FUSÃO TERMONUCLEAR CONTROLADA *

CONCEITOS BÁSICOS E PROGRAMA EUROPEU

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A fusão termonuclear promete ser uma importante fonte de energia no futuro. A Comunidade Europeia realiza actividades neste domínio por meio de um grande programa, que compreende todos os trabalhos em fusão por confinamento magnético nos seus estados membros e no qual também participam a Suécia e a Suíça. O objectivo a longo prazo deste programa é a criação de reactores experimentais seguros e viáveis do ponto de vista ambiental.

A linha principal de investigação e desenvolvimento é a fusão por confinamento magnético toroidal baseado no conceito de Tokamak. Alguns conceitos relacionados que poderão oferecer vantagens para um reactor são também estudados, sendo prosseguidas actividades nesse quadro. Foram construídos vários aparelhos de pequeno e médio porte nos laboratórios associados, assim como o «Joint European Torus» (JET) que é a maior e mais bem sucedida máquina de fusão em todo o mundo. Recentemente, foi obtida no JET uma potência de fusão da ordem de grandeza dos megawatts.

I. Energy: Sources and demand

Energy, and in particular electrical energy, is a prime requirement for a standard of living which in the industrialised world has become indisputable. Cheap energy has led to generous usage. Reductions are possible both by enhancing the energy efficiency of processes and by a reorientation towards avoiding unnecessary energy consumption. Globally, however, the potential for reduction is outweighed by the large increase of energy consumption which the Third World's population will demand in its quest for diminishing the gap between its standard of living and ours. This population is growing increasingly faster. On the basis of any reasonable extrapolation of how many people will be on this globe by mid-next century and what their energy demand per capita might be, the conclusion is that there will be a large increase in future world energy demand.

Environmental and safety issues of today's energy production and consumption have become dominant aspects in the articulate public opinion. In most industrialized countries energy policies continue to reinforce measures towards reducing the environmental impact of existing energy systems. Emission control of fossil power stations, cleaner cars or buildings insulation are only some of many aspects. However, considering the global dimension and the existential threat of climatic consequences, much more remains to be done to improve current techniques of energy production and use.

Energia: fontes e necessidades

Fusão termonuclear controlada

Conceitos básicos sobre fusão nuclear

O programa de fusão nuclear da Comunidade Europeia

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* Texto parcial da Conferência Plenária proferida na FÍSICA 92, Vila Real, 15-18 Setembro 1992. Em próximo número publicamos um segundo artigo, que completa este.

For new, better energy sources and systems there are not many options. All of them require trade-offs in terms of safety, environmental impact, supply, geographical distribution, availability, economy, etc.

Besides fossil energies for which it is understood that their use must be limited, there is nuclear fission, providing a substantial share of baseload electrical energy in many developed countries. Solar and other renewable energies will, in a few decades, cover more than just the few percent of our energy requirements that they achieve today. Predictions of experts diverge, however, on whether environmentally acceptable renewable energies could supply a major part of our needs by the middle of the next century.

Thermonuclear fusion remains the only known other large-scale option for our energy future. Although enormous progress has been achieved in fusion, its development into a large-scale energy source is still very demanding and will require long time scales and large resources.

DEUTERIUM-TRITIUM FUSION REACTION

D + T	—>	$^{4}He + n + 17.6$ MeV
$^{6}Li + n$	—>	$^{4}He + T + 4.86$ MeV
$^{7}Li + n$	—>	$^{4}He + T + n - 2.5$ MeV
Sum reaction: D + Li	—>	$2\,(^{4}He)$ + energy

II. Controlled thermonuclear fusion

The cross-sections of all fusion reactions are by far outweighted by the Coulomb cross-section. This makes fusion collisions so unlikely compared to simple Coulomb collisions that it is impossible to gain energy from fusion by targeting two accelerated beams, containing the species to react, onto each other. Instead, the energy expended into bringing the fusing particles to the needed relative velocity must be conserved through many Coulomb collisions. Therefore, the presently pursued approaches all embed the reacting particles into a confined thermal ensemble in which the particles, as long as they are confined, undergo permanently collisions, thereby greatly enhancing the occurence of fusion reactions compared to single encounters. At the temperatures needed, and compensating the space charge of the ions by electrons, this particle ensemble is necessarily a quasineutral plasma. The highest fusion cross-sections are obtained in the fusion reaction of deuterium (D) and tritium (T) which burns into Helium (^{4}He) plus a neutron (n) thereby releasing energy.

There are other fusion fuels than D-T which could be exploited for a fusion reactor, which react without or with less neutron production and which therefore could offer less environmental impact than the D-T fuel. However, still much higher temperatures would be needed for burning those fuels. Therefore, the present development goal is the D-T fusion reactor.

The core of a fusion reactor along the concept of toroidal magnetic confinement — the main development line in Fusion R&D — contains a ring-shaped reactor vessel, surrounded by magnetic field coils and a mechanical structure which will take up the magnetic forces. Also there are installations to heat and to control the plasma. Inside the vessel the fuel burns and heats the wall of the chamber. A heat exchange system will extract the heat and transfer it to the conventional balance of the plant where turbines generate the electricity. Basically, in a fusion reactor, only the core will be different from that of fossil or fission power stations.

Because of the high energy release in a fusion reaction, a fusion power station will need only very small quantities of fuel. For comparison: to generate 1 GW-year of electrical energy in a coal power station requires more than 3 Mio tons of hard coal, the load of about 150.000 railway waggons. With the deuterium-tritium fusion, less than 100 kg of deuterium would be needed plus about 3-4 tons of natural lithium which contains 92.5% of the isotope lithium 7 and 7.5% of lithium 6. Apart from the first fill, reactions between these lithium isotopes and the neutrons from the D-T fusion reactions will be used to breed tritium in a blanket which surrounds the plasma. To breed the needed amount of tritium is necessary because it decays radioactively with a halflife of 12.3 years and hence does not exist naturally in sufficient quantity.

Apart from the first fill, no radioactive fuel would have to be transported to, or processed outside, the reactor site; the outputs of a fusion reactor would be power and non-radioactive helium. There would, however, be the need for recycling tritium on-site and for processing and storing waste, i.e. materials of the reactor which have been activated mainly through irradition by fusion neutrons.

Cheap fuel for fusion is abundant: 0.015% of the hydrogen of all seawater exists as the isotope deuterium, lithium is a copious element in the earth's crust. Supplies would last for millenia. The availability of some construction materials needed for a fusion reactor might be a somewhat stronger limitation for energy production.

In coal power stations, the fuel contributes 50-60% to the electricity generating costs; for a fusion reactor, fuel cost amounts to some 2%. Capital coast for a coal power station amounts to 30% or less of the electricity generating costs; this share is about 40-50% for fission pressurized water reactors. For fusion, estimates range around 70-80%. The dominant economical factors for fusion will be the construction and decommissioning costs of a reactor as well as those for periodic replacement of parts which are exposed to the plasma or the neutrons.

For a process which has not yet been fully developed and which, in terms of reactor performance, still lacks all optimization, it is difficult to determine final market costs. Preliminary estimates indicate that the costs for electricity from fusion may be in the range of those from fission power.

III. Concepts for nuclear fusion

Magnetic Confinement Fusion research has a history reaching back to the time just after the second world war. Two distinct lines of approach exist. One, prominent for its connection with military applications is inertial confinement fusion where a tiny capsule of fuel is heavily compressed until fusion burn is initiated and the capsule explodes under the generated pressure. The fusion burn lasts only for a very short period, as long as the fuel is kept together by its own inertia.

Powerful laser or particle beam systems are needed to achieve the compression. Inertial confinement fusion is necessarily nonstationary.

The other approach is magnetic confinement fusion. Here, the fuel is a hot plasma, confined by magnetic fields which are made to form a magnetic cage within the reactor chamber. The magnetic fields are generated by currents in the plasma and by huge magnetic field coils located around the reactor chamber. In principle, stationary fusion burn is possible as long as the magnetic confinement is maintained.

Although the fusion reaction does not produce radioactive elements, there is radioactive waste: the neutrons from the fusion reactions are absorbed in the wall of the reactor chamber and in the structure which supports the chamber and the field coils against the strong magnetic forces. Here the neutrons deteriorate and activate the materials and reduce their useful lifetime: radioactive waste is generated. Calculations show that the quantity of this waste could be similar in volume to that of fission reactors. Qualitatively, however, fusion waste has much less hazard potential and, with some progress in materials research, the volume could possibly be reduced and a major part be recycled after comparatively short times.

Aspects of Magnetic Confinement

For a fusion reactor, technical constraints limit the magnetic pressure (which rises quadratically with the magnetic field strength) to values in the order of some hundreds of atmospheres. For stability reasons, the plasma pressure cannot exceed a few percent of this magnetic pressure. Plasma pressure is proportional to the product of plasma temperature and plasma density: at temperatures of 10-20 keV (i.e. 100-200 million centigrade), the fusion plasma's density must be kept very small. Typical values are in the range of some 10^{19} to some 10^{20} particles per m^3, many orders of magnitude below e.g. the density of air at normal atmospheric pressure.

An immediate consequence of this low plasma density is that there is very little fuel in the reactor chamber. For a steady fusion burn, fresh fuel must be continuously replenished since a single fill would sustain the fusion burn only for a few tens of seconds. (In contrast, a fission reactor contains fuel in its core for a year's or longer energy production). The extremely small content of reactive fuel in a fusion reactor is a major inherent safety feature: no sustainment of uncontrolled burn, no core melt-down can happen.

Recent progress in the development of the physical and technological basis of a fusion reactor makes it possible to treat the environmental, safety and economical aspects of fusion in greater detail and to identify critical R&D and design issues. Important considerations are to minimize the tritium inventory of a fusion reactor and the resultant activation of structural materials. The dominant safety aspect is to confine the tritium and to handle the activated materials safely.

Toroidal Magnetic Confinement Concepts

Many possible magnetic confinement schemes have been explored. From today's point of view, the most promising ones are toroidal: the plasma forms a ring inside a reactor vessel of the shape. Magnetic fields, produced by external coils and plasma currents, wind helically within and around the plasma, confining and thermally isolating it against the vessel.

The basic principle of magnetic confinement is, of course, the tight gyration of the charged particles, electrons and ions, around magnetic field lines allowing only for macroscopic motion parallel to the field lines. With the field lines bent to a ring, particles would de perfectly confined if Maxwell's equations did not dictate that inevitably a toroidal field decreases in strength proportional to the inverse of the major radius. Thus, the charged particles gyrate in an inhomogeneous field which leads to a small drift of electrons and ions in the direction of the major radius. (This drift is superimposed to the fast motion along the field lines.) As a consequence, the plasma would be lost and would hit the wall of the device. Superimposing a poloidal magnetic field component results in a helically twisted magnetic field; which makes particles moving around the minor circumference of the torus. Now, if they have drifted to a somewhat larger radius at the outside of their orbits, at the inside the same drift brings them back to a smaller radius, thus the drift can be compensated.

The confining magnetic field will be mainly generated by external coils.

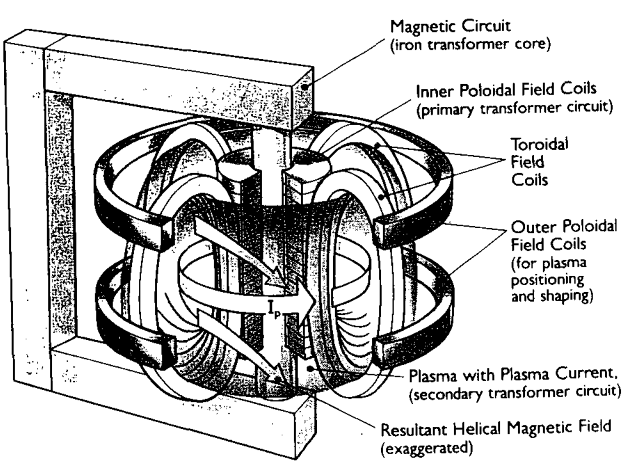
Different schemes can be distinguished according to the extent to which currents inside the plasma contribute a part of the confining helical magnetic field. The external coils will be superconducting in a fusion reactor; most of the present devices use coils with copper windings.

The Tokamak

So far, the most successful toroidal magnetic confinement scheme is the Tokamak. A strong toroidal magnetic field is generated by coils placed around the toroidal reactor vessel which contains the plasma. A large toroidal plasma current contributes by its poloidal self-field to establish the full magnetic confinement configuration.

The most efficient way to generate the plasma current and to maintain it, is to use the well-known transformer principle with the plasma as «secondary winding». However, this limits the possible duration of the plasma current. To make a stationary fusion burn,

Schematics of a Tokamak



additional means, e.g. so-called «non-inductive» current-drive techniques must be utilized. An operational problem in Tokamaks is that the plasma current may suddenly terminate due to possible topological changes inside the plasma. This is called disruption; the plasma current may commute into currents flowing in the metalic wall or in structures close to the plasma. The Lorentz force of these currents and the magnetic fields can cause severe forces in the reactor vessel. A major R&D effort aims at establishing means to eliminate or to reduce the occurrence of disruptions.

The Reversed Field Pinch

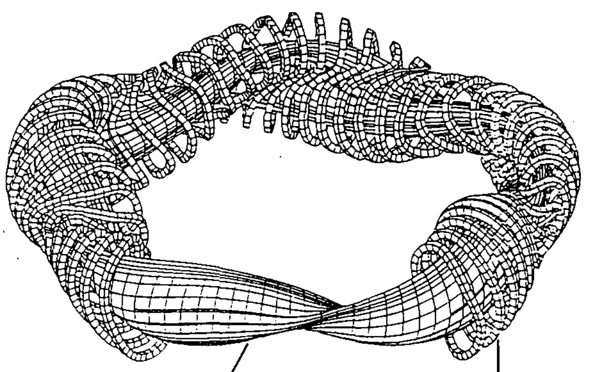
A configuration akin to the Tokamak is the Reversed Field Pinch (RFP). It relies to a much larger extent on self-organization of plasma currents for the creation of the proper configuration which is characterized by a relaxation towards a minimum energy state. During this relaxation the toroidal field reverses in the outer region of the plasma, therefore the name Reversed Field Pinch has been coined. The RFP principle offers better energy utilization than the Tokamak: more plasma pressure can be accomodated for a given magnetic field pressure. A reactor could therefore be smaller. However, in present experiments the RFP relies in its configurational stability on stabilization by a conducting wall close to the plasma. For a reactor a close-fitting conducting shell is not feasible. Additional means for control and stabilization of the plasma in a RFP must therefore be developed. The present status of research is significantly less advanced than for the Tokamak.

The Stellarator

Another interesting concept is the Stellarator which, unlike the other schemes, does not need a large toroidal plasma current. This may facilitate stationary operation of Stellarator reactors.

The basic configuration of a Stellarator is established entirely with magnetic field coils placed around the vessel. Two possibilities exist to generate the required helical magnetic field configuration: either a set of toroidal field coils plus a set of helical windings is used or, in the Advanced Stellarator, each toroidal field coils is three-dimensionally twisted in order to generate the required helical field. Vessel and plasma of an advanced Stellarator have both the shape of helically distorted rings. Due to its three-dimensional twist, the configuration is much more difficult to design and technically to achieve. Only with the advent of large computers has it become possible to design and manufacture competitive Stellarators. Advanced Stellarators can be constructed with a modular coil system which could facilitate replacement and maintenance but then, necessarily, the coils must be nonplanar. For the conventional Stellarator, the Tokamak and the RFP, two interlinked coil systems, made of planar coils, are used.

Schematics of an Advanced Stellarator (Wendelstein VII-X)



IV. The Community Fusion Programme

The present European Fusion Programme has its roots in national programmes which existed during the fifties in several European countries. In 1957, with the establishment of the European Atomic Energy Community (Euratom), controlled thermonuclear fusion by magnetic confinement became a European domain and in subsequent years the national activities were coalesced into a single European programme. This was achieved mainly by Contracts of Association with the national institutions which operated fusion laboratoires and by participation of the Community's Joint Research Centre. Starting in 1959, this system has developed strongly and comprises 13 Associations since 1990, when the Association Euratom-IST was established between the European Community and Portugal at the Instituto Superior Técnico. Sweden and Switzerland are fully associated to the programme which has today an annual budget of about 450 Mio ECU.

Fusion, as a long-term and large-scale programme, is a prominent example of how a European dimension can provide added value. The system of Associations, guaranteeing mutual access to, and exchange of, information and research potential, has made it possible to overcome limitations of the national research programmes. Duplication of work could be eliminated, greater efficiency be achieved and a common strategy be developed.

The Joint European Torus

By the joint effort, and by focusing on the most promising line of development, it was possible to enter a new dimension of fusion research: in the seventies, the world's largest and most powerful Tokamak was launched: JET, the Joint European Torus, a Joint Undertaking. JET went into operation in 1983. By this step, Europe was able to strive for the lead in fusion.

A feature of the European strategy has been to combine JET as the large, central device with several specialised machines which, by their smaller size, can provide solutions to detailed problems more cost-efficiently and which are cheaper and faster to modify. Results from these devices which were taken up by JET have contributed substantially to achieving JET's outstanding performance: JET has exceeded all its original milestones.

Also the other large programmes in the world, in the USA, in Japan and the former Soviet Union, operate large Tokamaks (besides smaller Tokamaks and devices for other development lines) as well as fusion technology facilities. However, in fusion performance, JET is unequalled — apart from, perhaps in the future, the newly rebuilt large JT-60U Tokamak in Japan. But progress in fusion has greatly benefited from all programmes and, in particular, from their intense international collaboration.

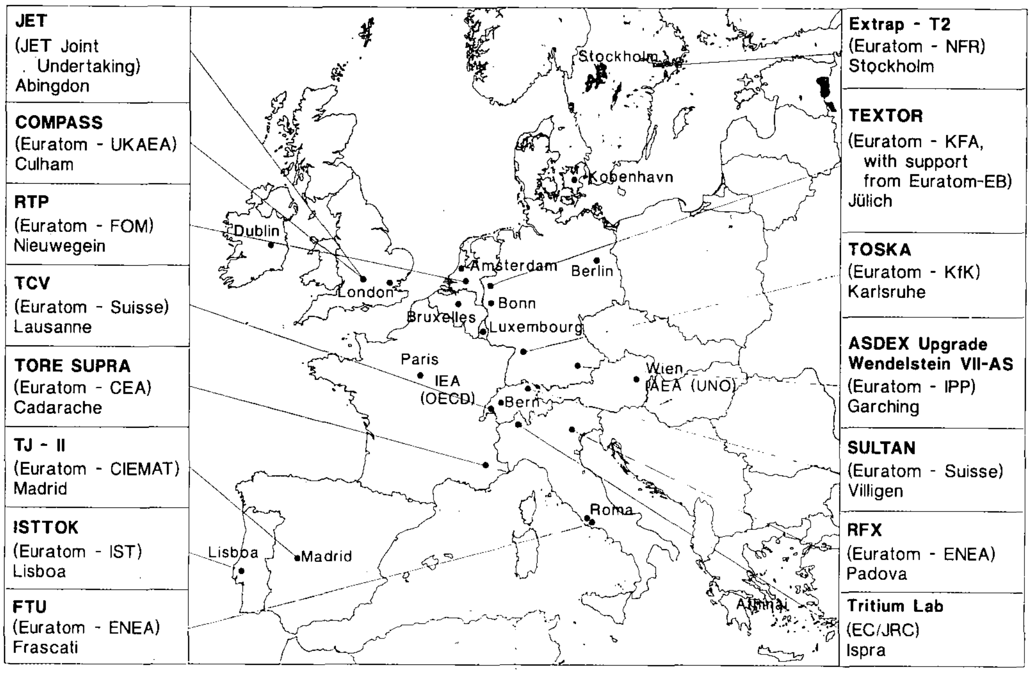
Specialised Tokamaks

The European specialised devices are operated by the Associations. TORE SUPRA, at Cadarache, is the word's largest Tokamak with superconducting coils and is used for studies of long-pulse operation, plasma current drive and plasma heating. ASDEX, now replaced by ASDEX-Upgrade at Garching, focuses on solutions for particles and energy exhaust from the plasma with a magnetic divertor.

TEXTOR, at Jülich, operated by the Association Euratom-KFA with the participation of the Association Euratom-Etat Belge and contributions from the Association Euratom-FOM, concentrates on the study of plasma wall interactions. FTU, at Frascati, explores a regime of high plasma density and high plasma current density. COMPASS, at Culham, has been designed for investigations of higher plasma pressure operation and related plasma stability studies. TCV, at Lausanne, is dedicated to aspects of elongated plasmas and current disruptions. RTP, at Rijnhuizen, is used for studies of plasma transport mechanisms and ISTTOK, at Lisbon, for investigations on plasma oscillations and fluctuations and current drive. Besides their programmatic importance, these devices provide an excellent basis for education and training of young professionals.

While the Tokamak provides the fastest approach to

Fusion Devices in Europe



truly thermonuclear reactor plasmas, the options for a fusion reactor are still open enough to warrant work on concept improvements — along the Tokamak line itself as well as for the Stellarator (Wendelstein VII-AS, an Advanced Stellarator at Garching, TJ-II, a Heliac-Stellarator at Madrid) and the Reversed Field Pinch (RFX, at Padova). The goal is to explore the essential features which will determine the reactor potential of these development lines. Basic research and a watching brief on inertial fusion complement the physics activities of the Community Fusion Programme.

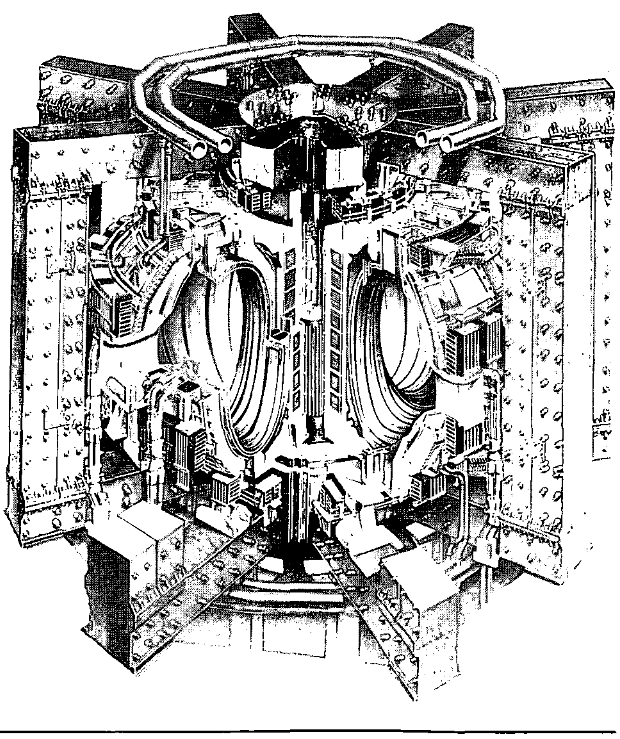
A prominent feature of the Community Fusion Programme is its high degree of cohesion. The results from work on the specialised devices and of groups with special know-how is transported and disseminated by a mobility scheme which facilitates access to information, joint work and transfer of techniques and skills. The Portuguese Association, for example, apart from their intramural work programme, has developed as a center of know-how for reflectometry, a highly advanced plasma diagnostic of central importance. Portuguese scientists and engineers work in this field at fusion devices of other Associations and thus contribute to the overall synergy and the rapid progress in the programme.

Fusion Technology

Currently, about 20% of the efforts in the Community Fusion Programme are dedicated to fusion technology. Technology-oriented work will have a tendency to increase. It is focalized towards the major development tasks and can roughly be divided into R&D for the Next Step (the next large experiment) and for the long term development aimed at the fusion reactor.

For the next experiment as well as for the future fusion reactor, large superconducting coils are being developed based on conductors made of Nb_3Sn which can be used at high currents and stronger magnetic fields. Test facilities for superconductors have been established near Baden (Switzerland) and at Karlsruhe.

JET - Joint European Torus



In the nuclear core of a fusion device it is mandatory to manipulate via remote handling; corresponding developments are undertaken at Karlsruhe and Ispra. Blanket modules for tritium breding which could be tested in the Next Step are being studied in several places; this is true also for materials research (e.g. for structural components and for first wall elements). For part of the nuclear testing of materials, research facilities at fission reactors can be used.

An important task is to develop the nuclear fuel cycle for the fusion reactor. While already at JET corresponding installations have been established for the D-T operation, the next experiment will have a much larger circulating tritium throughput and requires appropriate development. Laboratoires for this work have been established at the Joint Research Centre in Ispra as well as in KfK Karlsruhe.

Plasma engineering is a term used for techniques which relate to plasma handling like fuelling and heating. Large multi-megawat high-frequency systems, from some megahertz to 140 GHz are being developed for resonance at the main characteristic frequencies of the plasma, the cyclotron frequencies of electrons and ions and their hybrids. Also, powerful injectors for neutral deuterium atoms are being used at beam particle energies up to about 200 kV; development of systems at energies of 500-1000 keV with multi-ampère currents is underway.

Diagnostics play an important role in providing the information which is needed for the control of the plasma and the fusion burn. For most of these systems there exist strong interconnections with fusion physics — in fact, much of this work is managed within the physics part of the fusion programme.

Safety and environmental aspects are intrinsic elements for designing future D-T fusion experiments. These aspects are most important, of course, in the long-term perspective towards the fusion reactor. Development of a tritium-breeding blanket and materials research, especially for low-activation materials, are key R&D topics together with safety and environmental studies based on a conceptual design study of an electricity-producing fusion reactor.

Specialized Tokamaks in Europe

Device	Institution Place	Main Objective	Ip (MA)	Period
TEXTOR	KFA Jülich	Plasma/wall interaction poloidal divertor	0.5	81 —
TORE SUPRA	CEA Cadarache	Long-pulse operation in Next Step Relevant conditions	1.7	88 —
ASDEX-Upgrade	IPP Garching	Plasma purity control in reactor relevant conditions	1.6	90 —
FTU	ENEA Frascati	Confinement at high density and high current	1.6	89 —
COMPASS	UKAEA Culham	High-beta and MHD stability studies	0.4	89 —
TCV	CRPP	High-beta studies and disruption control	1.2	92 —
RTP	FOM Nieuwegein	Transport mechanisms studies	0.2	89 —
ISTTOK	IST Lisbon	MHD activity, ECCD	0.006	91 —

Stellarators in Europe

Device	Institution Place	Main Objective	Period
Wendelstein VII-AS	IPP Garching	Medium-size device with modular coil system to investigated plasma behaviour in an optimized magnetic field configuration	90 —
TJ - II	CIEMAT Madrid	Medium-size device with helical magnetic axis for confinement and high-beta studies	94 —
Wendelstein VII-X	IPP Garching	Large-size fully optimized advanced stellarator with modular superconducting magnetic field coils	In the design phase

Reversed-Field Pinches in Europe

Device	Institution Place	Main Objective	Ip (MA)	Period
RFP	ENEA Padova	Largest RFP device with the aim to give information on the reactor prospects of this concept	2.0	91 —
EXTRAP-T2	NFR Stockholm	Medium-size device for RFP and EXTRAP studies	0.05	92 —