra, CEA Cadarache, France
- M. Rubel, Royal Institute of Technology, Stockholm, Sweden

Additional information

The following web pages provide much additional information on all the topics discussed in this report:

Energy in general:

- International Atomic Energy Agency IAEA: www.iaea.org
- International Energy Agency IEA: www.iea.org
- Switzerland: www.suisse-energie.ch

ITER:

- www.iter.org

EURATOM:

- European Fusion Development Agreement EFDA: www.efda.org
- Joint European Torus JET: www.jet.efda.org
- European Commission: europa.eu.int/comm/research/fusion1.html
- Framework programmes of the European Union: www.cordis.lu

IEA Implementing Agreements:

- www.iea.org/impagr/imporg/impagpub/listof.htm#5

Switzerland:

- Plasma Physics Research Centre CRPP: crppwww.epfl.ch
- University of Basle: www.unibas.ch/phys-esca
- CRPP/SER: www.iter-industry.ch

Interested readers can also contact:

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Abbreviations

CD	Current drive
CEPE	Centre for Energy Policy and Economics
CERN	European Laboratory for Particle Physics
CRPP	Centre de recherches en physique des plasmas
CTA	Coordinated Technical Activities
CTI	Commission for Technology and Innovation
E	Exhaust
EC	Electron cyclotron
ECCD	Electron cyclotron current drive
ECH	Electron cyclotron heating
ECRH	Electron cyclotron resonance heating
EDA	Engineering design activities
EFDA	European Fusion Development Agreement
EIROFORUM	European Intergovernmental Research Organisations Forum
ELE	ITER European Legal Entity
ELM	Edge limited mode
EPFL	Ecole polytechnique fédérale de Lausanne
ESA	European Space Agency
EU	European Union
EURATOM	European Atomic Energy Community
EVEDA	Engineering Validation and Engineering Design Activities
FEC	Fusion Energy Conference
FP5	5th Framework Programme
FP6	6th Framework Programme
FP7	7th Framework Programme
FZJ	Forschungszentrum Jülich
FZK	Forschungszentrum Karlsruhe
IA	Implementing Agreement
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IFMIF	International Fusion Materials Irradiation Facility
IFRC	International Fusion Research Council
ILE	ITER International Legal Entity
IPP	Institut für Plasmaphysik
ITA	ITER Transitional Arrangements
ITER	International Thermonuclear Experimental Reactor
ITG	Ion temperature gradient

JET	Joint European Torus
JIA	JET Implementing Agreement
JOC	JET Operation Contract
LASEN	Laboratoire de systèmes énergétiques
MHD	Magnetohydrodynamics
OECD	Organisation for Economic Co-operation and Development
SER	State Secretariat for Education and Research (former FOES)
SFOE	Swiss Federal Office of Energy
PIC	Particle-In-Cell
PIREX	Proton Irradiation Experiment
PSI	Paul Scherrer Institute
RF	radio frequency
SINQ	Swiss spallation neutron source
SULTAN	Supraleiter-Testanlage
TCV	Tokamak à configuration variable
TORPEX	Toroidal Plasma Experiment
UKAEA	United Kingdom Atomic Energy Agency