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Design Proposal for the Joint European Torus

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The JET Project
(Design Proposal)

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to the Supervisory Board for transmission to the Partners for their recommendation according to articles 9 - 1D, 9 - 2, 10 - 4 of the JET DESIGN AGREEMENT No. 30-74-1FUA C.

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ABSTRACT

This proposal describes a large Tokamak experiment, which aims to study plasma behaviour in conditions and dimensions approaching those required in a fusion reactor. The maximum plasma minor radius (a) is 1.25 m and the major radius (R_o) is 2.96 m. An important feature is the flexibility to study, for plasma currents in the 1 → 3 MA range, a wide range of aspect ratios (R_o/a = 2.37 → 5), toroidal magnetic fields (up to 3.6 T), minor radii (0.6 → 1.25 m) and elongation ratios (b/a = 1 → 3.5).

The cost of the apparatus, power supplies, plasma heating equipment and specific diagnostics is estimated as 70.1 Muc (March 1975 prices, 1 uc = 50 FB). The total construction phase cost including commissioning, buildings and staff is 135 Muc. These figures include an average overall contingency of 30%. The construction time for the project is estimated at 5 years and requires 370 professional man years of effort in the construction organisation with additional effort deployed by the Associated Laboratories in such areas as diagnostics and plasma heating.

This design proposal is arranged as follows:
The Preface gives an introduction to the field of fusion research and relates JET to the European and international programmes. Chapter I is a concise summary of the design proposal, it describes the objectives of research with JET, and gives a brief description of: the apparatus; the cost and construction schedules; the proposed experimental programme and the possible modes of operation of the device. A detailed account of the project is given in the rest of the report of which Chapters IV and VII comprise the engineering design and the staff and cost estimates respectively.

PREAMBLE

The various national laboratories* studying controlled nuclear fusion within the European Community, all now operate under Contracts of Association with Euratom and carry out a co-ordinated programme of research in this field. They have recently initiated, as a joint effort, the study of a major new plasma physics experiment. Subject to appropriate financial approval, it is hoped that the experiment will be built within the Community during the next few years. The experiment is known as the JOINT EUROPEAN TORUS (JET).

The first discussion of a large European Tokamak Project took place in the Tokamak Advisory Group during the early months of 1971 and in October of that year the Groupe de Liaison set up the "Joint European Torus Working Group"* chaired by Henri Luc and after his untimely death (March 24, 1972) by Lorenzo Enriques. The group was to prepare various design concepts and compare them from the point of view of technology, finance and construction time. In March of 1973, the Group recommended that a project team be established to design and construct a 3 MA Tokamak. The Groupe de Liaison at its meeting in March 1973 recommended the setting up of a design team and following subsequent discussions by the Committee of Directors, the JET Design Team began work in accomodation at the Culham Laboratory in September 1973.

The Design Team issued an outline design and first set of dimensions in the "Preliminary Description" (EUR-JET-R1) November 1973 and the "First Project Proposal" (EUR-JET-R2) in April 1974. The first cost estimate for the project (EUR-JET-R4) was issued in July 1974.

On the basis of the advice of the JET Supervisory Board, the Groupe de Liaison at its meeting in September 1974 accepted the parameters (EUR-JET-R2) and cost estimates (EUR-JET-R4) as

* see Appendix E

a basis for continuing design. An agreement to release funds for the purchase of certain long delivery items was reached in April 1975.

The Design Team has prepared this document as the report requested in the JET DESIGN AGREEMENT (Article 9-1D). It includes the work carried out by the JET Design Team since September 1973 and the contributions of the Commission and the Associated Laboratories, working directly on contracts or participating in the six Workshops which have been held on JET and which are summarised in EUR-JET-R6, May 1975.

A. Introduction

In the search for new sources of energy, fusion offers great possibilities for the future with virtually inexhaustible reserves and a negligible basic fuel cost. On the other hand, the conditions for thermonuclear reactions are difficult and complex to implement because of the temperature of approximately 100 million degrees (~ 10 keV) necessary to initiate nuclear combustion. Two main approaches to controlled fusion are under study at present: magnetic confinement and inertial confinement. Research based on magnetic confinement where magnetic fields are used to contain the electrically conducting plasma was initiated in the fifties, and is at present at a more advanced stage than that based on inertial confinement where very short pulses of energy e.g. from lasers, are used to implode a small speck of matter producing high densities and temperatures before the speck flies apart. Among the wide variety of magnetic configurations studied to date, Tokamak-type devices have obtained the best experimental results and offer the best chances of obtaining a thermonuclear plasma within the next decade. The experiment known as the Joint European Torus (JET) involves building and studying a large Tokamak-type device and should yield decisive results on the practical feasibility and definition of a Tokamak reactor.

The decision to build a device of this type will enable Europe to continue to have an impact on fusion research over the period 1980-85. It is already the case that a device of the size of JET can only be built and operated by concentrating effort and coordinating research programmes within the European Community. The large, minimum size of a fusion reactor, and the complexity of its construction will mean that future research and development will have to be carried out with an increasingly coordinated overall programme, since only in this way will European research and industrial opportunities compare with those in the United States or the Soviet Union.

An illustration of the proposed JET apparatus appears as a frontispiece to this report. This device with a plasma current of more than three mega-amperes (MA) corresponds to an intermediate step between present experiments and a test reactor. The principal dimensions are:

Major diameter of torus	6 metres
horizontal plasma diameter	2.5 metres
vertical plasma elongation	4 metres (for D-shaped plasma)

The overall dimensions are a diameter of 15 metres and height of 11.5 metres.

The purpose of this Preface is to introduce the scientific background to the JET project. Section B gives a brief account of the plasma confinement and heating problems to be solved before a fusion reactor can be designed, while section C gives an account of the basic properties of the Tokamak configuration. Section D is a résumé of the present position of Tokamak research, and sections E and F indicate the relationship of JET to the international Tokamak research programme.

B. <u>Thermonuclear Fusion</u>

The complexity of achieving thermonuclear fusion comes from the need to reach high temperatures (5-10 keV) and from the need to contain the hot plasma for sufficiently long while fusion energy greater than that expended in producing the plasma is released. This temperature of ~10 keV is linked with the particular fusion reaction at present envisaged for a thermonuclear reactor i.e. the D-T reaction:

$$ {}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He \; (3.4 \text{ MeV}) + {}^{1}_{0}n \; (14.2 \text{ MeV}) \qquad (P-1)$$

This reaction is supplemented by reactions in a surrounding lithium blanket. The 14.2 MeV neutrons, which carry off 80% of the reaction energy (the 3.4 MeV α particles (${}^{4}_{2}He$) contribute to plasma heating) are absorbed by the blanket. Here neutron-lithium reactions produce tritium to replace the burnt tritium. Lithium, deuterium and tritium are thus the basic fuel. The reaction (P-1) has a significant cross-section at plasma temperatures above ~5 keV.

The essential difference between fission and fusion reactions is that fusion reactions take place between two positively charged nuclei which repel each other until attracting nuclear forces intervene, while such electrostatic repulsion does not exist in a fission reaction where one of the components is a neutron. As a result of the necessity to overcome this repulsion for fusion, each nucleus must have a kinetic energy which corresponds to the very large temperature of ~5-10 keV. The basic problem of thermonuclear fusion is to find a system which can contain the plasma in its thermonuclear state without external material entering the confinement region and quenching the thermonuclear reactions.

If this combustion temperature is to be maintained, the energy produced by the fusion reactions in the plasma must compensate the losses due to radiation, and thermal conduction to the surface etc. These losses impose minimum size requirements on the reactor (surface/volume ratio). Maintenance of the thermonuclear reaction is expressed by Lawson's criterion:

$$\bar{n}\tau_E \geq 3 \times 10^{14} cm^{-3}.s \qquad (P-2)$$

where $\bar{n}$ is the average ion number density (particles/cm^3) and τ_E is the confinement time of the plasma energy (seconds).

Of the two main fusion approaches presently under study, one involves using a very high density n and very short confinement time τ_E ($< 10^{-9}$ s), with the confinement being due to the inertia of the material. This therefore leads to the concept of a reactor based on a succession of micro-explosions of the type produced in the H-bomb. The reaction would be ignited using powerful lasers or electron beams.

The second method attempts to work with moderate pressure ($nT \sim$ 1-10 atmospheres) plasmas which, taking account of the temperature T, corresponds to confined densities of between 10^{14} and $10^{15} cm^{-3}$. An energy confinement time of several seconds is therefore necessary. To ensure this there is a magnetic field configuration which isolates the hot centre of the plasma where the thermonuclear reactions take place, from the material walls of the reactor.

Whatever the method chosen, the parameters to be achieved in a thermonuclear D-T plasma are: a temperature of 10 keV (~ 10^8 °K), and a $\bar{n}\tau_E$ product of $3 \times 10^{14} cm^{-3}$ s. Magnetic confinement systems have been under more sustained investigation than inertial confinement systems and at present seem to offer the most direct approach to reactor conditions. The Tokamak magnetic confinement system has been the most successful in improving plasma conditions towards the thermonuclear regime.

C. The Tokamak

The magnetic configuration of the Tokamak is one of the simplest which could be envisaged: an electric current is made to circulate inside the hot plasma and this produces forces which mainly balance the kinetic pressure of the plasma. A toroidal magnetic field parallel to the current is necessary for plasma stability. From a microscopic viewpoint the trajectories of charged particles which make up the plasma are (to a first approximation) helices centred on field lines. In a Tokamak the field lines lie on magnetic surfaces which are a set of nested toroids. These form an axisymmetric system which has advantages of simplicity and exact confinement invariants permitting a better confinement of the particles and more complete calculation than non-axisymmetric systems.

Properties of axisymmetric toroidal configurations

The electric and magnetic fields in this type of configuration are rotationally symmetrical, i.e. independent of angle about the Z axis, see Fig. P-1.

If the total magnetic field $\underline{B}$ is split into a toroidal field component B_{TOR} and a poloidal field component B_{POL} located in a meridian plane, the magnetic surfaces are generated by the rotation of the field lines of the poloidal field about the Z axis (Fig. P-1). (The magnetic field is always at a tangent to this family of surfaces) These magnetic surfaces are labelled by ψ, the magnetic flux between density is too low or if the pressure of the neutral gas emitted by the walls of the plasma containment vessel is too high. The loss process becomes less and less important as the size of the device is increased.

D. Present State of Tokamak Research

An attempt will be made in this section to give an overall picture of the present state of research on Tokamaks. The main devices at present in operation are: T-4 in the Soviet Union, ATC, Alcator and Ormak in the United States, and TFR and Pulsator in Europe.

The following performance data have been achieved by the French Tokamak TFR (see Fig. P-3) with a deuterium plasma.

ion temperature	- 1 keV
electron temperature	- 3 keV
product $\hat{n}\tau_E$	- 2×10^{12} $cm^{-3}.s$

Already fusion reactions in a pure deuterium plasma have been produced under these conditions. Table P-1 gives the principal parameters of several devices currently in operation.

Interpretation of the experimental results

(1) Equilibrium and magnetohydrodynamic stability

A discharge seems to attain gross equilibrium fairly easily in Tokamak configurations, at least in cases of circular cross-section plasmas. A "vertical" magnetic field is necessary to achieve equilibrium of the plasma ring. This field is produced either by image currents in a conducting shell surrounding the plasma or by "vertical" fields generated by the external windings. In the latter case, the strength of the magnetic field must be adjusted to the current flowing through the plasma and to the plasma parameters. It is therefore necessary to programme the strength of the external vertical field or to have a feed-back control system. Recent experiments on Tokamaks unanimously indicate that the radial position of the plasma can be controlled without posing any particular problems. The "vertical" stability of the plasma ring can be similarly ensured by a feed-back system.

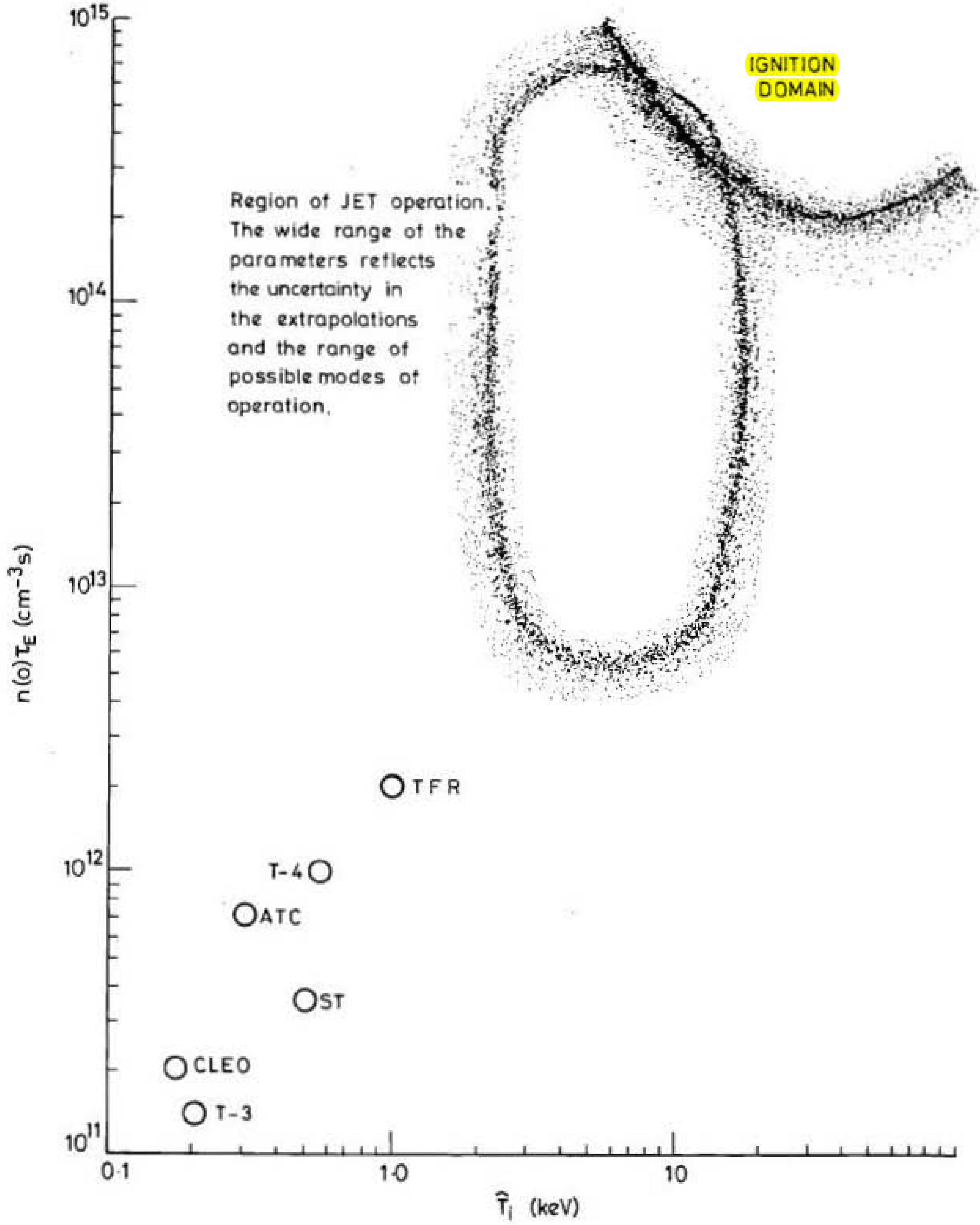

Fig. P-4 Possible Performance Data for JET

The density and power density at which a reactor will operate, is also dependent on the extrapolation of existing results.

The necessary conditions comprise a product $\bar{n}\tau_E \sim 3 \times 10^{14} cm^{-3}.s$ and a plasma temperature of approximately 10 keV. These figures are to be compared with the code predictions for JET which give a $\bar{n}\tau_E$ product in the range 10^{13}- 5×10^{14} $cm^{-3}.s$ and a temperature in the range 3 -∿10 keV (see Fig.P-4). Ignition of the reactor will require similar additional heating units to those envisaged for JET.

The fundamental aim of JET is to produce a large plasma which will represent a significant stage in research towards a reactor, with a view to testing the confinement principles of a Tokamak. The JET experiment will be used to define the minimum size required for a reactor, or more precisely to answer the question of the losses which govern the plasma energy balance, and the problem of the nature of the wall. JET will also test the methods of additional heating needed to reach ignition. These studies will be carried out mainly in hydrogen. Initial examination of the properties of plasma sustained in part by α particles from fusion reactions is expected to begin in the final operating phase of JET. Technical problems, for example maintenance operations by remote handling associated with active operation will also be encountered in this phase. These studies will give valuable experience for the device which follows JET and which is expected to operate for most of its life as a DT burner to study the first wall, the blanket and the associated neutronics problems.

In practice JET must not be considered as an isolated experiment, but as forming part of a more comprehensive research programme, and requiring complementary programmes consisting of several medium-sized Tokamaks with plasma densities and temperatures not too far from those of JET, and specially designed to study specific questions such as diagnostic techniques, methods of heating, choice of the first wall and control of the current density profiles.

I.1 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 realisation 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.

The main areas of work listed above are discussed more fully below.

I.1.1 Extension and scaling of plasma parameters

The first task is to measure the plasma parameters, density, temperature and confinement time, in a domain as close to ignition as possible. The observed scaling and behaviour of the plasma should indicate the size of a Tokamak reactor. The plasma current of 3 MA has been chosen (see I.2) to be within a factor 3 to 6 of that envisaged in a reactor. The flexibility of the experiment is essential for these studies. In addition to the usual parameter variations (current, density, etc.,) the proposed design will permit variation of: the plasma cross-section from circular to D-shaped, the aspect ratio, the discharge duration, and the plasma build-up phase (using compression or moving limiter techniques.)

The following studies are envisaged:

1. The study of transport processes over a wide range of parameters including the "collisionless regime" appropriate to a reactor. The study should establish the relative importance of binary-collision and fluctuation-driven transport. It should provide the information necessary to make reliable estimates of the density-energy confinement time product ($n\tau_E$) to be expected for reactor parameters, and establish the limits of the Ohmic heating.

2. The control of the plasma cross-section shape and of the various profiles of temperature, density and current. The diffusion and the stability of the plasma are very dependent on the profiles (for example the peaking of the current in the central region). Control of the power deposition profile (e.g. by additional heating)may allow control of the current density profile and hence of the stability of the discharge. The relation between the density and the temperature profiles may determine the rate of penetration into the plasma, of the impurities. Furthermore parameters at the edge of the plasma are of particular importance to the plasma-wall interaction. Feedback-controlled injection of various gases is a possible method of controlling these profiles and parameters.

3. Experiments to determine β_{crit}, the maximum possible ratio of plasma to magnetic field pressure, and q_{min}, the minimum "safety factor" value. These parameters define the minimum toroidal field for macroscopic stability and thus are crucial in determining the economics of a future reactor. They may be defined as follows (with the usual notation and appropriate units):

$\beta_{POL} = (8\pi/\mu_o)\cdot N_{total}\cdot \bar{T}/I_p^2$ — Plasma pressure/pressure of the poloidal magnetic field

$\beta_{TOR} = \beta_{POL}\cdot\left(\frac{a}{R_o}\right)^2\cdot\frac{1}{q^2}$ — (for a circular cross-section at large R/a)

where $N_{total} = \pi a^2\cdot(\bar{n}_e+\bar{n}_i)$ — is the total line density (ions + electrons/unit length)

β_{TOR}, here and elsewhere in this report, is an average value rather than the local maximum value sometimes quoted.

β_{POL} is expected to be limited by equilibrium and stability considerations to $\beta_{POL} < (1 \rightarrow R_o/a)$. Experiments on the limiting value of β_{POL} will require additional heating to raise β_{POL} above the Ohmic limit (typically ~ 0.1 for JET).

The D-shaped cross-section of the plasma permits a gain in the maximum value of β_{TOR}. Stable, peaked current, D-shaped equilibria have been predicted for JET (see II.1.2) for which β_{TOR} ~ 3%. Control of the plasma current density profile may lead to an increase of this value.

4. Extension of $n\tau_E$ and T as far as possible towards the reactor regime. In a favourable case, experiments in hydrogen may indicate that the Lawson criterion can be reached.

5. Investigation of long-time Tokamak equilibrium, stability, and impurity behaviour.

6. Search for, and study of the important diffusion and injection-driven currents.

I.1.2 Plasma-wall interaction; impurities

This question is a very serious one and the interaction may strongly limit the performance of JET. It is of primordial interest for a reactor to know the behaviour of the impurities inside the plasma and the interaction between the plasma surface and the wall under plasma conditions similar to those needed for a reactor. It is to be expected that the wall bombardment associated with charge exchange and subsequent impurity behaviour will be qualitatively different in JET than in smaller Tokamaks.

This is because the penetration distance of neutrals from the wall will be a small fraction of the plasma radius (~ 10%) in JET whereas in present Tokamaks neutrals are readily able to penetrate the whole cross-section.

The following studies are envisaged :

1. Study of the choice of material for the limiter and the first wall: investigation of low Z materials.

2. Study of the role of plasma-limiter interaction, possibly using limiter detachment experiments (e.g. compression or expanding limiter).

3. Investigation of the possibilities for control of the external layer of plasma (T_e, n_e) by gas injection and control of the energy deposition.

4. Examination of the effect of a divertor, probably in a later phase of the experiment.

I.1.3 Additional heating

In order to reach temperatures of several keV it is necessary to heat the plasma by some method other than Ohmic dissipation. Several additional heating methods will be developed and tested on JET. Their efficiency in heating a plasma into the reactor domain should be studied. The following heating methods are envisaged:

(i) fast adiabatic compression by changing the major radius of the plasma.

(ii) the injection of fast neutrals (60 - 150 keV) into the plasma.

(iii) the high-frequency heating at the low hybrid resonance.

(iv) the radio-frequency heating at harmonics of the ion cyclotron frequency.

I.1.4 α particle effects

α particle production, confinement and heating must be studied, as they will play an essential role in the power balance of a reacto[r]

The α particles may be produced by direct reactions from an energetic beam of deuterium injected into a tritium plasma, and in this case it is likely that the break-even condition will be reached.

The break-even condition is obtained when the energy injected by the beam is equal to the energy released by the induced fusion reactions. In the event that the confinement of energy is long enough, thermonuclear reactions between the particles of the plasma itself may produce enough α particles to play a significant role in the energy balance. In this case, powerful additional heating will be necessary to heat the plasma up to the required temperature (~ 10 keV). These above experiments will involve working with tritium and will produce a large neutron flux.

Initial work using a D-D plasma will already lead to substantial neutron production (say up to a few x 10^{17} neutrons/pulse) leading to appreciable activation of the inside of the torus after a few thousand shots. This activation level would not seriously limit access to the outside of the torus. Beam-plasma D-T operation near the "break-even" condition would lead to about 10^{19} neutrons/pulse, while achievement of true ignition could lead to up to 10^{20} neutrons/pulse (this figure has been used as an upper limit for safety assessments.)

These levels would make maintenance operations very difficult and time consuming after a few thousand or a few hundred discharges respectively. In view of the extensive operational experience that will have been accumulated during H_2 operation it is anticipated that at least a few thousand D-T discharges will be possible without extensive modification or repair.