Tokamak Reactors for Break-even

H. Knöpfel, Frascati

A critical study of the near-term fusion reactor programme

At a time when discussions on the definition of the Joint European Torus programme (JET) are still going on, it may be useful and interesting to look back for a moment to the Course held in Erice in September 1976 on Tokamak Reactors for Break even — A Critical Study of the Near Term Fusion Reactor Program. The title refers to Tokamak devices (Fig. 1) in which the thermonuclear energy produced from a deuterium-tritium plasma, represents a substantial fraction of the energy required to sustain the machine cycle and heat the plasma. The discussion at Erice was thus centred on the steps that should follow JET; implicitly, it also provided a valuable contribution to the definition of the aims and prospects of a much needed near-to-medium term European fusion programme. Such a definition could be of much help to Euratom, which is in charge of coordinating the West European fusion effort.

The present effort in the field of controlled thermonuclear fusion (Table 1) represents a substantial new experience for all those concerned with research and development programmes. In fusion, we find an intriguing mixture of fundamental and applied research, and of technological developments as well; moreover, the further the work proceeds, the more these R & D programmes (all equally important) will have to match the ultimate promise of fusion as a new energy source. The unusual but necessary variety of interweaved approaches and motivations is what makes fusion research so confusing — and, at the same time exciting; it also makes it so essentially different from other major technological and scientific adventures, such as the exploration of space, or the development of nuclear breeders.

Table 1: Controlled Fusion 1977

1. Effort required to reach reactor stage may be larger than the NASA Apollo Programme.
2. Fusion has now entered into competition for funds and support with other important R & D programmes.
3. World effort in magnetic fusion is supported by more than 3000 professionals and an estimated 700 M$, more than 2/3 are directly or indirectly for the Tokamak line.
4. There is as yet no clear indication on the scientific feasibility.
or research in high energy physics, where the technical component is much better separated from — or even independent of — the physics programme.

Among the many requirements imposed on a thermonuclear magnetoplasma, are two that are fundamental to the practical application of fusion:

a) A positive power balance is required; in a plasma with the energy confinement time $\tau_E$ [i.e., total plasma energy/(ohmic heating power)] this condition can be expressed approximately in the form:

$$Q = \frac{\text{power out}}{\text{power in}} \approx \frac{n^2 (eV) W_f}{nkT / \tau_E + P_{\text{rad}}} > 1 \tag{1}$$

where $n$ is density, $n^2 (eV)$ is the mean fusion reaction rate, $W_f$ the nuclear fusion energy, $nkT$ the thermal plasma energy and $P_{\text{rad}}$ the power loss through radiative phenomena. When the latter term is negligible, then $Q \approx n n^2 (eV/T) W_f$, where for a deuterium-tritium plasma ($eV/T$) has a maximum around $T \approx 25 \text{ keV}$.

b) A high power density is required for economic energy production:

$$P = n^2 (eV) W_f < \beta B^4 (eV/T) \tag{2}$$

Notice that the (toroidal) field $B$ is limited at different levels by technical restraints (see Sect. 3) and the parameter $\beta$ (plasma energy)/(magnetic energy) by plasma physical effects (see next Section). Nevertheless, typical power densities of $\beta \approx 10 \text{ MW/m}^3$ would be conceivable (compared with 300 MW/m$^3$ in a fast breeder reactor).

There is, however, a fundamental upper limit of $\beta$ defined by the fusion reactor surface constraint. In practice, the (neutron) power flux through the first plasma container wall is limited by material properties (structural damage) to less than e.g., 5 MW/m$^2$ for stainless steel liners. For a reactor with plasma and liner radii of 3 and 3.5 m respectively, the mean power density would thus be limited to 4 MW/m$^3$.

### Table II: Current Experimental Status of Magnetic Fusion Systems

<table>
<thead>
<tr>
<th>$n^2_E$ (cm$^{-3}$s)</th>
<th>$\beta$ (%)</th>
<th>$T_i$ (keV)</th>
<th>$Z_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion Feasibility</td>
<td>10$^4$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Tokamaks</td>
<td>10$^{13}$</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Mirrors</td>
<td>10$^{11}$</td>
<td>50-100</td>
<td>10</td>
</tr>
<tr>
<td>Pinches</td>
<td>10$^{11}$</td>
<td>50-100</td>
<td>4</td>
</tr>
</tbody>
</table>

### Plasma physical aspects

From the previous expression (1), the following typical set of minimal parameter conditions can be deduced to arrive at the necessary power gain in a deuterium-tritium plasma:

- $n n^2 (eV/T) \approx 10^4 \text{ cm}^{-3} \text{s}$ (Lawson criterion);
- $T_i \approx 6 \text{ keV}$; $Z_{\text{eff}} < 2$, where $Z_{\text{eff}}$ is the mean effective ion charge that reflects the impurity content. (For example: $Z_{\text{eff}} = 1$ for a pure hydrogen plasma, but $Z_{\text{eff}} = 2$ with 2% fully ionized oxygen impurity in it.)

In addition, if a realistic evaluation is made of the technical and economical constraints that limit the maximum magnetic field, expression (2) imposes, in practice, the condition $\beta \approx 10^4$ for reactor applications.

These fundamental parameters have improved steadily in Tokamak plasmas over the past 10 years (Fig. 2), but probably not as much as many hoped (Table II). It is commonly accepted that further appreciable progress in understanding and in performance can be obtained only with larger and/or technologically more advanced devices, and with substantial new heating capabilities.

#### a) High Power Densities ($\beta$)

There are several methods by which, in principle, $\beta$ can be improved from the present 1-2% to above 5-10%: elongating the cross section (as in JET); shaping the current profile (which also requires auxiliary heating); establishing a force-free current zone that surrounds the main plasma (as in toroidal pinches); applying the so-called flux conserving Tokamak scheme (as proposed by Oak Ridge). Numerical studies with two-dimensional magneto-hydrodynamic codes show, however, that it is difficult to reach values higher than about 5%, because of MHD stability problems of ballooning modes. These instabilities are a consequence of the large density and magnetic field gradients in the outer equatorial regions of high $\beta$ discharges; they tend to make the pressure profiles across the whole discharge evolve into large bulges.

#### b) Containment ($n^2_E$)

The increase of the $n^2_E$ parameter over the past 20 years in various fusion experiments is very impressive: $10^9 \text{ cm}^{-3} \text{s}$ in 1955; $10^{11}$ in 1965; more than $10^{13}$ in 1976! It is thus tempting to speculate on future improvements in Tokamaks by matching experimental results with empirical scaling laws. For example, within the limited parameter range of (small) Tokamak experiments, the scaling $n^2_E \approx n^2 a^2$ holds fairly well, where $a$ is the minor toroidal plasma radius. By applying the conditions that express MHD equilibrium constraints, from this expression an upper limit can be obtained:

$$n^2 \beta \approx \frac{q^{3.5} R_0}{a(R_0)^4}$$

$q$ is the so-called safety factor: $q = 4,...,6$ in actual Tokamaks, and hopefully may approach 2 in future experiments. If the recent results of the two largest Tokamaks are taken into account, the scaling is somewhat less favourable, $n^2 E \approx (na)^{2/3}$. In any case, the important temperature scaling of confinement is missing as it is difficult to determine from present experiments, because of the inherent coupling between confinement and ohmic heating in the Tokamak confi-
Neutral injection heating has been an outstanding success story (Fig. 3). In several machines, the auxiliary injected power is approaching the ohmic power (though at levels of only some hundreds of kilowatts), and the heating of ions has continued to behave neoclassically. The electron temperature, on the other hand, shows a puzzling reluctance to increase correspondingly; this behaviour is somewhat disturbing, but the experiments are still inconclusive and leave room for different explanations and for hopes of improvement. Electromagnetic wave heating, after about 20 years of benevolent attention, has now the opportunity to show its practical relevance in different experiments. For example, 5 MW of ion cyclotron heating (typically in the 25 to 150 MHz range) is foreseen for the PLT-Tokamak in Princeton.

d) Impurities \( Z_{\text{eff}} \)

In some experiments, impurities are apparently ejected by instabilities, or held outside the discharge by temperature gradients; high density discharges are surprisingly pure \( Z_{\text{eff}} \approx 1 \). There is, as yet, no real understanding of the somewhat confusing dynamics of impurities but the situation is more promising than was the case even two years ago.

Main hopes rest on the use of diverters, on a careful choice of limiter materials, on operation at higher densities and on the reduced surface to volume ratio of larger machines.

Technologies and Systems

The technological requirements of future large toroidal devices — at first, machines of the dimensions of JET and later the Tokamak Reactor System — are very substantial. On this general level there are at present two rather different attitudes to the development of systems and their required technologies.

Either they could evolve with experiments and new ones be added as the experiments slowly develop into the future reactors, or systems specific to the future reactors could be studied now, in parallel with current experiments. The first method — which could be called the "evolutionary approach" — is probably the most economic in that no unnecessary system or technologies would be generated. However, current experiments not actually aimed at reactor conditions, could be a misleading guide for the development of systems and technologies.

The second method — the "planned approach" — has the advantage that the Reactor System Studies could help guide the next stage of the experiments and indicate future problems. Such studies have, in fact, highlighted certain technical problems, such as materials problems and plasma-wall interaction problems, which will take a long time to resolve and hence should be started in parallel with the present day confinement experiments in order to reduce the time to a fusion reactor. However, if there is no effective management, technological studies can easily grow out of control, thereby absorbing a great deal of money at the expense of the experiments presently under way.

There are some specific technical systems that may be important for near term experiments, as well as for the ultimate reactor. Typical examples are: neutral particle injectors (Fig. 3) and superconducting magnets. Some megawatts of neutral particles will be injected into the PLT Tokamak in Princeton towards the end of 1977.

A power of approximately 30 MW of neutral injection heating is foreseen for the Tokamak Fusion Test Reactor \((R_o = 250 \text{ cm}, a = 85 \text{ cm}, B_T = 5 \text{ T})\) which should become operational in 1988 in Princeton; for JET \((R_o = 300 \text{ cm}, a = 210/120 \text{ cm}, B_T = 2.7 \text{ T})\) one now requires, on the basis of scaling laws as given in Sect. 2b, an injected power of more than 25 MW. Such large heating systems represent a substantial investment, estimated to be 1.5-2 $/W of neutral beam power.

The importance of magnet technology with respect to obtainable fusion plasmas is demonstrated directly by expression (2); on the other hand, there are the aspects and the limitations imposed by mechanical stresses and, particularly, by ohmic dissipation in the coils.

It is convenient to consider four different magnetic field ranges, each characterized by its particular problems and specific advantages. Notice that \( B \) indicates here the magnetic field on the toroidal axis \((R = R_o)\); due to the \( 1/R \) dependence, the maximum toroidal field at the inner equatorial region of each coil is \( R_e/(R_o - a) \) times larger (typically 70 % larger).

a) \( B < 5 \text{ T} \): Conventional water-cooled copper magnet, made typically of 16 to 32 single coils that give good access for auxiliary heating and diagnostics to the plasma container (e.g., DITE Tokamak at Culham or PLT at Princeton); possibility of using proven NbTi superconductors with partial or full cryostatic stabilization (e.g., T-7 and T-10M Tokamaks in Moscow, operation foreseen in 1978 and 1981).

b) \( 5 \text{ T} < B < 8 \text{ T} \): Mechanically advanced and reinforced copper magnets that still allow reasonably good access (e.g., TFR Tokamak at 6 T in Fontenay-aux-Roses); possibility of using high field A 15 superconductors such as NbTiSn.

c) \( 8 \text{ T} < B < 14 \text{ T} \): Compact magnet of the Bitter disk type at cryo-


Zeff have been obtained in high field

interesting approach to fusion that is

ALCATOR C designed for 14 T at

compact devices. In addition, so far

operation of denser plasmas in more

Since magnetic fusion reactors will,

complementary to the low field and

and high density operation. High field

Tokamaks pose challenging technical

problems, but represent today an in­

interesting approach to fusion that is

complementary to the low field and

high density regimes contemplated up

to now in larger devices (Table III).

Since magnetic fusion reactors will,

most probably, require superconduct­

ing magnets for economical reasons,

the long range high field prospects

concentrate on the magnetic field

range b). On the other hand, devices

operating in the range c) or d) may

be very interesting in the intermediate

phase, to demonstrate controlled igni­
nation of a deuterium-tritium plasma, or

as a material testing device.

Conclusions

Unless a substantial scientific break­

through emerges in the next five years

(which is not at all impossible) and

unless the world-wide fusion techno­

logy effort is increased manyfold, it

looks unlikely that a fusion demon­

stration reactor (at the level repre­

sented, for example, by the Phénix

Reactor in the fast breeder pro­

gramme) could be effectively working

before the year 2000. In the next years

it will be necessary to work out long­
term programmes that are sufficiently

flexible — and credible — that they

can accommodate delays or funda­

mental reorientations in fusion re­

search and development, even if that

means shifting the target date of the

demonstration reactor to the year 2010

or beyond. Medium-term programmes

that give useful guidance on the

choices open in fusion research, exist

in the United States and are now

particularly needed in Europe. In view

of the future large prototypes and of

the related costs and risks of the com­

plex research and development pro­

grammes, medium-term planning on

a broad international level is becoming

ever more desirable, even necessary.

Discussions at the Erice meeting

have shown that a majority of the

scientific community is realistically

aware of the many important implica­
tions of the future fusion research pro­

gramme. It was clear to all that

magnetic fusion has now reached a

level of political attention and fund­
ing (270 M $ in 1978 in the U.S.

alone) that a strong, competent and

imaginative management has become

necessary. Only gradually is the com­

community becoming aware of the fact

that fusion research and development,

if it is finally to be carried through
to success, will probably surpass in

impact and in technological and finan­
cial dimensions, for example, the

NASA Apollo Programme.

At the same time, there is a second

aspect, namely the scientific and in­
tellectual motivation for this activity

that will make it possible to survive

inevitable pauses or drawbacks during

its progress. In fusion-oriented plasma

research and development there is a

challenge of new frontiers in physics,

of new numerical and theoretical

working methods, of sophisticated

diagnostic systems and of advanced

technologies that in its totality is

hardly matched by any other scientific

field of human endeavour.

Table III: Build Larger Tokamaks now?

Yes, because:

1. Fusion reactors will necessarily be

large (minor radius: 2-5 m, major ra­

adius: 5-8 m; the sooner one is con­

fronted with the physics and technology

of large systems, the better).

2. Alpha particles will be contained (the

physics of thermonuclear heating can

be studied).

3. General physical considerations and

results from present Tokamak genera­
tion, suggest a favourable scaling with

size.

4. Surface to volume ratio is reduced

(the impurity influx, and thus heat

losses, should be reduced).

5. Quality of magnetic topology may be

improved.

6. Good access for injection heating and

magnetics is provided.

7. Solutions to important new technology

problems (superconducting magnets?)

will be sought.

No, because:

1. The outstanding physics questions

(containment, heating, plasma beta, im­
purities) will barely be answered by

1985.

2. Within limited budgets, the priority

must be given to basic physics pro­blems.

3. The so-called scaling laws in support

of larger devices are not based on

sufficient scientific data (for example,

temperature scaling in Tokamaks can

be studied only with future injection

heated devices).

4. No fusion concept can scientifically

claim at present to be the most pro­
mising (a high field device, for example,

may turn out to be more convenient).

Waiting for JET

Still no decision has been taken on the

project to build the Joint European Torus,

JET, although it had been hoped that

some solution might have been found at

the meeting of the heads of State of

western European countries that took

place in London in June. Now it is hoped

that something positive may emerge from

the meeting of the Council of Foreign

Ministers of the countries of the Euro­

pean Community on 23 September. P

While publicity has been given to the

problem of selecting a site with, at vari­

ous times, the centres at Cadarache, Culham,

Garching and Ispra being quoted. The site

is not, however, the only decision that

has to be taken. The Committee of Per­

manent Representatives of the Communi­
ties has to recommend a management

structure for the Project and this also

has been the subject of controversy.

Everyone seems to be in agreement that

JET is a project of great importance for

the development of fusion and is vital for

the promotion of the technology in western

Europe but this has only served to ac­
cerate the divergences and regretably

the politics of collaboration have seemed

to dominate the scientific imperatives.

A certain parallel exists between the

discussion of the future JET situa­tion and that encountered with the CERN SPS in the latter part of

the 1960's, but at CERN it proved possi­

tle to appoint without too much argument a project leader who was able then to cata­

lyse the subsequent accord. There was

also, of course, an existing single inter­
national site whereas, although Euratom

has been successfully coordinating west­

european research on fusion devices

over many years, there is as yet no single

European centre devoted to fusion re­

search. JET has so far no project leader,

but a design team leader in the person

of Paul Redut. The remit of his team at

Culham has been extended to cover the

months of August and September but it

seems unlikely that the members of this

team will be prepared to continue on such

a hand to mouth existence indefinitely.

In the meantime, the only large, new

tokamak presently being built in Europe

is the ASDEX device in Garching near

Munich shown in the photograph on the

opposite page.