FUSÃO TERMONUCLEAR CONTROLADA *

FUTUROS DESENVOLVIMENTOS

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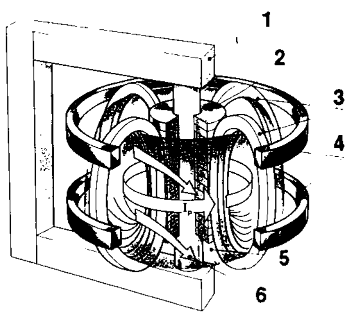
Depois de, no último número da Gazeta, se terem descrito os conceitos básicos e o programa europeu de fusão termonuclear controlada (Gazeta de Física, vol. **16**, n.° 2, 1993), *apresenta-se aqui uma perspectiva dos desenvolvimentos futuros.*

Ao JET seguir-se-á, no programa europeu, uma máquina chamada NET (Next European Torus), no quadro do programa «Next Step». Comercialmente, a energia da fusão só deverá estar acessível a meio do próximo século. A fusão nuclear é um dos maiores esforços científicos humanos, necessitando por isso de um planeamento rigoroso a longo prazo.

Status of fusion research



Esquema de um Tokamak
(estado actual)

1. *Circuito magnético (núcleo de transformador, em ferro).* **2.** *Bobinas internas (circuito primário do transformador; campo magnético poloidal).* **3.** *Bobinas de campo magnético toroidal.* **4.** *Bobinas externas de campo magnético poloidal.* **5.** *Plasma, transportando uma corrente de plasma I_p (circuito secundário do transformador).* **6.** *Campo magnético helicoidal resultante (escala expandida).*

To improve the performance of fusion devices, a large number of complex, interconnected physical and technological developments have to be optimized. Progress in fusion research is therefore not a simple matter to describe. However, for an overall judgement, a figure of merit is the triple product of fuel density, fuel temperature and the energy confinement time. The first two factors determine how many fusion reactions will occur, the energy confinement time indicates how long it would take for the plasma to cool down if heating would be switched off: it is a measure of the thermal insulation between the hot plasma and the cool reactor vessel. Today, temperature gradients of 3 million degrees per centimetre can be maintained at the boundary of the plasma. The better the energy confinement time, the less heating power is required to maintain the fuel at the required temperature in a device. Of course, the energy confinement time rises with the volume of a given plasma.

Until now, there exists no fully satisfactory theoretical picture of the complicated transport and confinement properties of a fusion plasma. Many aspects like macroscopic and microscopic plasma oscillations and fluctuations, the configurational features and effects caused by technically necessary deviations from ideal configurations have been studied in much detail, but still this field is governed by semi-empirical scaling laws and global models. However, the basis for extrapolations has greatly improved by statistical evaluations of large data bases assembled on many different devices.

A display of the triple product against the temperature for various Tokamaks of the large fusion programmes gives an impression of the requirements needed for a fusion reactor and shows that a temperature of about 15 keV (roughly 150 million degrees) must be achieved depending on the combination of the three factors in the triple product which can be varied to some extent. A measure for the approach to the reactor regime is given by the quality factor Q_{DT}, the ratio of the generated fusion power to the heating power. Curves of constant Q_{DT} can be plotted in the graph which shows

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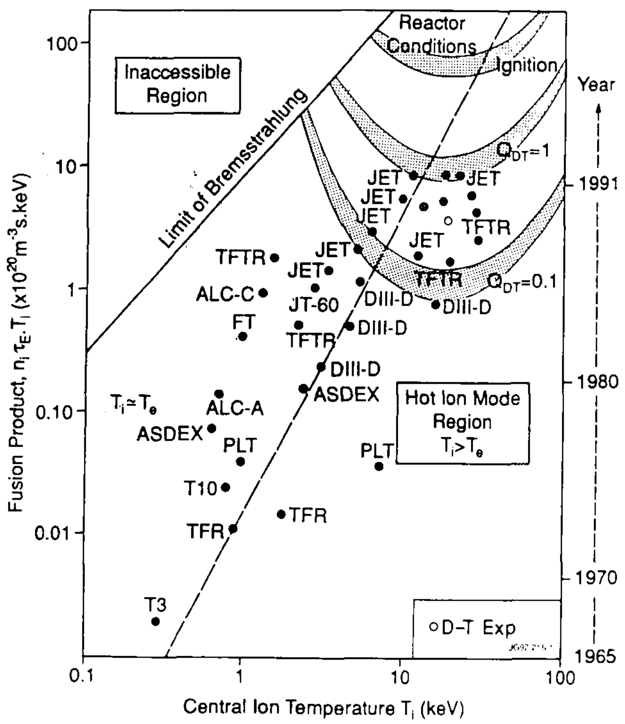
* Texto parcial da Conferência Plenária proferida na FÍSICA 92, Vila Real, 15-18 Setembro 1992. (conclusão).

the fusion performance of Tokamaks. $Q_{DT} = 1$ is called (scientific) break even: the fusion power equals the heating power which is needed to make the fuel react, For self-sustained burn of the plasma, i.e. ignition, $Q_{DT} > 5$ is necessary because only 1/5 of the fusion power is released via alpha-particles which can heat the plasma. The rest is in neutrons which direcly transport their part of the fusion power to the breeding blanket at the inside of the reactor vessel. Here the neutron loose their energy, which converts into heat and is processed by the balance of plant, and they react with lithium to form tritium.

Tokamak Performance



All data (except one) in the figure are from experiments in pure deuterium fuel (D-D) which is much less reactive than D-T fuel. Concerning the Q-value, a recalculation has been undertaken for assumed D-T operation. A time scale of progress in the triple product has been indicated; progress in recent years has been much faster than in previous decades. The best data result from experiments at JET which has more than attained the fuel temperature needed for a reactor. JET's D-D performance has already approached the (recalculated) break even; thus there remains only about a factor 5 in the triple product to achieve ignition.

In November 1991, the world's first experiments with deuterium-fuel containing a few percent tritium have been carried out in a preliminary D-T operation at JET. These experiments have confirmed the high performance of the device: for two seconds, fusion power in the megawatt range has been released in accordance with the expectations for the specific fuel mixture (white dot in graph).

Future prospects

The Next Step and Related R&D issues

The development headed by JET has done more than just to provide the global performance. Many physical and technical problems, hitherto considered as serious obstacles, could be overcome, others were identified more clearly so that strategies towards their solution can be devised. In fact, a great step towards the demonstration of scientific feasibility of fusion has been taken and there now exists a substantial basis for heading towards the Next Step, the next, large experiment, which then should achieve reactor-like fusion power under long-burn conditions. Thereby, this Next Step machine would complete the demonstration of scientific feasibility and address the problems which must be solved for the demonstration of technological feasibility of fusion.

Several issues remain to be solved in order to have viable solutions for the Next Step experiment. JET and the Associations with their specialised devices are working on these problems which to some degree, however, will also be generic R&D issues for the Next Step programme itself. Some of them are explained below.

Power and Particle Exhaust

An important problem are the rather small surface areas which absorb power and particles exhausted from the plasma. Therefore, the power load on these areas, mainly on the so-called target plates, is extreme and material may be eroded. So far, a major limitation to JET's performance have been exhaust and impurity effects. The influx of particles from the target plates and the walls into the plasma must be controlled to keep the plasma pure.

Concepts to overcome this problem have been tested on specialized Tokamaks. Now, a magnetic divertor is being installed and JET aims at establishing reliable methods for plasma purity control in Next Step relevant conditions before it resumes, at the end of its life, operation with optimum D-T fuel, For these tasks, the duration of the JET Joint Undertaking has been extended for another four years, until end of 1996.

Operation and Disruption Control

Another difficulty is connected with the fact that temperature and density of the plasma, as well as current and magnetic field immersed into it, have radial profiles which must be maintained rather carefully in order to keep the performance optimum, and also to avoid disruptions or «vertical instabilities» which can drive the hot plasma against the wall. Position, shape and profile control are therefore important aspects and special heating and current-drive techniques must be developed.

Effects of Plasma Self-heating

The regime where fusion power becomes the dominant contribution to the heating of the plasma has not yet been accessible to experimental investigation and will be the proper domain of the Next Step. New effects may arise. The situation has been studied theoretically and some issues have been identified which need attention. As already explained, by the fundamentals of magnetic confinement fusion, it is impossible to get excessive fusion burn, Rather one has to devise means not to extinguish the burn: with fusion power, helium is produced — the ash of the fusion burn. It dilutes the fuel and therefore will reduce the fusion power. Thus, the helium particles must be transported efficiently to the outside of the plasma without, however, undesirably affecting the self-heating of the plasma and the energy transport.

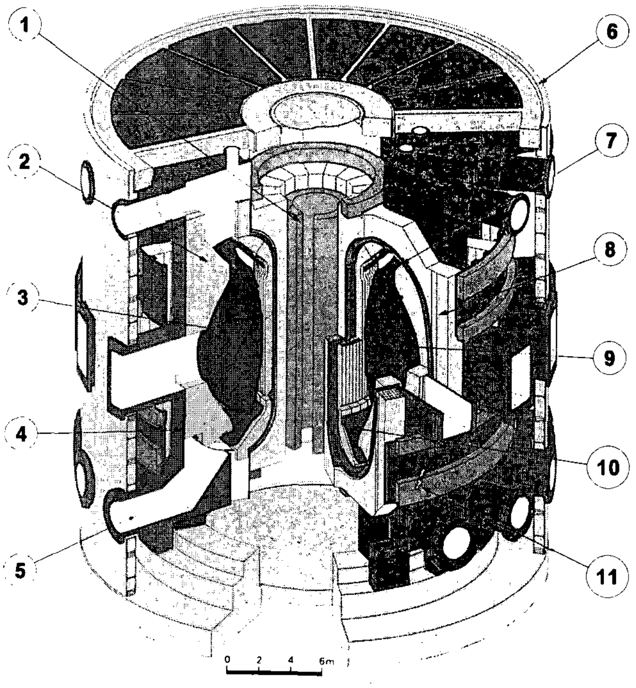
The Next Step: NET and ITER

During the last decade, parallel with the progress at JET, the Community Fusion Programme has prepared itself for the conception of a Next Step device, called Next European Torus (NET). However, in view of the large capital investment and the attraction of combining the know-how and potential of the world's major programmes, a quadripartite approach to the Next Step Tokamak has been started by Japan, the European Community, the United States and the Russian Federation (formerly the Soviet Union). By 1990, the conceptual design of the International Thermonuclear Experimental Reactor, ITER, was established. This device, with a major radius in the order of 6 m, about twice as large as JET, would have about three times the plasma current of JET and would use NbSn3 superconducting magnetic field coils. The confined plasma would have a volume in the order of 1000 m3 and produce around 1 Gigawatt (GW) fusion power in extended burn pulses. Conceived as an experimental device, ITER is not designed to have a full blanket for tritium breeding but would rather be used as test-bed for blanket concepts. Also, the conventional part of a power station, the balance of plant for electricity production, will not be added.

ITER Engineering Design Activities

The Engineering Design Activities (EDA) for ITER are projected to last six years and to cost 1 billion Dollars; the negotiations for the EDA were concluded with the signature of an agreement by the four parties in July 1992. A team of about 200 professionals is now in the course of being established to work at three sites in Europe (Garching), Japan (Naka) and the USA (San Diego). Europe provides the ITER Director.

The ITER Device

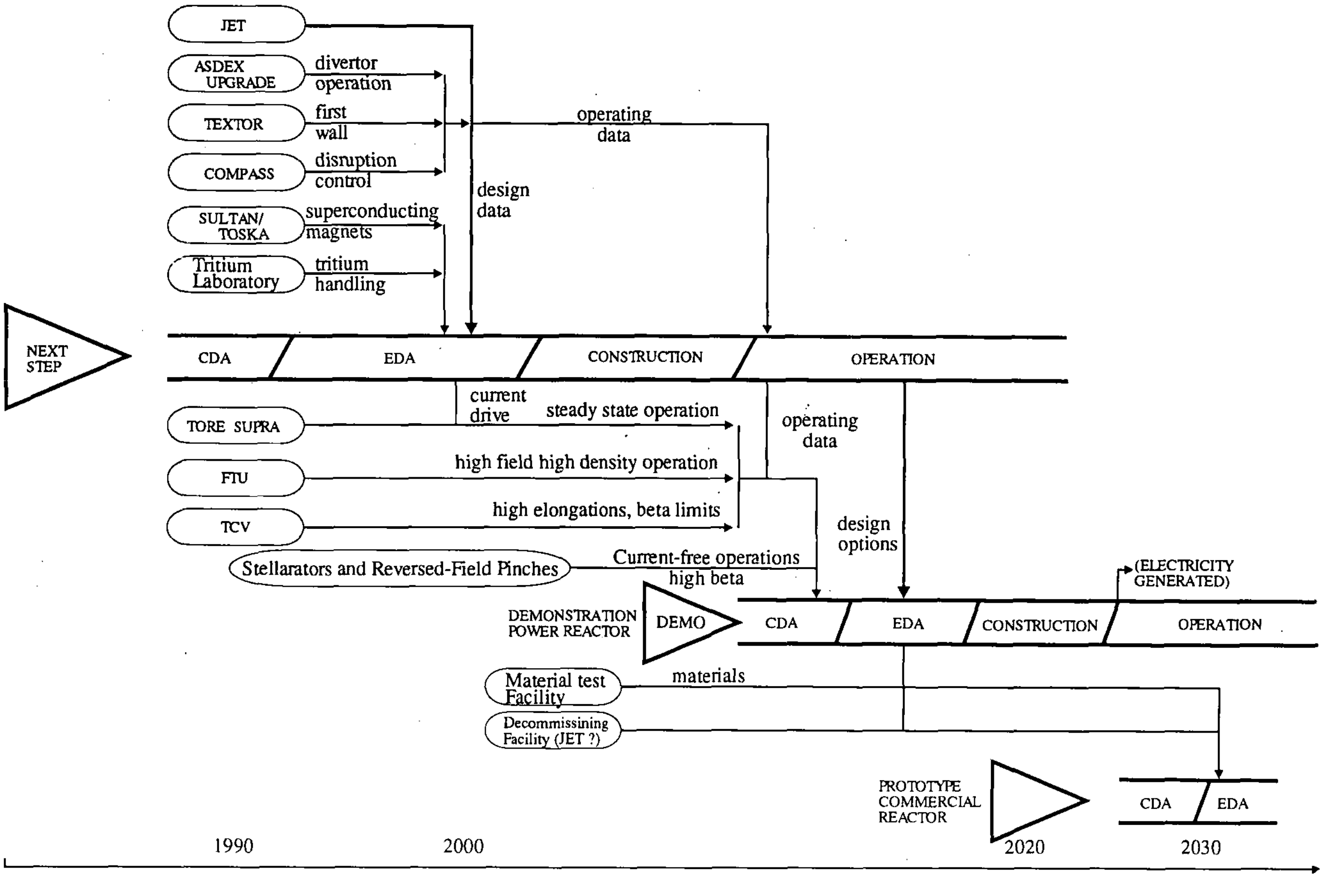


1 Central Solenoid
2 Shield / Blanket
3 Plasma
4 Vacuum Vessel - Shield
5 Plasma Exhaust
6 Cryostat
7 Active Control Coils
8 Toroidal Coils
9 First Wall
10 Divertor Plates
11 Poloidal Field Coils

During the ITER EDA the decision will have to be taken where to build the reactor. Europe will be a strong candidate for hosting this device. Its construction, estimated at about 5,000 million dollars will last approximately eight years. If the ITER collaboration would prove impossible beyond the design phase, the Community would be prepared to consider the realization of its own Next Step device.

The ITER time schedule foresees that ITER will start its operation within the mid-next decade, entering a first phase of Physics operation in order to complete the scientific information on a full-size fusion power

The European Fusion Strategy



producing plasma. The development of technological solutions for components of a fusion reactor would be the primary objective in the subsequent Technology Phase. As explained before, ITER itself already demands substantial technological developments. The major part of the EDA costs will go into these developments and the construction of prototypes for components. Part of this work goes beyond the capabilities of research institutions: industrial involvement in fusion becomes important. ITER, by its size and cost, is unlikely to test many modifications of concepts and components; its development plan must therefore be guide carefully: work on relevant specialised devices and a sufficient breadth of complementing R&D will also be necessary in the future.

Beyond the Next Step

In the European strategy the experience gained with the specialised devices and, in particular, with the Next Step will form the basis for the design of a Demonstration Reactor. Its conceptual design could be performed in parallel with the operation of ITER. It is envisaged that the Demonstration Reactor will be the first electricity-producing fusion reactor. Concept improvements could enter its design: possible extensions of the parameter regime for Tokamak operation as well as the reactor potential of the Stellarator and of the RFP should be known by this time. In this context, the engineering design of a large Stellarator, Wendelstein VII-X, has been started. As mentioned, with progress in physics, work on the technological aspects of fusion increases in its importance. Development must be guided by environmental and safety criteria. In the perspective towards the ultimate goal, the prototype reactor, issues in particular are the conceptual design study for an electricity-producing fusion reactor and studies of its safety and environmental impact, as well as the development of suitable materials and of the reactor blanket. As a new facility, an intense neutron source for the testing of materials will be needed.

Conlusions

Fusion research has entered the phase where the experimental generation of fusion power in the gigawatt range is within reach. To make further progress in reactor-oriented R&D, it is important to take this step.

The size and cost of the lead experiment in fusion R&D will be similar to those of other gigawatt power stations, and the timescales for design, construction and exploitation will be as long as those of other mega-projects. ITER, the Next Step, is becoming a central focus of the European (and the other Parties') magnetic confinement fusion programmes. In Europe, fusion research has been constantly streamlined to give maximum support to the central development line and to the lead project while maintaining a healthy breadth, necessary for a programme which needs and promises much innovation. While maintaining the support of JET, in the future, work in the Associations will be oriented increasingly towards ITER and towards collaborative efforts on some larger specialized devices.Such collaborations exist already to a significant extent; for example, the Portuguese Association is involved substantially in important research activities at other laboratories. As a source for innovation as well as for much needed education and training of young professionals, a solid basis of general fusion research has to be maintained. As in the past, also in the future such a well-balanced programme may save cost and time and will reduce the development risk.

Beyond ITER, taking into account all necessary development, engineering and construction times, a Demonstration Reactor might be envisaged to start operation around the year 2025. Commercially, fusion power will be available not before the middle of the next century: fusion is one of mankind's biggest and longest planned development efforts.

The expenditure of the Community Fusion Programme is about 450 Mio ECU per year of which 45% are provided by the Community budget. This compares to about half a percent of the annual electricity bill in the Community. In terms of the progress achieved so far and of the vanguard which Europe has achieved in fusion research, this effort has paid off — and it should be pursued in order to develop one of the few options to meet Europe's and mankind's future energy needs.

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Status Report on Controlled Nuclear Fusion, IAEA Vienna (1990) STI/PUB/872.

PRÉMIO EUROPHYSICS HEWLETT-PACKARD - 93

O *Prémio Europhysics Hewlett-Packard* é o mais importante atribuído na Europa a físicos da matéria condensada. Este ano foi atribuído aos físicos da ex-União Soviética, B. Alshuler, A. Aronov, D. Khmelnistskii, A. Larkin e B. Spivak, pelo seu «pioneiro trabalho teórico sobre fenómenos coerentes em condutores desordenados» (v. Europhysics News 24 (1993) 18). O estado dramático de desagregação da ciência na ex-União Sovietica é testemunhado pelo facto daqueles investigadores se encontrarem actualmente todos emigrados, três nos Estados Unidos, um em Inglaterra e outro em Israel. Talvez o júri do Prémio, para além do reconhecimento de uma famosa escola de física teórica, estabelecida por Lev Landau, tenha querido chamar a atenção para o colapso da ciência nos países de Leste, que infelizmente ocasionou e continua a ocasionar a fuga ou o desemprego de muitos «cérebros». Aqueles físicos que trabalhavam em Moscovo e Leninegrado (hoje São Petersburgo) obtiveram, na linha de Landau, uma compreensão física simples da condutividade eléctrica e outros fenómenos de transporte em metais desordenados. Um dos laureados, A. Aronov, descreveu em Europhysics News 24 (1993) p. 98, os seus resultados sobre «coerência e interferência electrónica em condutores desordenados».

A comissão de selecção para o Prémio Europhysics convidou a comunidade de físicos europeus a efectuar propostas para o prémio de 1994. Os premiados devem ter efectuado contribuições no domínio da matéria condensada nos últimos cinco anos, que mostrem o potencial para possíveis aplicações em electrónica, ciências dos materiais ou outros domínios da engenharia. Os padrões de selecção têm sido bastante elevados, como mostra o facto de alguns premiados, no passado, terem depois obtido o prémio Nobel.