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Nature and Prospects of the EURATOM Fusion Programme

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Nature and prospects of the EURATOM fusion programme

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The seriousness of the energy problem and the attractiveness of providing mankind, through the use of nuclear fusion, with a potentially inexhaustible and environmentally friendly new fuel, was already obvious in the 1950s. We were aware of the formidable scientific and technological difficulties that lay ahead and that a long-term effort would have to be sustained through all possible fluctuations of an economic and political nature; this is what motivated us to establish a common European Fusion Programme more than 25 years ago. This programme designed, in conformity with reiterated Council decisions, to lead to the joint construction of prototype reactors (provided that they appeared feasible) has absorbed the fusion activities of the member countries and has even attracted two non-member countries to join. The main results obtained in the associated European Laboratories will be briefly reviewed. A full-size test of the efficiency of the programme is the creation of JET. In fulfilment of our task we are now operating JET and preparing the Next Step, NET, two strictly linked activities, with support to both from a number of associated laboratories.

For the reasons listed above there is hardly another research area that is more suited than fusion for world-wide international cooperation, and in this respect the EURATOM programme is particularly attractive mainly because of JET. The suitability of such a cooperation could become even more manifest for the Next Step, which is a much more sophisticated and expensive device than JET.

1. The energy problem

The importance of the energy problem at world level can easily be illustrated by a few considerations. According to generally accepted scenarios, the combined effect of the expected increase in both world population and in the average energy consumption per head, will lead to the present-day world requirement of 6000–7000 Mt o.e. (million tonnes oil equivalent) per annum being raised by a factor of 2 or 3. A startling illustration is that the U.S.A., with only 5% of the world population, is responsible for nearly 30% of the global energy demand. It is expected that more than 80% of the world's oil supply will be depleted by the middle of the next century and so a smooth transition into the 'post-oil society' can only be assured if strategies aimed at the use of alternative energy sources are implemented early enough.

In addition, by burning the remaining coal and oil, which in any case constitute an irreplaceable source of raw material for the manufacturing industries, ecological problems are already appearing such as the increasing level of atmospheric carbon dioxide and the possible production of acid rain. According to some estimates fossil fuels should not be used significantly after the early decades of the next century and so there remain little more than 30 years for the development of worthwhile alternative options capable of supplying long-term energy needs; the major examples being solar, breeder reactors and fusion.

In Europe, the primary energy consumption per year within the Community of Ten over the last few years has fluctuated around the 1000 Mt o.e. mark. In 1984 the cost of primary energy imports was 90000 Mecu (European Currency Units) of which more than 70000 Mecu was for oil. On a world scale, solar energy is superabundant but its utilization, depending upon latitude and climate turns out in most cases, such as Europe, to be uneconomic except under the most favourable circumstances. The case for nuclear energy in Europe cannot be circumvented!

I do not intend to make an exhaustive comparison of the two long-term nuclear energy sources already mentioned. Compared with fusion, fission breeders have an advantage that they already exist but probably require further development and have ecological aspects that are certainly magnified by the density of population in Europe. Fusion is still uncertain and the least developed of all long-term energy sources but it has valuable potential advantages for Europe. Indeed, the availability of the constituents of its fuel supply, being practically unlimited compares well with the situation regarding Europe's meagre reserves of uranium. Deuterium can be extracted from the ocean and Europe appears to have adequately large reserves of the metal lithium. This element could also be extracted from the sea. Independence of supply is an important factor. Now, the fusion reaction does not produce radioactive by-products and although it does use radioactive tritium as a fuel, the inventory is small and remains within the internal circuit of the reactor.

It must be acknowledged that neutron activation of the inner structure during operation of the fusion reactor poses a serious problem, which has to be solved if long-term storage of used components is to be avoided. Great attention is now being given to the development of highly advanced technologies principally in the metallurgical field to mitigate this effect, which would have consequences for the economic operation of the reactor. Here I touch again on the argument that these developments need to be initiated early enough to bear fruit in time for their employment in the construction of the first reactors. Investments made in these technologies can benefit not only the long-term objectives but also mid-term advantages may be gained by use of the high technology content in other branches of science and European industry; the so-called 'spin off' effect.

Last, to those who might be tempted, by looking at the gallon price displayed at the petrol station, to see no incentive for efforts in solving problems for the next century, it must be remembered that the present fluctuations will not change the general trend that any consumable product is more expensive when it becomes rare, unless it can be replaced by another one.

2. The problems for fusion

When presenting his Introduction and background of the JET project, Dr Pease (this symposium) familiarized you with the physical basis of fusion, in particular the principle of toroidal magnetic confinement, which is the major line of research followed in Europe. At the early stage of fusion research, the problem appeared to be one of building an appropriate device for heating the plasma to high enough temperatures and converting the thermonuclear heat into electrical energy. This turned out to require a better understanding of every aspect of the physics and engineering involved and people soon became aware of the difficulties to be met on the path towards the prototype fusion reactor.

At the end of the fifties, it finally became evident that magnetic fusion was going to be much more difficult to achieve than originally anticipated. As Grad (1977) nicely pointed out:

> A reasonable analogy for the fusion-energy problem would be a mission-oriented programme to land a man on the moon where, as part of the project, one must at the same time discover (and exploit) Newton's laws of motion, Maxwell's equations, electronics and solid state physics.

Even at the Geneva Conference in 1958, in spite of the enthusiasm for a task that had such promise of almost unlimited power in relatively clean and safe conditions, the difficulties we would have to face were not overlooked. Such difficulties were well documented, especially by Teller (1958) when he said:

> It is likely that we shall be dealing with an intricate machine which is inaccessible to human hands because of radiation and on which all control and maintenance must proceed by remote control.

and:

> If we want to shoot for the jackpot, for energy production, I think that it can be done, but do not believe that in this century it will be a thing of practical importance....

Artsimovich, at the Salzburg conference (1962) was also very forthright when he said:

> It is now clear to all that our original beliefs, that the doors into the desired region of ultrahigh temperatures would open smoothly at the first powerful pressure exerted by the creative energy of physicists, have proved as unfounded as the sinner's hope of entering Paradise without passing through Purgatory. And yet there can be scarcely any doubt that the problem of controlled fusion will eventually be solved. Only we do not know how long we shall have to remain in Purgatory.

3. The rise of European fusion programme

The year 1958 saw also the creation of EURATOM, in which the fusion programme was already included. Considering both the possible advantage of fusion for Europe and the enormous difficulties to be solved for its realization, it was decided to create a *single* European programme supporting and coordinating the activities of the national laboratories in the member states, by means of contracts of associations. Each contract provides for staff and the financial participation of EURATOM. The present situation is illustrated in figure 1, where the location and the strength of the different associations is represented.

Official recognition of this collective spirit is found in the reiterated statement contained in the council decisions that

> The Community Fusion Programme is a long-term cooperative project embracing all the work carried out in the Member States in the field of controlled thermonuclear fusion. It is designed to lead in due course to the joint construction of prototype reactors with a view to their industrial production and marketing.

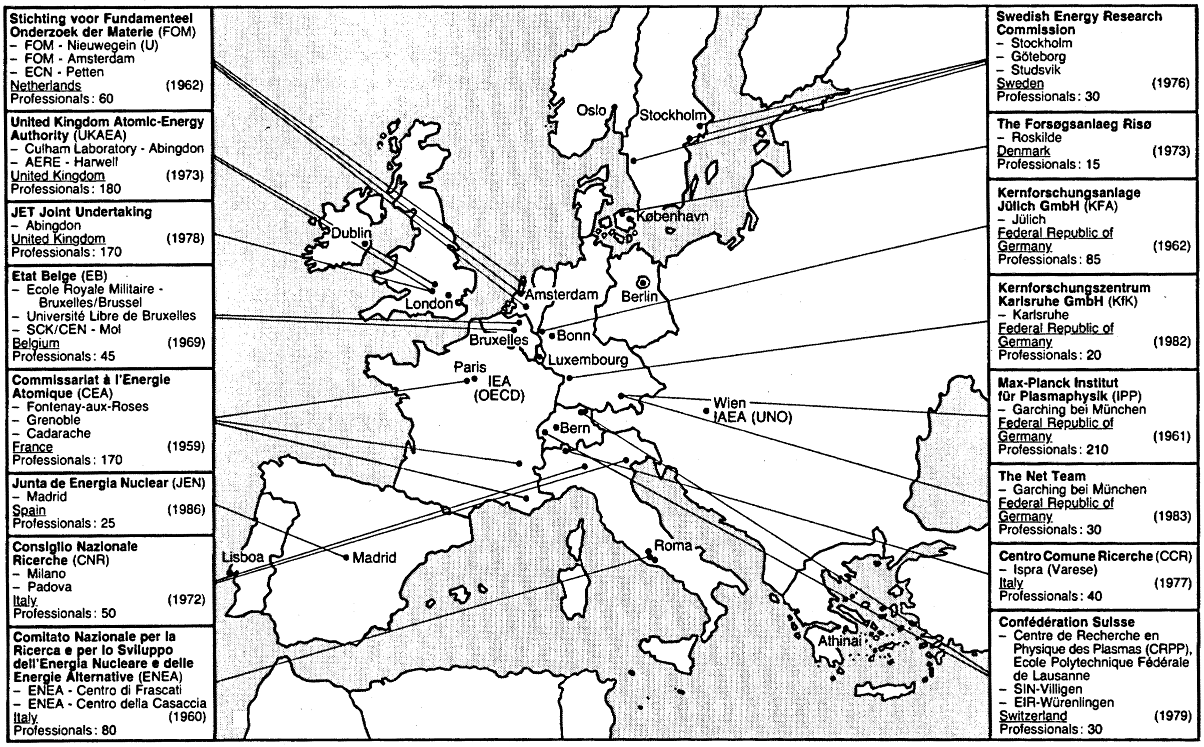

Figure 1. Location of fusion laboratories in Europe.

In the 1960s the main problems were connected with plasma confinement and to a lesser extent with heating. The nature of the work was basic and exploratory. The role of the commission was to help avoid, where reasonable, the duplication of experimental ideas and to promote the exchange of 'know-how', particularly on problems of general interest. Experimental results gave little reason for optimism: the open configuration was demonstrating its limitations and results from stellarators were not significant. In Europe, only the existence of a *common* programme has helped to overcome this period of depression during which most laboratories now active in the fusion field were established and enlarged.

The end of the 1960s was characterized by the success of the tokamak in the U.S.S.R. The problem was then to fill the gap and to extend the Russian results. In order to encourage and help laboratories, the financial support level was raised from the normal rate of 25% for running costs to a level of about 45% for the capital investments necessary to build large experimental devices that, according to the consultative bodies, had a scientific value of interest to the whole community programme. However, the need to cover a wide range of parameters meant that a number of different experiments had to be built, with the principle that each machine should be accessible to all partners: this principle led to the arrangement for easy transfer of staff under the Mobility Agreement.

The 1970s saw a concentration on the tokamak line by the construction of many such devices: some of these experiments were conducted as joint ventures between several associated laboratories. The culmination of such cooperative activities was the design and the start of construction of JET. JET was the first to be proposed of the large machines in the world, and was from the start intended as a combined effort by all the associated laboratories. The associations have launched the JET Joint Undertaking in order to equip themselves with a large device which goes beyond the capability of any individual association. For JET, the financial support given by the commission is 80%.

The 1980s so far are characterized by scientific and technical achievements that place the European fusion programme in the forefront of world-wide fusion research. JET is the leading fusion experiment in the world. The European medium-sized machines contribute in a powerful way to the progress of fusion and the future success of JET. A possible next joint undertaking is NET: this structure is thought to be well adapted to the future when the role of the presently physics-oriented associations will eventually be taken over by technology-oriented national institutions and later by industry.

The European Fusion Programme has efficiently built a truly scientific and technical community from large and small laboratories to the common and mutual benefit. For example, the Ecole Royale Militaire at Brussels has set up and operates the ion-cyclotron resonance heating on the device TEXTOR at Jülich, the FOM laboratory at Nieuwegein is running the electron-cyclotron resonance heating on the device TFR at Fontenay. The programme has also allowed for a vigorous exchange of staff between European laboratories by means of the Mobility scheme. It has been found so attractive that two European countries, non-members of the European Community, have joined it. It is now ready to welcome newcomers and integrate them in view of the common goal. Fusion is the programme in Europe with an absolute community character. Its structure and its content make it a model for other possible European efforts in science and technology.

4. THE OBJECTIVES

The purpose of the short historical background was to illustrate the formidable complexity of problems we were facing, not only in Europe, but throughout the world.

Nevertheless, the long-term objective of the European fusion programme has been well defined from the start: 'to construct jointly a prototype fusion reactor', but the main questions immediately occurring were 'how?' and 'which type of reactor?'

As has been remarked by the historian Bromberg (1982), 'the fifties were dominated by trial and error, the sixties by basic research, and the seventies by research more closely tied to a final, reactor product'. As a matter of fact, there was a period of hesitation during the 1960s, which nevertheless was necessary to arrange the problems and to set priorities. At the beginning of the 1970s the supremacy of toroidal magnetic confinement compared with open configurations was well established and the tokamak line was unanimously favoured by the world fusion community. The building of many tokamaks in the 1970s and their operation has contributed to widen the gap between the tokamak approach and other approaches, such as stellarators and reversed field pinches, which, due to their reactor potential, are nevertheless pursued.

The way towards such a prototype reactor (DEMO, which should prove the economic feasibility of fusion) goes first through the demonstration of the scientific feasibility of fusion (hopefully to be made by JET and its foreign equivalents in the early 1990s), and second through the demonstration of the technological feasibility of fusion (to be achieved by NET, the Next European Torus, and its equivalents; NET is presently in the phase of conceptual design).

Concerning the medium-term objectives of our current programme 1985–1989 these are:

(*a*) to establish the physics and technology basis necessary for the detailed design of NET; this implies the full exploitation of JET and of several medium-size specialized tokamaks in existence or in construction and the strengthening of the technology programme;

(*b*) to embark, possibly in 1989–1990, on the detailed design of NET;

(*c*) to explore the reactor potential of some alternative lines (Stellarator and Reversed-Field Pinch).

The evolving world situation over the last five years confirm this medium-term strategy chosen by Europe:

(*a*) the favourable prospects for magnetic confinement;

(*b*) the leading position of the tokamak approach on which Next Step devices will certainly be based; this supports the general strategy chosen by the community: to concentrate most efforts on the tokamak line, and to explore the reactor potential of some alternative lines within the toroidal magnetic confinement family.

The structure of the European fusion programme has made such implementation possible: all fusion activities of the member states (plus Sweden and Switzerland) and in the JRC are integrated into one, and this with a relatively small financial participation of the Community.

In 1984 the total volume of expenditure in Europe on fusion was 300 M ECU (a little more than the cost of oil imports for one day). The Community participation amounted to 130 M ECU; somewhat more than 40% of the total.

5. The contents of the European fusion programme

Let me now consider in some detail recent scientific and technical achievements of the European fusion programme.

JET is the leading fusion experiment in the world, which already in its first two and a half years of operation has made important progress towards demonstration of the scientific feasibility of fusion.

The specialized medium-size devices in operation in Europe have contributed in a powerful way to the progress of fusion: these devices and others, presently in construction, will further contribute to the progress of fusion and the future success of JET. It is impossible here to make a full list of the contributions, but let me mention some of them:

in the TEXTOR tokamak at Jülich, carbonization, pumped limiter and the RF system (operated by ERM, Brussels), which deposited up to 2.3 MW in the plasma;

at Risø laboratory in Roskilde, deuterium pellets accelerated up to about 2 km s^{-1};

in the TCA tokamak at CRPP Lausanne, the Alfvén-wave heating experiment;

the discovery of a régime of high confinement of plasma (the H-mode discharge) in the ASDEX tokamak at Garching;

in the Wendelstein VII-A stellarator at Garching (which concluded ten years of successful operation), electron cyclotron heating (70 GHz), which produced central electron temperatures in excess of 1 keV at densities of 5×10^{13} cm^{-3};

in the FT tokamak at Frascati, lower hybrid heating with good efficiency and no degradation of the energy confinement time;

in the TFR tokamak at Fontenay-aux-Roses, advanced diagnostics and ECRH experiments in collaboration with the Dutch team from FOM, where the electron temperature rose from 1 to 3 keV for $n_{e0} = 2\times10^{13}$ cm^{-3};

in the PETULA tokamak at Grenoble development and use of lower hybrid wave launching structures for heating and current drive;

in the CLEO tokamak at Culham, combined use of 28 GHz and 60 GHz ECRH resulting in absorbed RF power more than ten times the ohmic-heating power and in a rise by a factor of eight in the electron temperature;

in the DITE tokamak at Culham, evidence of the Ohkawa current;

in EXTRAP TI at Stockholm, poloidal-confinement studies.

Results achieved to date with the physics machines have been impressive and I draw attention to figure 2, which shows the advances made in raising the value of $\hat{n}\tau$.

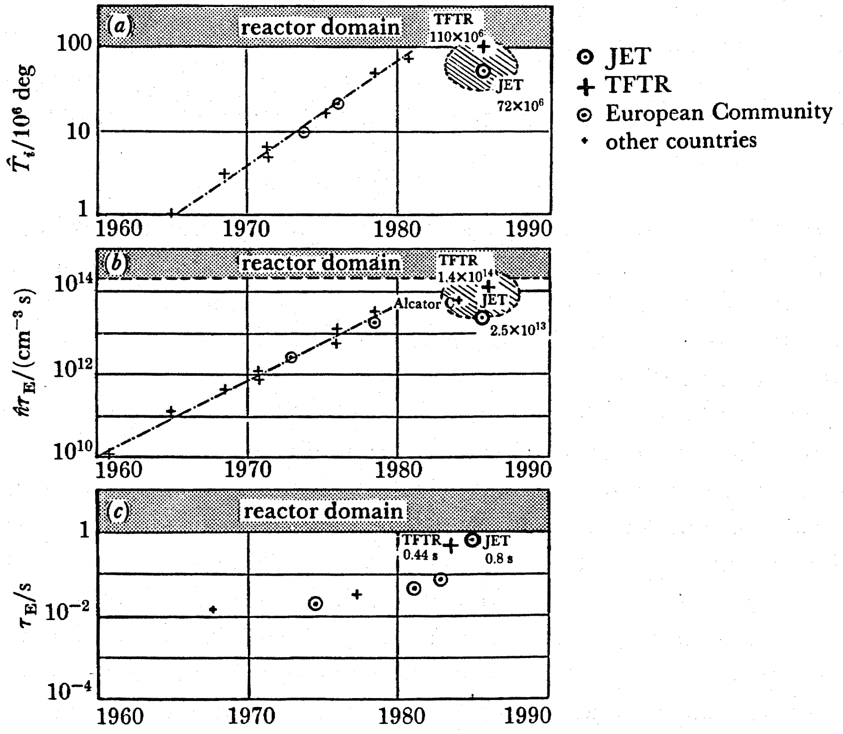

FIGURE 2. Advances made in raising the value of $\hat{n}\tau_E$. (*a*) Plasma temperature in tokamaks; (*b*) figure of merit ($\hat{n}\tau_E$) of the confinement; (*c*) energy confinement time τ_E.

At the moment several new machines are under construction in the Community:

a superconducting tokamak, TORE-SUPRA at Cadarache, in Provence;

an uprated version of the ASDEX tokamak, ASDEX-UPGRADE at Garching;

a new high-field tokamak, FTU, at Frascati;

the COMPASS tokamak at Culham;

a new stellarator in the Wendelstein series, W VII AS, at Garching and

a reversed-field pinch, RFX at Padua.

In parallel with the plasma physics experiments a rather large programme on the development of the technology necessary for the Next Step, and in the longer term for the fusion reactor, has been started.

This activity has been subdivided into the following lines:

superconducting magnets;
blanket and first-wall engineering;
tritium technology;
structural materials;
breeding materials;
maintenance;
safety and environment.

The involvement of industry has of course been important for the construction of JET and the other experimental machines. In fact, the specialization of industry in the building of components for these machines has occurred quite naturally. The possibility of some 'spin-off' is currently being carefully looked at.

Here I would like to expand a little on two recent European contributions in two completely different areas. The first, the H-mode operation of a tokamak, is an entirely new finding, the second, reflectometry, is a recent non-trivial application of a very old finding.

The H-*mode*

ASDEX is the most advanced of the second-generation tokamaks constructed at a EURATOM associated laboratory. It has a poloidal divertor that preserves the axisymmetry of the configuration and is capable of a high exhaust efficiency. The ASDEX finding that has received the greatest attention is the discovery of the so-called H-régime of neutral-beam-heated plasmas in 1982.

In general terms, what was discovered in ASDEX and was later reproduced in other tokamaks with axisymmetric divertor is essentially as follows.

There is a density range where auxiliary-heated tokamak plasmas can exist in two distinct stable configurations having the same gross *equilibrium* characteristics (dimensions, average beta, toroidal current, etc.) but having very different *transport* characteristics. The one configuration, the H-discharge, can be sustained with much less auxiliary heating power (but above some critical value) than the other, the L-discharge already known from limiter tokamaks.

Both types of configurations are possibly universal in the sense that they are largely independent of the specific auxiliary heating method used (but this remains to be proved). What discriminates between the two equilibria is a difference in the radial pressure profiles, in particular the values of the edge temperature and temperature gradient, which are higher in H-discharges.

In the experiments the parameters of the discharge evolve in time within a more-or-less long pulse, and a steady state is only obtained sufficiently well below the beta limit. What is directly observed is the occurrence of abrupt L→H transitions as shown by the immediate increase in average density and beta poloidal and by the abrupt return of all particle and energy fluxes into the divertor to approximately their ohmic levels (see figure 3). These transitions can be spontaneously initiated by the sawtooth-triggered heat pulses into the plasma boundary, when a fraction of the energy stored inside the $q = 1$ surface is suddenly released and propagates outwards while the L-mode peaked current density profile still remains frozen in. The arrival of a thermal wave of sufficient amplitude in the edge region forms there a transport barrier

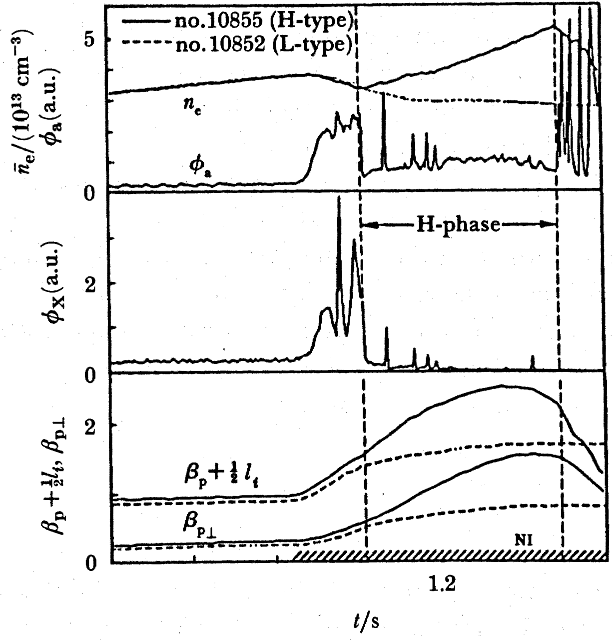

FIGURE 3. Characteristic features of H-discharge (solid curves) as compared with L-discharge (dotted curves). $\bar{n}_e$, line-averaged bulk plasma density; ϕ_a, flux of neutral atoms backscattered from collector plate; ϕ_X, hard-X-ray flux; $\beta_p+\frac{1}{2}l_i$ and $\beta_{p\perp}$, beta poloidal from plasma equilibrium and from the diamagnetic loop, respectively. Neutral injection ($P_{NI} \approx 2$ MW) starts at 1.11 s. (Source: *Nuc. Fusion* **9**, 1049 (1985).)

which not only reduces the energy and particle fluxes across the separatrix but also reduces the electron thermal diffusivity everywhere.

The important aspect of the H-régime is good confinement at high heating power. In H-discharges the scaling of τ_E, the energy confinement time, is completely different from that of ohmic discharges. It is independent of the density and is proportional to the current, the coefficient being almost twice as good as that in the L-mode. What limits its value are the edge localized modes (ELMS), corollaries of the edge barrier, which frequently interrupt the H-mode by brief expulsions of particles and energy (see figure 3). During the 'burst-free' H-phases, τ_E in ASDEX is well above 0.1 s. Unfortunately, in these cases the superior particle confinement leads to accumulation of metal impurities in the plasma core followed by radiation collapse of the discharge.

At present the important question whether H discharges can also be produced in limiter tokamaks is still open, as it is not yet known whether in the divertor case it is the high magnetic-field shear close to the separatrix which matters or the improved recycling of the device.

Reflectometry

In large tokamaks far-infrared density *transmission interferometry* with the spatial resolution necessary for measuring radial profiles and localized fluctuations would require an excessive number of observation chords in relation to the access available on the vacuum chamber.

When Marconi, ignoring the theories that had forseseen its impossibility, was able to send radio waves over long distances, first from Southampton to La Spezia and shortly after

(December 1901) from Poldhu (Cornwall) to St John (Newfoundland), the physicists, including Marconi himself, suspected that the waves were reflected by some mechanisms in the high atmosphere. Indeed shortly afterwards Eccles proved that it was due to the existence of the ionosphere and that a wave of frequency f propagating in an ionized gas with n_e electrons per cubic centimetre is reflected from the critical layer, where $f_p \equiv e(n_e/\pi m_e)^{\frac{1}{2}} = f$.

Recently, Cano and Cavallo proposed to use this same effect to measure locally the value of the electron density in a tokamak: electromagnetic radiation at frequency f is launched at the plasma along the density gradient in the ordinary mode, either horizontally or vertically. The radiation is reflected back from the critical layer. Provided that the density profile is not hollow and is such that at each point the plasma frequency remains below the electron gyrofrequency, at which the plasma absorbs and emits radiation in the ordinary mode as a black body, the wave just undergoes the phase change

$$\phi(f) = \frac{4\pi}{c}\int_a^{r_c(f)} \mathrm{d}r(f^2 - f_p^2(r))^{\frac{1}{2}} - \tfrac{1}{2}\pi, \tag{1}$$

where a is the plasma minor radius and $r_c(f)$ is the radius of the critical density layer, $f_p(r_p) = f$.

Different density layers can thus be probed by measuring $\phi(f)$ for different microwave frequencies, and if the frequency is swept at a known rate $\mathrm{d}f/\mathrm{d}t$, the whole density profile can be determined. The important point is that according to (1) the density information obtained in the measurement is largely localized to the region of the critical layer, rather than being distributed along the whole line of sight as in transmission interferometry.

Reflectometry represents a considerable simplification over the present methods. It will be installed on JET for which purposes the frequency will be swept between, say, 20 and 110 GHz in a 1 ms time scale so as to give a spatial resolution of about 1 cm.

6. PROSPECTS

At present our strategy can be represented by figure 4. Our final aim as an R & D programme is the construction of the demonstration reactor, DEMO, which is an apparatus having a net energy production and a tritium breeding ratio slightly in excess of unity. Of course between JET, which is a machine having only physics objectives and DEMO there is a large gap. It is generally thought, and hoped, that a single step between JET and DEMO will suffice. So the medium-term objective of the programme is the construction of a machine that will have in a primitive sense all the components required in a fusion reactor. This is what we call NET, and we assume it will be a tokamak even if, as is shown in the figure, this will not necessarily be the system adopted for DEMO. Nevertheless, we think that the technological development required for DEMO are more or less common to other possible toroidal confinement schemes.

As we also did 12 years ago for JET we have set up a study group for NET and this is located at Garching. We hope that with the experience and results obtained in operating JET and the medium sized machines already operating or under construction, and by progress in technology, we well be able in a few years to start the engineering design of NET. Further encouraging results in science and technology will lead to the start of its construction in the first half of the next decade. A tentative schedule for these activities is given in figure 5.

For the more distant future it is difficult at the moment to formulate an indicative timetable, even under the hypothesis that NET should be a purely European enterprise. But today there

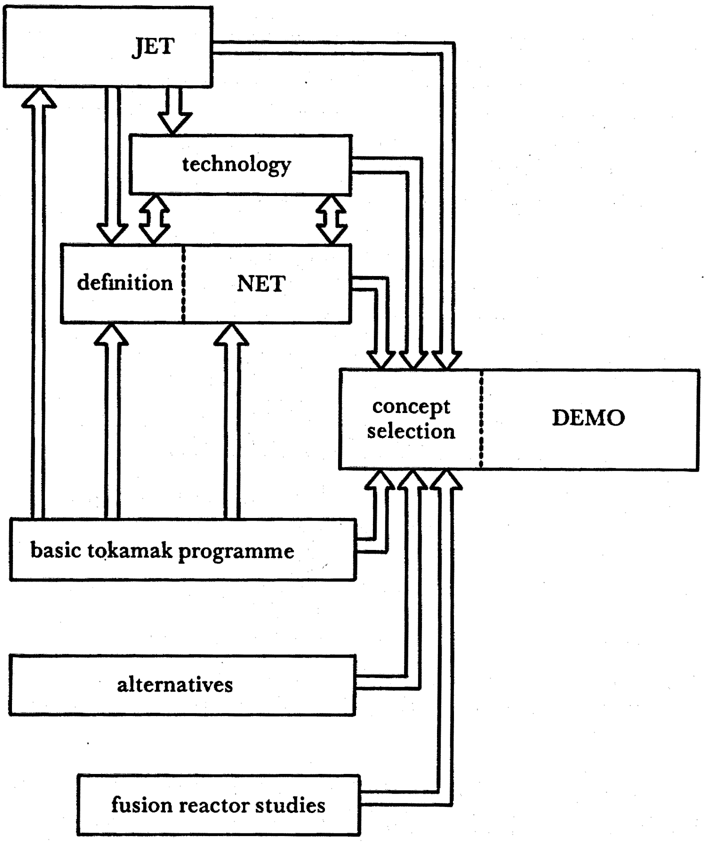

Figure 4. Programme strategy.

are some signs and aspirations that due, among other reasons, to the high cost of this intermediate step, such a machine could be realized in the framework of a larger, perhaps world-wide collaboration...but this brings me to my next and final topic.

7. International collaboration

Making available the energy from the fusion reaction would be an enormous advantage for all mankind. This advantage would be much larger than the possible benefit and prestige to be gained by any one country which succeeded in doing it alone. In any case the advantage would soon be available worldwide. As a consequence, the engagement of any large scientific and technical community in fusion is more than a moral obligation, and it is evident that this should be done in the spirit of collaboration rather than in competition. In fact it is clear that a coordination of the efforts would make it easier, quicker and cheaper to realize the achievement of these aims.

In this direction, the European Fusion Programme represents the first attempt of a supranational character that has made a sizeable contribution to scientific and technical progress. Such European collaboration has helped us to overcome the depression in fusion during the 1960s. At the end of this depression, when the results of the T3 tokamak were presented at the Novosibirsk Conference in 1968, a great contribution towards overcoming the

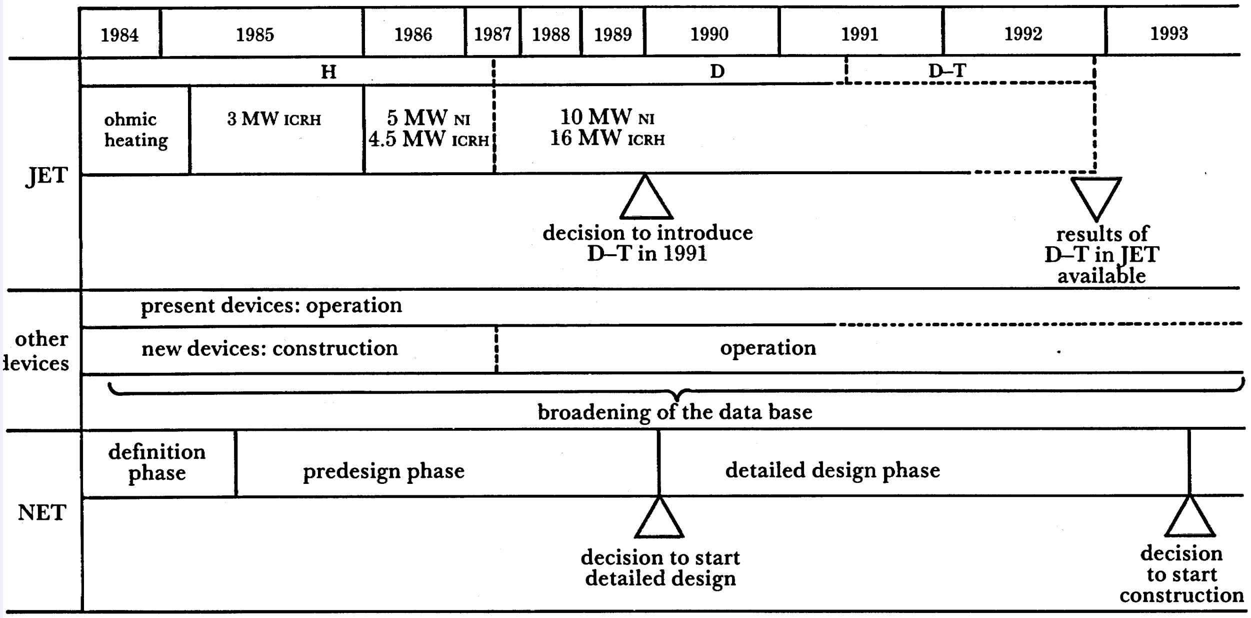

FIGURE 5. Milestones in European fusion research. MW, megawatts coupled to the plasma; NI, neutral injection; ICRH, ion cyclotron resonance heating; H, D, T, hydrogen, deuterium, tritium.

remaining doubts about tokamaks was made by a British team that went to the Kurchatov Institute and was able to confirm the Russian results. This was the first example of international collaboration (collaboration at world level).

In fact, there are in the world four, more or less equivalent, programmes on fusion, those of: Euratom, U.S.S.R., U.S.A. and Japan, which have comparable size, degree of achievement and objectives.

Between these programmes collaboration has already been established in a number of ways.

As far as the present situation is concerned, the content and the structure of the European Fusion Programme have made Europe an appealing partner for international collaboration.

In the frame of the International Energy Agency (IEA), implementing agreements are in force on:

plasma–wall interaction on the tokamak TEXTOR at KFA, Jülich (Euratom, U.S.A., Switzerland, Turkey, Canada);

the development and testing of superconducting coils, or large coil task (Euratom, U.S.A., Japan, Switzerland);

a cooperative programme for investigation of toroidal physics in, and plasma technologies of, tokamaks with poloidal-field divertors (Euratom, U.S.A.);

cooperation in the development of the stellarator concept (Euratom, U.S.A.);

a programme of research and development on reversed-field pinches (Euratom, U.S.A.);

cooperation among the three large tokamak facilities (Euratom, U.S.A., Japan) signed January 1986.

Bilateral agreements are also being undertaken with Canada (signed); U.S.A. (ready for approval); Japan (in preparation). In the frame of the International Atomic Energy Agency (IAEA), the Community participates with the three other large fusion programmes in the

INTOR workshop. In the frame of the follow-up of the Versailles Summit, the Commission has played the role of coleader with the U.S.A. for the strengthening of cooperation on fusion.

Throughout the negotiations leading up to the conclusion of the above agreements, and for their signature, the European Programme has shown its strength and coherence by acting as a single entity. This character should be maintained, for the benefit of the programme, in future negotiations of a smilar nature.

On the other hand, following the Reagan–Gorbachov meeting at Geneva, and in view of the high cost and complexity of the NET generation devices, it could be appropriate to envisage an almost world-wide joint venture. The recent declaration at Geneva has been received with interest by the world fusion community, and in the West we are actively working on examining in some detail the feasibility of such an initiative. Of course, the engagement of the world fusion community will be a prerequisite, but it is also evident that a lot of political, managerial and administrative problems have to be solved. For this, good will and the commitment of the political authorities is necessary.

However, we should avoid thinking that the solution of our problems can be in the hands of ambassadors and foreign ministers. The main problems remain with the physicists and engineers. Supposing, and hoping, that Nature will allow the magnetic confinement of very high temperature plasmas (for example, by the heating of a tokamak; and the H-régime seems to show that there is at least one way in which it can be done), the physicists still have to find the simplest way of establishing the conditions, and the engineers have to develop the most economical and reliable way of exploiting them on a large scale, relying on advanced technologies.

We hope that the first problem can be solved by the present generation of machines, in particular JET, and this will enable us to go on to tackle the Next Step towards the construction of an experimental fusion reactor, possibly in the frame of a large international collaboration.

References

Artsimovich, L. A. 1962 In *Proc. 1st International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Salzburg, September 1961.* (*Nucl. Fusion Suppl.*, part 1), pp. 15–20. Vienna: IAEA-CN-10.

Bromberg, J. L. 1982 *Fusion: science, politics and the invention of a new energy source.* Cambridge, Massachusetts, and London: MIT Press.

Grad, H. 1977 Magnetic confinement fusion energy research. In *Mathematical aspects of production and distribution of energy.* Proceedings of Symposia in Applied Mathematics (ed. P. D. Lax), **21**, 10.

Teller, E. 1958 In *Proc. 2nd UN International Conference on Peaceful Uses of Atomic Energy, Geneva, September 1958*, vol. 31, pp. 27–33. United Nations Publication, A/CONF 15/1.