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The JET Project: Introduction and Background

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The JET project: introduction and background

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The Joint European Torus, JET, is an experiment, undertaken by 15 partners from 12 nations of Western Europe, to get information on the magnetic confinement of high-temperature plasma in conditions close to those needed for energy-producing controlled thermonuclear fusion reactors. Physically, JET is a very powerful toroidal-pinch electric discharge in a strong stabilizing magnetic field, a system known as a tokamak. The paper summarizes the main features of a tokamak and relates them to the papers in this symposium.

Introduction

The primary physics aim of the research programme being reported here is to find out whether or not it is possible, in a controlled and potentially useful way, to create high-temperature matter so that thermonuclear reactions in hydrogen isotopes can sustain the high temperatures and produce a net yield of energy. The existence of nuclear fusion energy and its vast potential was identified in the 1920s (Eddington 1920). Exploratory research on the possibility of releasing it by magnetic confinement of high-temperature matter began in the decade 1946–1955 (Artsimovich 1959; Teller 1959; Thonemann 1959). By about 1970 the research had reached a stage (IAEA 1970) when it appeared worth building a large experiment with sufficient capability to explore directly conditions approaching those needed for self-sustained thermonuclear reactions. The scale of the experiment required the combination of resources from the fusion research programmes of the countries of Western Europe. This experiment is the Joint European Torus, JET, approved by the Council of Ministers in 1978 and commissioned in 1983. The early history of JET and its origin has been given by Willson (1981). The purpose of this symposium is to present the main features of the JET apparatus, the results of experiments so far carried out, and to discuss the scientific implications in so far as they can be drawn at the present interim stage.

The JET project is a substantial international enterprise, involving some 15 member organizations, listed in table 1, led by the fusion-directorate of the Commission of the European Communities, which is the major funding body. Legally, JET is a Joint Undertaking set up under articles 45–51 of the Treaty of Rome. It is managed by the JET Council, consisting of representatives of the member organizations, and by the director of JET, Dr P. H. Rebut, who leads the team consisting of an international staff seconded to the project by the members. Dr Rebut also led the team during the design phase. His paper describes the main concept of the machine, the overall programme and the future of the project. The construction of the apparatus itself has been implemented almost entirely by European industry working to competitive contracts let by the JET team. In some cases, notably the development of the additional heating system and of diagnostics systems, development work has been carried out for JET by the members. The design and construction of the apparatus is described in Dr Huguet's paper.

Table 1. Members of the JET joint undertaking

(February 1986.)

EURATOM	ENEA } Italy	Luxembourg	Energy Research Commission, Sweden
Belgium	CNR } Italy	Ireland	Switzerland
CEA,	Greece	KFA, Julich } West Germany	FOM, The Netherlands
France	Risø, Denmark	IPP, Garching } West Germany	UKAEA, U.K.

The main method of experimental measurements and analysis are described in the papers by Dr Stott and by Dr Düchs. The main results of the experimental programme are described in the papers given by Dr Gibson, Dr Engelhardt, Dr Duesing and Dr Jacquinot; Dr Bickerton's paper relates the observations to theoretical prediction.

The work of JET is carried out in conjunction with a substantial complementary programme of experimental and theoretical research being carried out in the EURATOM programme throughout twelve nations in Western Europe. The relation of JET to this EURATOM programme is discussed in the paper by the director of the EURATOM Fusion Programme, Dr Palumbo. Moreover, in America, Russia and Japan, there are fusion research programmes all of which include major tokamak experiments. We can draw on results of this other research; and in this symposium, in particular, we have a presentation by Dr Hawryluk of results from the American experiment TFTR; and a presentation by Academician Kadomtsev of theoretical work at the Soviet Union's Kurchatov Laboratory, which played the major role in pioneering the tokamak system that is the basis of JET. Additionally, to help keep the ultimate practical aim in focus we have a paper from Dr Toschi, who leads the European NET team studying the possible next step, describing the engineering requirements of a power reactor. The principal purpose of this introductory paper is to introduce the main nomenclature and language of the subject by summarizing the main principles upon which JET is based.

Thermonuclear reactions

The most accessible of the nuclear fusion reactions is that between deuterium and tritium, namely

$$\mathrm{D+T \rightarrow {}^4He + n + 17.6\ MeV}.$$

The cross section rises to a maximum of about 5 b† at a deuteron energy of 70 keV. Thermonuclear reactions in a deuterium–tritium mixture are detectable at temperatures of a few million degrees and can become energy-producing at temperatures greater than about fifty million degrees, depending on the degree of thermal insulation achieved. In our papers temperatures are expressed usually in electronvolts. A temperature of 1 eV = 11600 K. The power P_N per unit volume produced by D–T reactions at a temperature T can be expressed

$$P_N = n_T n_D f(T) E_n, \tag{1}$$

where n_T and n_D are number densities of tritons and deuterons, respectively, $f(T)$ is a function of temperature, and E_n is the energy released in each nuclear reaction. The neutrons produced in the reactions escape from the tenuous high-temperature plasma generally envisaged. Consequently, to obtain a self-sustained reaction in the gas, the heating can be provided only by the

† $1\ \mathrm{b} = 10^{-28}\ \mathrm{m^2}$

α-particles, because these can be trapped. The energy in the α-particle is 3.52 MeV. At the required temperature, the minimum energy losses are due to radiation from electrons colliding with the ions. This radiated power varies approximately as $n_e^2 Z_i T_e^{\frac{1}{2}}$ per unit volume, where T_e is the electron temperature, and Z_i is r.m.s. ion charge number. This radiation loss sets (when $Z_i = 1$) the lower temperature limit of 4.5 keV for self-sustained thermonuclear reactions. If $n_D = n_T$, then above this temperature, the energy released by the D(T, n) α reactions (assuming ion temperature and electron temperature are equal) in the charged helium nuclei exceeds the radiation loss; and the high temperatures can become self-sustaining.

To give general expression to the other forms of heat loss, the concept of energy confinement time τ_E is introduced, defined by:

$$\tau_E = \frac{\text{total thermal energy content of the hot plasma}}{\text{power in all other forms of loss}}. \tag{2}$$

Then the conditions for the power produced in the helium reaction products to exceed the losses due to radiation and to the other losses are plotted as a simple curve giving $n_e \tau_E$ as a function of temperature assuming the ion temperature and the electron temperature are the same (figure 1). At the optimum temperature of about 25 keV, the maximum tolerable losses are set by

$$n_e \tau_E \gtrsim 1.5 \times 10^{20}\ \text{m}^{-3}\ \text{s}; \tag{3}$$

and exceed the minimum radiation loss by a factor of about 30.

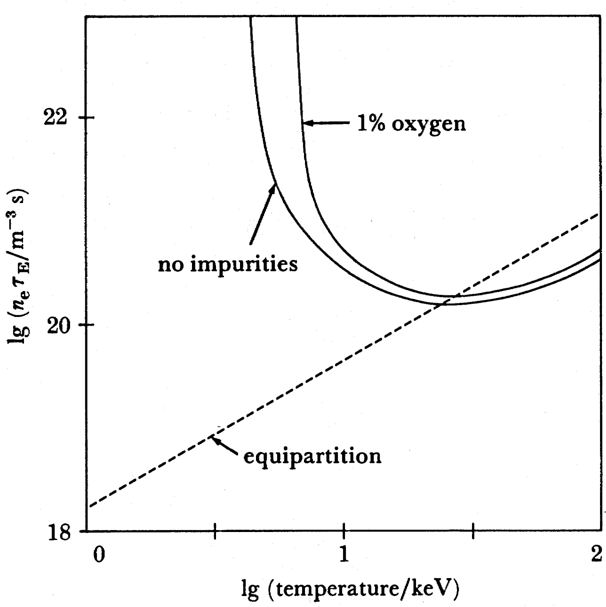

FIGURE 1. Ignition criteria for an isothermal D–T plasma. The continuous curve shows the quantity $n_e \tau_E$ for which the total rate of energy loss is equal to the thermonuclear α-particle power, with equal number densities of D and T. Thermonuclear reaction rates from Peres (1979); bremsstrahlung radiation rates including relativity corrections from Vrejoiu *et al.* (1982), Landau & Lifshitz (1971), Chen *et al.* (1982); oxygen radiation from Vernickel & Bohdansky (1978). The dotted line shows the product $n_e \tau_{eq}$, a condition for nearly equal ion and electron temperatures (see text). Calculations by Arter (personal communication 1986). Least $n_e \tau_E = 1.5 \times 10^{20}\ \text{m}^{-3}$ s; least $n_e T_e \tau_E = 3.0 \times 10^{21}\ \text{m}^{-3}$ s keV.

At temperatures in the region of 10 keV we can combine these criteria with the temperature to get an overall criterion for a self-sustained reaction:

$$n_e \tau_E T > 3 \times 10^{21}\ \mathrm{m^{-3}\ s\ keV}. \quad (4)$$

In most experimental work, including that on JET, the energy-confinement time used is defined as:

$$\tau_E = W/(P_{tot} - \dot{W}), \quad (5)$$

where W is the thermal energy in the plasma and P_{tot} is the total power input. This definition differs from that of figure 1 only by including the bremstrahlung radiation which is so far a small faction of the losses actually encountered experimentally.

The results shown in figure 1 assume $n_D = n_T$; and that the electron and ion temperature are the same. Also shown in figure 1 is the product $n_e \tau_{eq}$, where τ_{eq} is the characteristic time for the collisional equalization of electron and ion temperature, defined in Spitzer (1962). If the energy confinement criterion is satisfied, then at temperatures below about 10 keV the temperature will be closely the same; but at temperatures significantly above this, the divergences between the two can be considerable. This leads to the favourable possibility of a so-called hot-ion mode of operation, envisaged for experiments in TFTR, when $T_i > T_e$.

High-temperature plasma

Properties of high-temperature matter are the subject of plasma-physics text books. The approximate model used is that of a gas of free electrons and ions, colliding with a frequency set by the Rutherford-scattering cross section, with the electron fields screened out with a screening length set by the Debye length. Experiments indicate that this approximation is generally satisfactory for the case where Debye length exceeds the interparticle distance, i.e.

$$n_e^{\frac{1}{3}}(\epsilon_0 k T_e / n_e e^2)^{\frac{1}{2}} > 1, \quad (6)$$

which always applies in the case of the plasmas in JET. Here k is Boltzmann's constant, ϵ_0 the dielectric constant of free space, and e is the electronic charge. Another important set of

TABLE 2. JET PLASMA: SOME ILLUSTRATIVE CONDITIONS

		symbol
dimensions		
major radius	3 m	R
minor radius	1 m	a, b (vertical)
electron number density	$2 \times 10^{19}\ \mathrm{m^{-3}}$	n_e
electron temperature	2 keV	T_e
ion temperature	2 keV	T_i
magnetic fields		
poloidal field	0.6 T	B_θ, B_p
toroidal field	3 T	B_ϕ, B_T
derived plasma parameters		
inter-electron distance	3×10^{-7} m	$n_e^{-\frac{1}{3}}$
Debye length	7×10^{-5} m	h
90° collision mean free path	1×10^{4} m	λ
mean electron Larmor radius	5×10^{-5} m	ρ_{He}
mean proton Larmor radius	2×10^{-3} m	ρ_{Hi}
mean proton Larmor radius in the poloidal-field component	10^{-2} m	$\rho_{Hi\theta} = \sqrt{(2m_i/kT_i)}/eB_\theta$
mean electron thermal velocity	$2 \times 10^{7}\ \mathrm{m\ s^{-1}}$	
mean ion thermal velocity	$4.5 \times 10^{5}\ \mathrm{m\ s^{-1}}$	

quantities are the collision frequencies of the electron ν_{ee} with each other, ions with each other ν_{ii}, and of the electrons with the ions ν_{ie}. These collision frequencies all decrease as the temperature is raised, and the corresponding collision mean free paths increase as T^2/n. Consequently, the electrical resistivity of the plasma falls as the temperature is raised. In JET, the electrical conductivity of the plasma is roughly that of pure copper at room temperature.

In the presence of magnetic fields, the particles move in helical paths about the lines of force to a first approximation. The particles are displaced from their helical paths by collisions; they also drift across the lines of force when the field is non-uniform and when there are electric fields present. All these phenomenon are important to the confinement of high-temperature plasma in JET. In particular the field non-uniformity causes the particles to drift in closed surfaces whose radial orbit size is of the order of the Larmor radius in the poloidal field component alone, as discussed below. To give a sense of numbers, some characteristic values of these quantities in JET are summarized in table 2.

Tokamak toroidal discharges

JET is a toroidal electrical discharge taking place in a strong toroidal magnetic field. Toroidal discharges have been studied since the early patent of Thomson & Blackmann (1946), and the pioneering experiments of Ware and of Thonemann (Ware 1951; Thonemann & Cowhig 1951) as a means of creating the high temperatures and thermal insulation required by the conditions of figure 1. To achieve stability there is added a toroidal magnetic field; and the particular case of a sufficiently strong toroidal magnetic field is known by the Russian acronym, tokamak. The arrangement of magnetic fields and currents is sketched in figure 2. The notation used is shown in figure 3. The principal results available at the outset of the JET enterprise were reviewed by Artsimovich (1972). In particular, the principal stability requirement, discussed below, which determines the minimum strength of the stabilizing magnetic field B_ϕ, was established by experiment to be in agreement with theory. More up-to-date accounts are given by Rosenbluth & Rutherford (1981) and by Furth (1981).

Equilibrium

The high-temperature plasma is held in equilibrium by the interaction of current density $\boldsymbol{j}$ and magnetic field $\boldsymbol{B}$. In the simplest case of non-accelerated isotropic plasma, it is described by:

$$\boldsymbol{j} \times \boldsymbol{B} = \nabla p. \tag{7}$$

Here p is the plasma pressure. In a toroidal pinch, the primary confining force is provided by the pinch effect, i.e. the interaction of the current with its self-magnetic field. In the minor cross section, this equilibrium condition can be written

$$\beta_p I_\phi^2 = (8\pi/\mu_0)\, N_e k(\overline{T}_e + \overline{T}_i/\overline{Z}_i). \tag{8}$$

Here I_ϕ is the total discharge current, μ_0 is the permeability of free space, N_e is total number of electrons per unit length of the discharge, k is the Boltzmann constant, $\overline{T}_e$ and $\overline{T}_i$ are the mean electron and ion temperatures and $\overline{Z}_i$ is the mean ion charge number. Of course, in a pure hydrogen plasma, $\overline{Z}_i$ has the value 1; but because of the presence of highly ionized impurities, Z_i is generally somewhat greater in practice. The coefficient β_p in (8) describes that

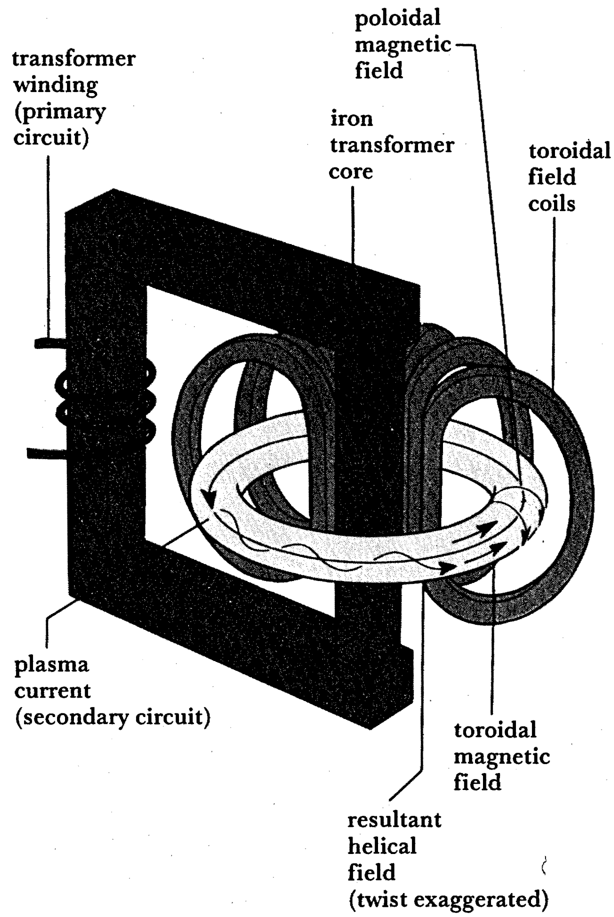

FIGURE 2. The tokamak configuration.

proportion of the available magnetic pressure exerted by the pinch effect, which is taken up by the plasma pressure. If there is no stabilizing field B_ϕ, β_p would have to be unity in a static equilibrium; but in the presence of B_ϕ it is possible for the entire pinch pressure to be absorbed by a compression of the B_ϕ, in which case β_p would be zero and the current-density vector would always be parallel to the lines of force; on the other hand, if the B_ϕ contributes to the magnetic pressure, then β_p can be greater than unity. In practice, values for β_p in the range 0–10 have been obtained, at least in transient conditions. As we shall see, in JET, β_p is in the range 0.1–0.2 so far. The expected value in ohmically heated discharge with the inward convection balancing outward diffusion is $\beta_p \approx 1$ (Hinton & Hazeltine 1976), as in the classical case of simple pinch discharge without a stabilizing field.

The natural tendency of the plasma ring to expand in major radius R is counteracted by an additional vertical magnetic field B_z. In the limit of large aspect ratio R/a

$$B_z = \frac{I}{R}\left[\ln(8R/a) + \beta_p + \tfrac{1}{2}(l_i - 3)\right]. \tag{9}$$

Here l_i is the internal inductance per unit length, and a is the minor radius of the current-carrying plasma ring.

The purpose of the distribution of poloidal windings is to provide this vertical field to maintain major radius equilibrium and stability. Generally B_z has to be shaped, as in betatron,

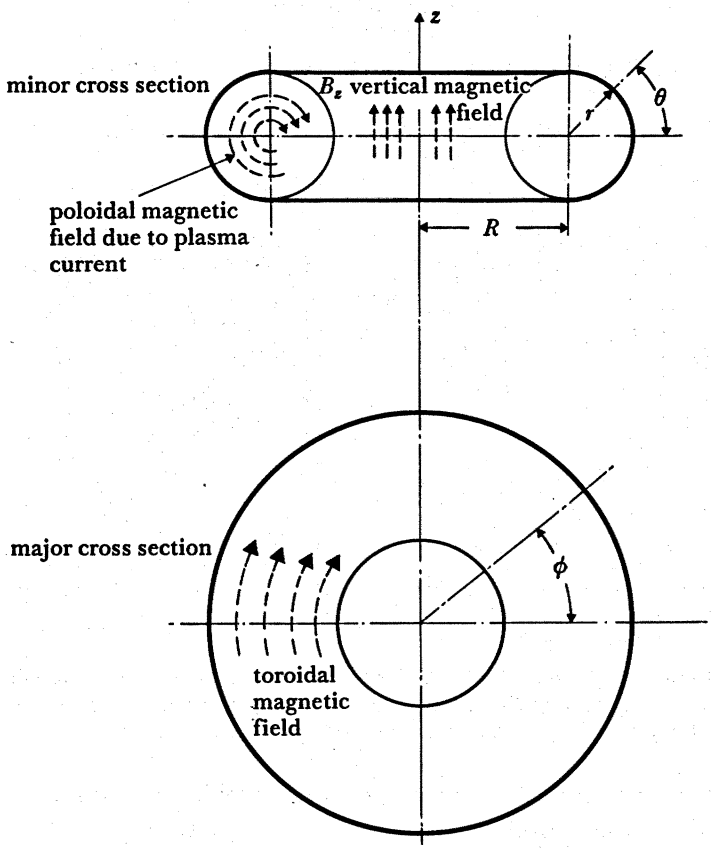

FIGURE 3. Notation of toroidal geometry.

to stabilize the current-carrying ring against gross vertical or horizontal motion. In practice, feedback amplifiers are used to maintain the gross equilibrium of the ring in the presence of small variations of pressure (β_p) and magnetic field errors; and, in the case of elongated plasma, instability.

A more accurate description of toroidal equilibrium is provided by the Grad–Shafranov equation (see Rosenbluth & Rutherford 1981), which is solved numerically. By using the appropriate boundary conditions the actual positions of the external current-carrying conductors in axisymmetric toroidal pinch systems can be provided for. Common to this equilibrium is the formation of axisymmetric nested toroidal magnetic surfaces of generally non-circular minor cross sections. An example of such surfaces is shown in figure 4.

Sufficiently far outwards, the lines of force encircle individual windings, and the magnetic surface breaks open to form a so-called X-point. The limits of the closed discharge region can in practice be determined by such an X-point; alternatively it can be determined mechanically by a so-called limiter, a solid piece of metal or graphite that limits the region of current flow in the gas (figure 4). In principle, the current channel can be surrounded either with a complete vacuum or with largely non-conducting gas in outer regions. If stability were to allow it, such an isolation might become very useful, and would correspond more closely to the original idea of a toroidal pinch included in the patent of Thomson & Blackmann. However, in practice, plasma extends out to the limiter or to the X-point, partly by outward diffusion of the plasma, and partly by the ionization of gas fed in from the outside, or dislodged from the walls.

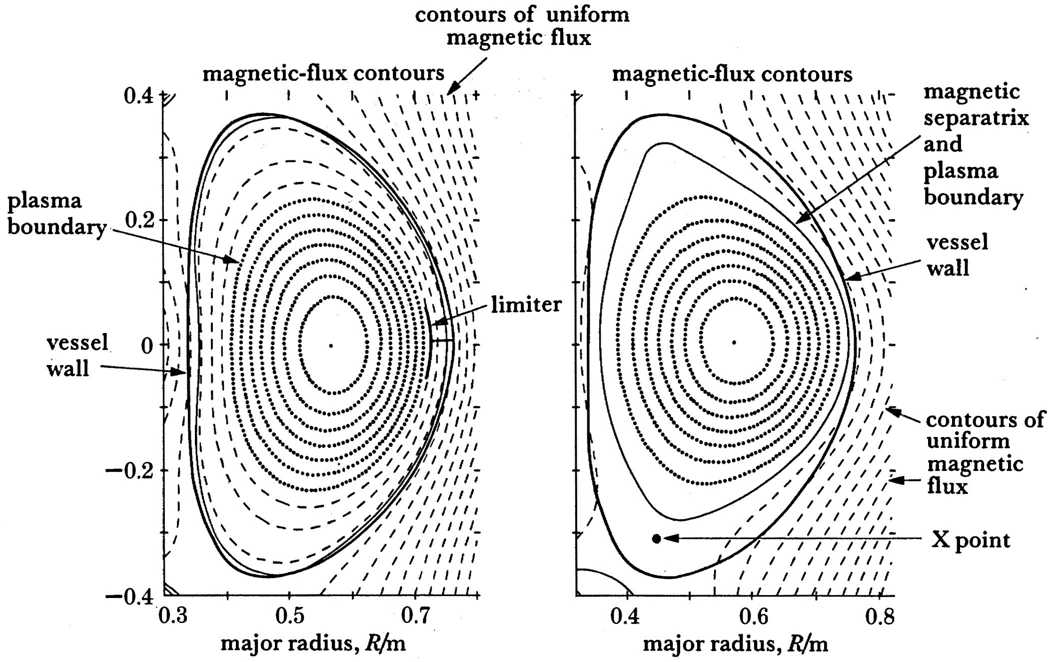

FIGURE 4. Minor cross section of a D-shaped tokamak, showing the calculated intersection of magnetic surfaces with the R, θ plane (surface of constant flux). Also shown are X-points where the surfaces cease to close (RHS) and the (graphite) limiter used to define the edge of the current channel (LHS).

Finally, all these equilibrium calculations presume toroidal axisymmetry. If this symmetry is lost, the description of the equilibrium becomes entirely a matter for numerical solutions of (7). Direct experiments (Stodiek *et al.* 1971) suggest that the small departures from axisymmetry necessarily present in any practical device will not dominate the general performance of a tokamak.

Fluid Stability

The stability of these equilibria is investigated by the use of the energy principle, which in toroidal geometry requires numerical methods as discussed by Troyon (this symposium). However, some simple guiding principles are very useful in an overview. These are based on a large aspect ratio (or quasi-cylindrical) viewpoint.

It is usual to describe instabilities of the plasma ring in the large aspect rate $R/r \rightarrow \infty$ approximation. The supposed perturbation of the plasma ξ is resolved into cylindrical modes:

$$\xi = \xi_{mn}(r) \exp -2\pi i(m\theta + n\phi). \tag{10}$$

Here m and n are integers, θ, ϕ, and r are the coordinates shown in figure 3, and ξ_{mn} is the amplitude of each mode.

The most dangerous modes are those whose pitch lengths coincide with that of the lines of force at some point inside the plasma. The strength of the stabilizing field B_ϕ is characterized by the pitch length of the helical lines of force, normalized to the major circumference of the torus. This quantity

$$q \equiv B_\phi r / B_\theta R$$

is known as the safety factor. As B_ϕ increases, q increases; and the modes $n = 1$ which can occur are limited to those with mode number m

$$m > q.$$

The condition $q = 1$ is known as the Kruskal–Shafranov limit. Condition $q > 1$ is the basic definition of the strong magnetic field needed in a tokamak. It ensures that a simple $m = 1$ corkscrew deformation of the current-carrying ring is suppressed. It does not in itself provide complete stability, because instability of modes with high values of m and n are possible; and indeed occur. The safety factor q is generally a function of the minor radius, being about unity on axis, and increasing to a few at the outside (figure 5).

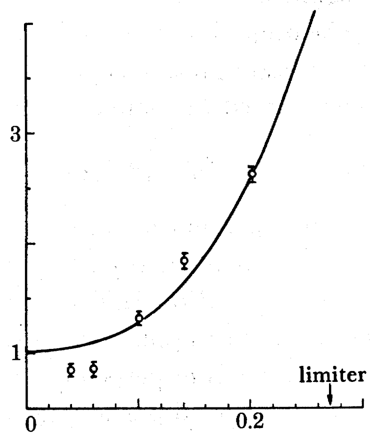

FIGURE 5. The safety factor $q(r)$ in the DITE tokamak measured as a function of the minor radius by light scattering (ϕ) and inferred from the temperature profile assuming Spitzer (1962) resistivity, constant impurity content and no skin-effect (Forrest *et al.* 1977). If the Taylor (1976) relaxed states occurred then $q(r)$ would in this case be equal to about four for all values of r.

The condition $q > 1$ turns out to have two other important properties, not foreseen at the outset. First, as regards pressure driven instabilities, it ensures that the tokamak magnetic configuration is a mean magnetic well; that is, the magnetic field strength averaged over the magnetic surface increases as one moves away from the plasma centre. This is known experimentally to be a strong stabilizing effect.

Secondly, if $q > 1$ then a stable connection can be made to the vacuum field configuration near the limiter in the outer region of the discharge where no currents can flow (Robinson 1969). These considerations of linear theory are reinforced by the general theorem of Taylor (1976), which shows that the minimum magnetic energy of a discharge in a closed torus is obtained when the configuration follows the force-free prescription

$$\boldsymbol{j} = \mu \boldsymbol{B}, \tag{11}$$

where μ is a constant in space determined by the total current and the stabilizing flux. This result provides confidence that a stable discharge can be reached. The required practical departures, namely that $\boldsymbol{j}$ has to fall to zero at the walls and that there are some plasma pressure gradients, can be treated as a departure from the stable force-free configuration. In practice, a tokamak configuration allows quite substantial departure without losing gross fluid stability (figure 5).

Disruptions

Experimentally, discharges in a tokamak are usually obtained quite easily, with currents being started up by potential differences of some tens of volts a turn, and settling down into a steady state sustained by EMFs of 0.5–2 V per turn, and showing a low level (not more than about 10^{-3}) magnetic fluctuations. The self-stabilization mechanism accounted for by Taylor's theory seems to occur relatively easily provided that the equilibrium is properly provided for, and the discharge is not quenched by excessive impurities. There is, however, one important exception, namely at sufficiently high electron number densities, a relatively violent instability can develop that quenches the current flow in a very short time (*ca.* 10 ms). These quenches are known as *disruptions*; in all tokamaks they restrict the range of parameters at which the discharges will operate, to levels significantly below those at which we would like to operate to satisfy the criterion of figure 1. The origin is thought to be excessive radiation losses (Gibson 1976; Ashby & Hughes 1981). Such losses must also occur because of bremsstrahlung alone (i.e. excluding line radiation), which exceed the ohmic heating when

$$\beta_p I \gtrsim 1.6\ [Z_i/(Z_i+1)]\ \mathrm{MA}, \tag{12}$$

Z_i is the mean charge on the ions. If the current exceeds that given by (12), then the discharge undergoes radiation collapse unless additional energy is supplied.

So far this criterion has not been exceeded on JET with ohmic heating. The result (12), though first deduced for a simple pinch, also applies in a tokamak because the conductivity of the plasma is closely similar, the change from perpendicular to parallel conductivity being almost exactly counter-balanced by the trapped particle correction (Pease 1957).

The question of the origin of disruptions and their relation to the equilibrium configuration is a key issue in the experimental work on JET; both for the electromechanical engineer and for the physicist trying to get high values of the product $n_e \tau_E$.

Thermal Insulation

The magnetic fields provide thermal insulation normal to the line of force by restricting the motion of the plasma particles to their Larmor radii. For plane slab geometry with uniform magnetic fields the transport coefficients have been worked out by Chapman & Cowling (1953) and in more detail by Braginskii (1965). The central result is that thermal diffusivities are reduced from their values in the absence of magnetic field by a factor of $[1+(\lambda/\rho_H)^2]$ where λ is the collision mean-free path and ρ_H is the Larmor radius, the quantities given in table 2. With plasma parameters of JET the value of $(\lambda/\rho_H)^2$ is about 10^{14} for the ions.

The thermal diffusivity χ across the field has the order of magnitude

$$\chi \approx \rho_H^2 \nu_{ii}, \tag{13}$$

where ν_{ii} is the ion–ion collision frequency. The ion thermal conductivity is the larger than that of the electrons by the ratio $Z_i\sqrt{(m_i/m_e)}$. Here m_i and m_e are the ion and electron masses, respectively.

In a tokamak configuration the fields are non-uniform; and the consequent drift of the particles has to be taken into account. The so-called neo-classical theory (Hinton & Hazeltine 1976) shows that, in the important case where the collision mean free path is very long compared to the major radius of the torus, the Larmor radius has to be taken in the field component B_θ due to the current flow alone. The large toroidal field B_ϕ introduces a modest correction of the order of the (aspect ratio)$^{\frac{1}{2}}$, but otherwise does not affect the thermal diffusivity which is given by the poloidal field alone; consequently, the neo-classical thermal diffusivity is given by

$$\chi_{nC} \approx \rho_{Hi\theta}^2 \nu_{ii} (r/R)^{\frac{1}{2}}. \tag{14}$$

If we apply this expression for the thermal diffusivity to calculate the energy confinement times in a tokamak then for a uniform density of plasma we find

$$n_e \tau_E \sim I^2 (T_i/m_i)^{\frac{1}{2}} (R/a)^{\frac{1}{2}}/Z_i. \qquad (15)$$

If we relate the desired thermal insulation of figure 1 for an ignited plasma, then for $n_e \tau_E \sim 2 \times 10^{20}$, $T_i \sim 10$ keV with $Z_i = 1$, requires the discharge current I to exceed about 1 MA. The value depends sensitively on the distribution of plasma number density. Full numerical calculation by Hughes (personal communication 1984) for JET gives a current of about 1.7 MA. This condition is equivalent to requiring of the order of ten ion poloidal Larmor radii in the plasma minor radius, so that of the order of a hundred 90° collisions between ion pairs are needed for the heat to be conducted to the walls. The effect of impurities is roughly indicated by the factor $1/Z_i$, i.e. impurities reduce the energy-confinement times.

A further physical factor determining the total current is the need to contain the 3.5 MeV α-particles from the D(T, n) α-reaction. The Larmor radius of the α-particle in the poloidal field must be less than the plasma radius for most α-particles to be magnetically confined. An elementary evaluation shows that $I \approx 3$ MA. This current was chosen as the central design feature of JET, as elaborated by Rebut (this symposium).

With a hoped-for electron number density of about 10^{20} m^3, then the energy confinement time has to be a few seconds if the α-particle heating is to exceed the losses.

Experimental thermal insulation

It is known from both the early Russian and from other experiments in tokamaks of comparable size, that experimental measurements of the confinement time do not agree with the ideal expectations of (15), not only are the losses greater, but the confinement time varies with density in the opposite way to that expected from (15). Only at the highest densities do the experimental confinement times approach the ideal (Hugill 1983).

A central point of interest in the JET experiment is whether or not the same situation is encountered in near-reactor conditions. Moreover, it is highly desirable to understand the basic physics underlying any observed departure from (15). For this reason extensive diagnostics have been built into the JET apparatus, and are described in the paper by Dr Stott. The overall results of the behaviour of the JET plasma with ohmic heating alone are described by Dr Gibson. The reduction of the extensive data and the comparison with theory of the discharges, including additional heating (see below) are discussed in the papers given by Dr Düchs and Dr Bickerton.

Additional heating

An immediate consequence of the likelihood of the thermal insulation falling below that indicated in (15) is the need to supplement the ohmic heating of the plasma in order to reach the high temperature; this requires additional heating. This essential additional heating, which is a major engineering feature of JET, and its effects is the subject of the papers given by Dr Jacquinot and Dr Duesing. Another important aspect of additional heating is that it provides a means of varying the temperature of the electrons and of the ions, while keeping other quantities, such as the current, constant.

Impurities

Loss of energy because of excessive radiation is a serious threat to achieving the required conditions (figure 1). Impurity ions in the plasma cause much stronger radiation than hydrogen

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not only because of their greater charge, but because, when the ionic charge number Z_i exceeds about twenty, the predominant ion species are not fully ionized and emit line radiation much more strongly than they emit bremsstrahlung. Generally, this radiation is expected to be a more serious consequence of impurities than the increased collision rates implied in (15). Thus the level and behaviour of impurity species in the plasma, and the mechanism of their production at the walls is of special interest to JET. Work on it is reported in the paper given by Dr Engelhardt.

Objectives of JET

I complete this introductory paper by summarizing the objective of JET as adopted by the partners in this project at the outset (EUR 5516e).

> *The objectives of research with JET*
>
> The essential objective of JET is to obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclear reactor. These studies will be aimed at defining the parameters, the size and the working conditions of a tokamak reactor. The realization of this objective involves four main areas of work:
>
> (i) the *scaling of plasma behaviour* as parameters approach the reactor range;
> (ii) the *plasma–wall interaction* in these conditions;
> (iii) the study of *plasma heating* and
> (iv) the study of α-*particle production*, *confinement* and consequent plasma *heating*.
>
> The problems of plasma–wall interaction and of heating the plasma must in any case be solved in order to approach the conditions of interest.
>
> An important part of the experimental programme will be to use JET to extend to a reactor-like plasma, results obtained and innovations made in smaller apparatus as a part of the general Tokamak programme. These would include: various additional heating methods, first wall materials, the control of the plasma profiles, and plasma formation.

In conclusion, my fellow organizers and I hope that from the programme of papers in this symposium, it will be possible for you to get an impression of the results of the large international technical effort needed to construct, operate and research JET and to assess the progress towards the above objectives laid down at the outset. The research programme on JET is by no means completed, and there are a number of physical enhancements still to be installed on the machine. An excellent start has been on the first three objectives. However, it will probably be a number of years before the conditions achieved in JET, and our understanding of them, will justify the introduction of tritium into the machine with consequent penalty of neutron activation. JET has of course been designed for experiments where α-particle heating is of power comparable to that of the additional heating. However, the experiments for objective (iv) will require extensive remote handling, and will be more cumbersome. The experimental programme is expected to run at least until the end of 1992. This symposium is thus a progress report. However, my fellow organizers and I hope that the results so far achieved will be of interest to and will promote interaction with a wider scientific community, from which we hope the research can gain in strength and effectiveness.

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