JOINT EUROPEAN TORUS

JET

JET JOINT UNDERTAKING

ANNUAL REPORT 1998

EUR 19252-EN-C
EUR-JET-AR21

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Preface

The major technical achievement in 1998 was the highly successful exchange, by remote handling without manned intervention in the JET vessel, of the Mark IIA divertor target structure for the Gas Box divertor (Mark IIGB). The Mark IIGB is the last in a series of three progressively more "closed" JET divertor configurations and the experimental results from all of these will contribute to the validation of the ITER divertor design. The exchange of the two divertor structures was carried out during a 4 month shutdown which commenced in early February and which was completed on schedule. It provided a clear demonstration of remote handling as a method of maintenance, repair and upgrading of fusion devices. During all this work particular emphasis was placed on safety. Of the 20g of tritium inventory at the start of deuterium-tritium operations in 1997, 16g were removed from the vacuum vessel and accounted for in detail, about one gramme was removed with the Mark IIA divertor target tiles and a further half gramme with dust/flakes, leaving about 2.5g in the vacuum vessel at the end of the shutdown. As expected, the quality of the vacuum obtained was better than after previous shutdowns because personnel had not entered the vessel. The first plasma pulse was obtained in early July, and the machine conditions allowed a plasma discharge with a 20 second flat top to be obtained by the fourth plasma pulse. This had never been achieved so quickly after a major shutdown. The plant upgrades necessary for operation at toroidal fields of up to 4 Tesla were completed during 1998 and three 4 Tesla pulses with plasma were run successfully towards the end of the year.

JET was operated in two phases in 1998, a short one before the Remote Handling shutdown and a longer one after. The aim of the ITER Physics Phase experiments during January 1998 was to reduce the uncertainties in extrapolations to ITER by obtaining improved data on confinement, H-mode threshold power, divertor behaviour and stability in ITER-like plasmas in hydrogen and deuterium. Of particular note were the experiments carried out in collaboration with ASDEX Upgrade, DIII-D and ALCATOR C-MOD in which directly comparable plasmas were set up to allow better extrapolation to ITER.

Following the Remote Handling shutdown, JET operation with the new divertor structure had the aim of further qualifying the ELMy H-mode for ITER, and of producing high performance plasmas in the optimised shear mode. The new divertor geometry produces many of the expected results, such as improved deuterium exhaust, more symmetric detachment and a somewhat higher density limit. In addition, access to the H-mode is found to be dependent on divertor geometry. The fuelling efficiency with pellets injected from a centrifuge injector at 250ms^{-1} into ELMy H-modes is higher than with gas puffing, but the trade-off between density and confinement is not substantially changed. The removal of helium from the plasma, necessary in a power plant, has been demonstrated with the ratio of the helium replacement time to the energy confinement time as low as 4 in ELMy H-modes, which easily meets the requirements of a reactor.

High fusion performance in the optimised shear mode of operation results from the formation of an Internal Transport Barrier in which the confinement in the core plasma is much improved. With the Mark IIGB divertor, transiently high performance has been more difficult to achieve largely due to the earlier onset of an H-mode. On the other hand, steady state operation has been easier to establish. Profile control techniques have been used in this advanced mode of tokamak operation to engineer high fusion performance and to develop these conditions into steady state. In particular, current profile control using lower hybrid current drive and plasma density profile control using pellet injection have been used. In addition to the control of current and density profiles, the duration of the high performance phase has been extended by preventing excessive edge pressures using impurities to increase the edge radiation. In this way, steady state plasmas with good confinement have been achieved for 4-5 seconds, showing promise for the development of such plasmas for use in a future power plant.

A number of organisational changes occurred in 1998. In October, the Council of the European Union approved the necessary amendment of the JET Statutes which enabled the Austrian Academy of Sciences to become a member of the JET Joint Undertaking. The same approval covered amendments which enabled the Dublin City University (replacing Ireland), the Forschungszentrum Karlsruhe (replacing the Forschungszentrum Jülich) and the Instituto de Cooperaçao Cientifica e Tecnológica Internacional (replacing the Junta Nacional de Investigaçao Cientifica) to become members of the JET Joint Undertaking. Following on from the judgement in December 1996 of the European Court of First Instance concerning the status of the UKAEA employees assigned to JET, the JET Council's proposals for modification to the "illegal" provisions of the JET Statutes were approved by the Council of the European Union in October 1998. In March 1998 the JET Council appointed a firm of lawyers to provide legal advice on matters relating to further actions by the JET UKAEA Team staff in the European Court of First Instance which remained unresolved at the end of 1998.

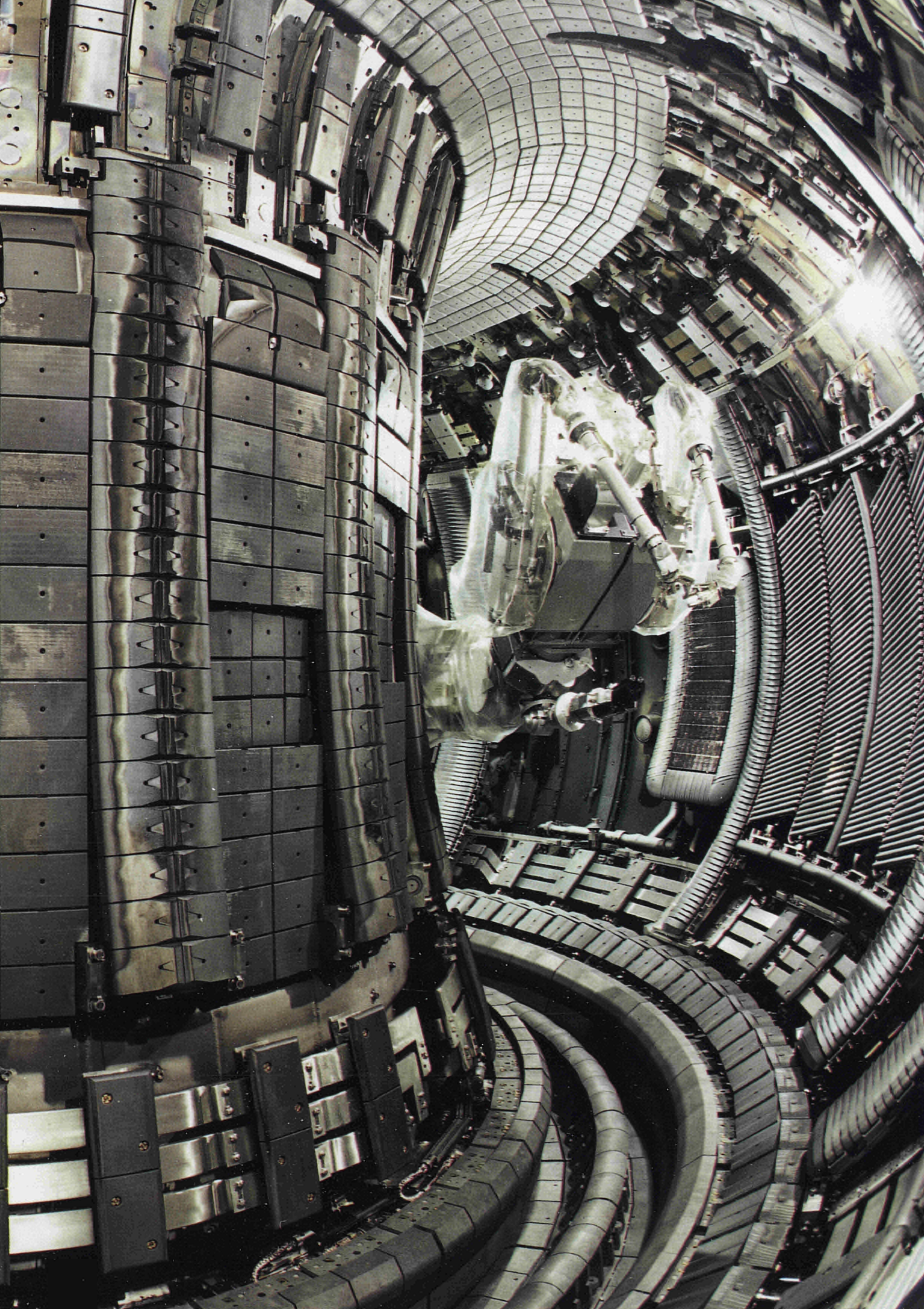
During the year the JET management began to consider arrangements for the winding up of the JET Joint Undertaking which will commence when its existing legal mandate expires in 1999. A report on the matter was presented in October 1998 to the JET Council who then appointed a Working Group, chaired by Dr. G. Leman, to oversee completion of the work on the preparation of instructions for the appointment of a Liquidator. Dr. Mancini's Group continued working on the administrative and structural options for operating the JET facilities following the winding up of the Joint Undertaking. Much progress was made but the final decisions on this topic belong to 1999. The adoption of the Fifth Framework Programme on Research and Technological Development, by the Council of the European Union in December 1998, provided some optimism for the continued use of the JET facilities beyond 1999.

On behalf of my colleagues on the JET Council, I congratulate the Director, Professor Dr. Martin Keilhacker and the staff for their dedication and hard work, and for again achieving such excellent results. These achievements were especially remarkable since 1998 saw the loss of a significant body of expertise with the departure of more than half of the Euratom staff who mainly took up new posts in the Commission. 1998 also saw the untimely deaths of Drs. David Start and Brian Keen whose respective contributions to RF and fast particle physics and to the JET Committees and Publications (including the preparation of the JET Annual and Progress Reports for over ten years) were immeasurable. I thank the members of the JET Council for their constant support throughout the year, the members of the JET Scientific Council for their sound advice, the members of the JET Executive Committee for continuing to monitor financial, contractual, and personnel aspects of the Project, and the Members of the various working groups and sub-committees set up during the year for carrying out the special tasks which were delegated to them. Dr. Alan Gibson who had been Deputy Director at JET for many years and who had been at JET since the beginning of the design phase in 1973 retired in May 1998. His significant contributions and wide experience were of great benefit to the Project. On behalf of the JET Council, I wish him well in his retirement.

F. Troyon

Chairman of the JET Council

September 1999



Introduction, Summary and Background

Introduction

The Joint European Torus (JET) is the largest project in the fusion programme of the European Atomic Energy Community (EURATOM), whose long term objective is the joint creation of safe environmentally sound prototype fusion reactors.

The Statutes setting up the JET Project include a requirement for an Annual Report to be produced which:

> *" ... shall show the current status of the Project, in particular with regard to timetables, cost, performance of the scientific programme and its position in the Euratom Fusion Programme and in the world-wide development of fusion research."*

This Report is designed to meet this requirement. It provides an overview of the scientific, technical and administrative status of the JET programme, which is intended to be comprehensible to the average member of the public. Where appropriate, descriptive sections (in italics and boxed) are included to aid the reader's understanding of particular technical terms used throughout the Report.

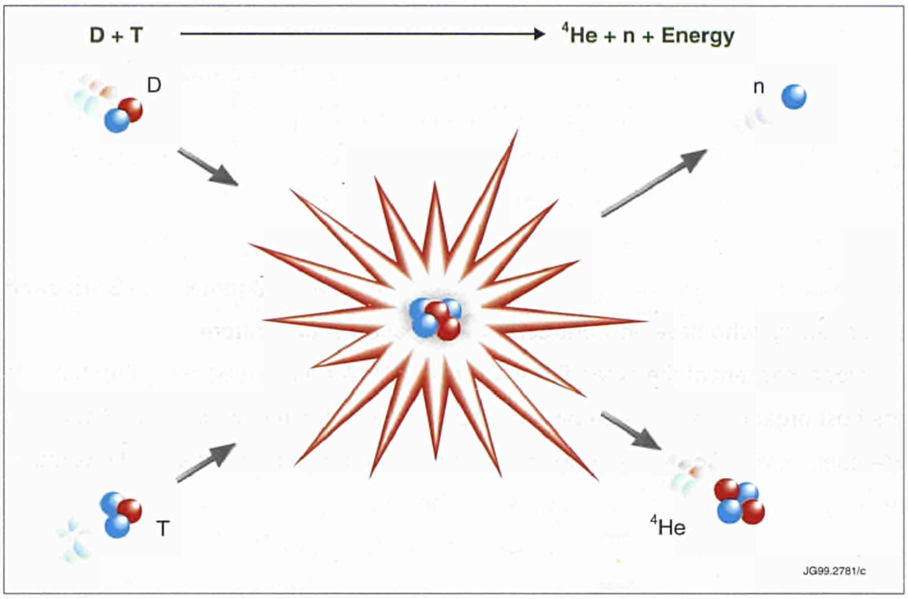
A more detailed and comprehensive description of the technical aspects of the JET Project can be found in the JET Progress Report.

Report Summary

The Report is essentially divided into two main parts:

- the scientific and technical programme of the Project;
- the administration and organisation of the Project.

The first part of the Report includes a brief introduction, provides an overview of the planning of the Report and sets the background to the Project. This is followed by a description of JET and its experimental programme and explains its position in the overall Euratom and International Fusion Programmes. In addition, it relates and compares JET to other large fusion devices throughout the world and confirms its pre-eminent position in fusion research.



Nuclear Fusion

Energy is released when the nuclei of light elements fuse or join together to form heavier ones. The easiest reaction to achieve is between the two heavy isotopes of hydrogen (deuterium and tritium).

Most of the energy released in this reaction is carried away by a high speed neutron. The remaining energy goes to the alpha particle (helium nucleus, ^4He) which is also produced in the reaction. In a fusion reactor, a jacket or blanket around the reactor region would slow down the neutrons, converting their energy into heat. This heat could be extracted to raise steam for conventional electricity generation.

The following section reports the technical status of JET including: remote handling, the Remote Tile Exchange Shutdown and preparations for 1999; tritium recovery methods; health physics, safety and the environment; heating, current drive, fuelling, exhaust, diagnostics, control and data management systems; summary of operations; and technical developments to enhance performance. This is followed by a section on scientific achievements during 1998. It shows the substantial achievements made by JET since the start of operations in 1983 and then concentrates on the main scientific objectives of 1998, namely the ITER Physics Mission, the ELMy H-mode Physics Mission for ITER and the Performance Optimisation Physics Mission for JET and ITER. It also sets out progress towards reactor conditions and compares the performance of JET and other tokamaks. The scientific part of this Report concludes with an overview of the programme and a description of the proposed future programme of JET until its planned conclusion.

The second part of the Report explains the organisation and management of the Project. It describes the administration of JET, in which it details the budget situation; contractual arrangements; and sets out staffing arrangements and complement.

Background

In the early 1970's, discussions were taking place within the European fusion research programme on a proposal to build a large tokamak fusion device to extend the plasma parameters closer to those required in a reactor. In 1973, an international design team started work in the UK, and by mid-1975, the team had completed its design for a very large tokamak device.

On 30th May 1978, the Council of Ministers of the European Communities decided to build the Joint European Torus (JET) as a Joint Undertaking of the European Fusion Programme. To implement the Project, the Joint Undertaking was originally established

Fusion Fuels

As deuterium is a common and readily separated component of water, there is a virtually inexhaustible supply in the oceans of the world. In contrast, tritium does not occur naturally in any significant quantities and must be manufactured. This can be achieved by using reactions that occur between neutrons formed in the fusion reactions and the light metal lithium.

Therefore, although the fusion reactions occurring in a reactor will be between deuterium and tritium, the consumables will be deuterium and lithium.

Fusion Reaction $D + T \rightarrow {}^4He + n$

Tritium Breeding Reactions $^6Li + n \rightarrow T + {}^4He$

$^7Li + n \rightarrow T + {}^4He + n$

There are sufficient reserves of lithium available to enable world electricity generation using fusion reactors, to be maintained at present levels, for several hundreds of years.

for a period of 12 years, beginning on 1st June 1978. The device would be built on a site adjacent to Culham Laboratory, the nuclear fusion research laboratory of the United Kingdom Atomic Energy Authority (UKAEA), and that the UKAEA would act as Host Organisation to the Project. Figure 1 shows an aerial view of the site of the JET Joint Undertaking at Culham in the United Kingdom.

The Members of the Joint Undertaking are Euratom, its Associated Partners in the framework of the Fusion Programme, including Switzerland, together with Greece and Luxembourg, who have no Contracts of Association with Euratom.

Eighty per cent of the expenditure of the Joint Undertaking is borne by Euratom. As the host organisation, UKAEA pays ten per cent, with the remainder shared between Members having Contracts of Association with Euratom in proportion to the Euratom financial participation in the total costs of the Associations.

The Project Team is formed mainly by personnel from the Associated Institutions, although some staff are assigned on a secondment basis from the Institutions and the Directorate General of the Commission responsible for Science Research and Development (DGXII).

In July 1988, the Council of Ministers agreed the prolongation of the JET Joint Undertaking to 31st December 1992. A further proposal to prolong JET to 31st December 1996 was approved by the Council of Ministers in December 1991. The extension was to allow JET to implement the new Pumped Divertor Phase of operation, the objective of which was to establish effective control of plasma impurities in operating conditions close to those of the Next Step. An extension of the JET programme to the end of 1999 in support of ITER while satisfying the requirements of JET D-T operations was approved by the Council of Ministers in May 1996. The legal mandate for the JET Joint Undertaking expires in 1999, but administrative and structural options for operating the JET facilities following the winding up of the Joint Undertaking are being discussed.

Objectives of JET

The original decision of the Council of Ministers in 1978 states that the JET Joint Undertaking's mandate is to:

> *"... construct, operate and exploit as part of the Euratom fusion programme and for the benefit of its participants in this programme, a large torus facility of tokamak-type and its auxiliary facilities in order to extend the parameter range applicable to controlled thermonuclear fusion experiments up to conditions close to those needed in a thermonuclear reactor."*

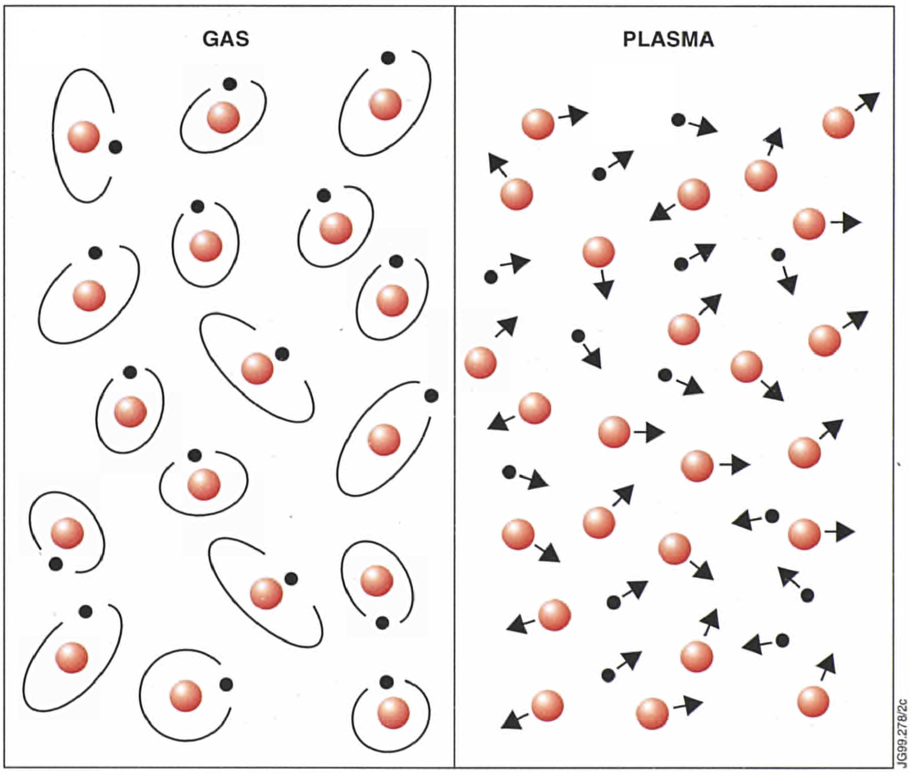
The principal objective of JET is to enable the essential requirements of a tokamak reactor to be defined. To implement this, it was necessary to create and study plasma in near-reactor conditions.

Objectives of JET

The essential objective of JET is to obtain and study plasma in conditions and with dimensions approaching those needed in a thermonuclear reactor. These studies will be aimed at:

1. *Scaling of plasma behaviour as parameters approach the reactor range;*
2. *Plasma-wall interactions in these conditions;*
3. *Plasma heating; and*
4. *Alpha particle production, confinement and consequent plasma heating.*

Fig.1: Aerial view of the JET Joint Undertaking, situated near Oxford in the United Kingdom



Plasma

As the temperature of the fuel is increased, the atoms in the gas become ionised, losing their electrons, which normally orbit around the nuclei. The mixture of positively charged ions and negatively charged electrons is very different from a normal gas and is given a special name - PLASMA.

The fact that a plasma is a mixture of charged particles means it can be controlled and influenced by magnetic fields. With a suitably shaped field, it should be possible to confine the plasma with a high enough density and a sufficiently long energy confinement time to obtain a net energy gain.

The configuration that has so far advanced furthest towards achieving reactor conditions and on which most data is available is the TOKAMAK, originally developed in the USSR.

Fusion Reactor

In a fusion reactor a lithium compound would be incorporated within a blanket surrounding the reactor core so that some neutrons can be utilised for manufacturing tritium. The tritium produced would then be extracted for use in the reactor.

The blanket would also provide the means of utilising the energy carried away from the reactions by the neutrons. As the neutrons are slowed down within the blanket, its temperature would rise thus enabling steam to be raised so that electricity could be generated in the conventional manner.

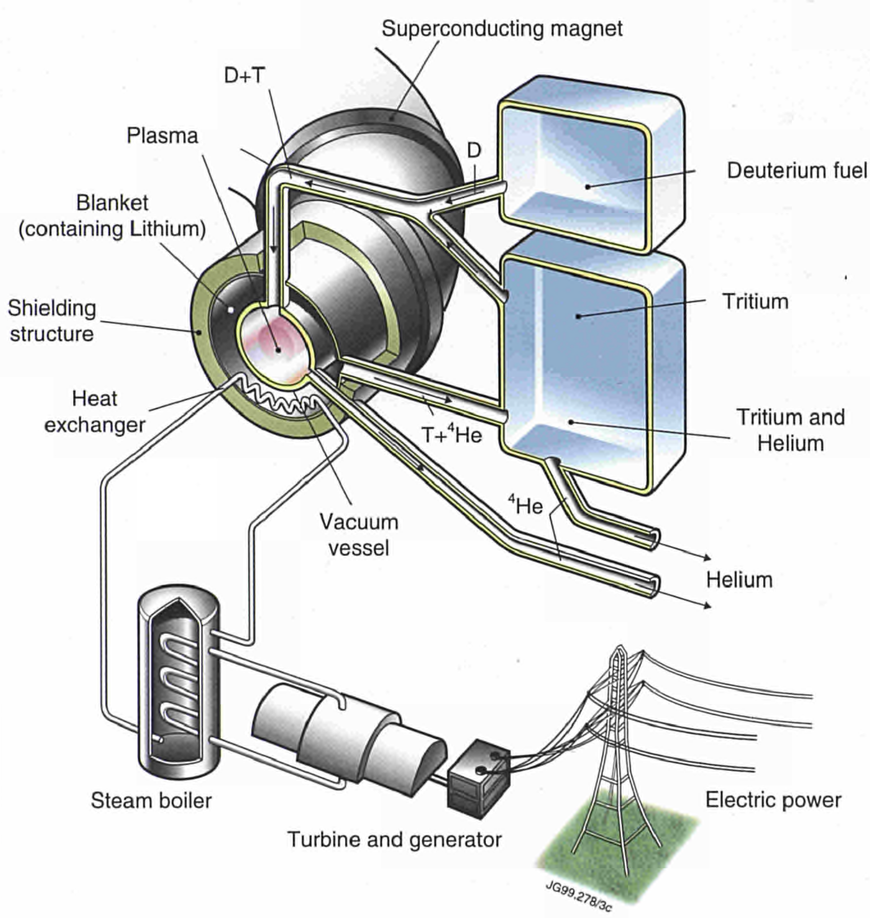
Ultimately, it is hoped that the conditions would be reached to enable a reactor to be built utilising the deuterium-deuterium reactions below:

$$D + D \rightarrow {}^3He + n$$

$$D + D \rightarrow T + p$$

In this case there would be no need to manufacture tritium and a virtually inexhaustible reserve of energy would become available.

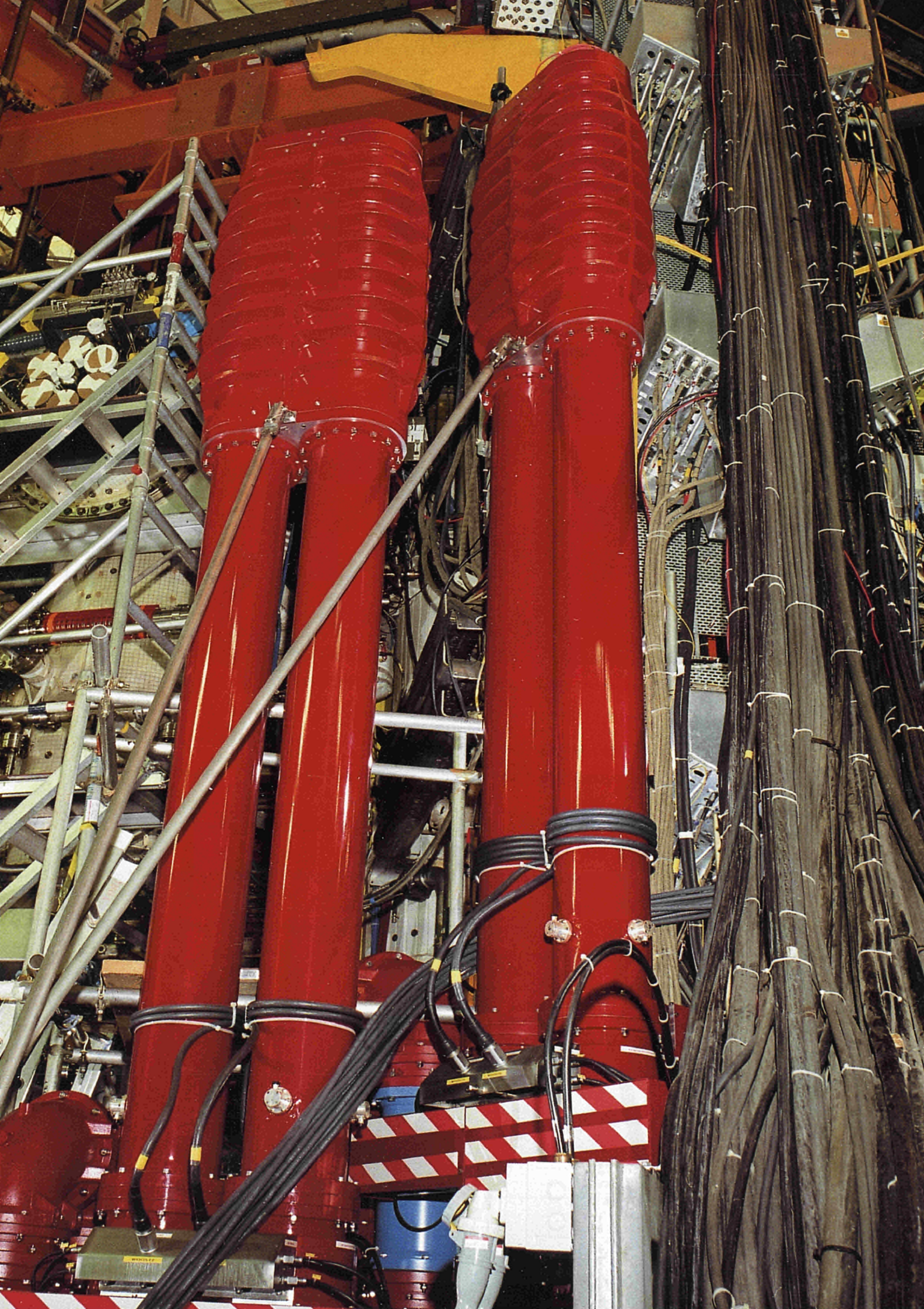
Schematic of a Fusion Reactor



There are four main areas of work:

1. the study of scaling of plasma behaviour as parameters approach the reactor range;
2. the study of plasma-wall interaction in these conditions;
3. the study of plasma heating;
4. the study of alpha particle production, confinement and consequent plasma heating.

In addition, JET is pioneering two key technologies required in fusion reactors: the use of tritium and remote handling techniques.



JET, Euratom and other Fusion Programmes

The Joint European Torus

JET uses the tokamak magnetic field configuration to maintain isolation between the hot plasma and the walls of the surrounding vacuum vessel. A diagram of the JET apparatus is shown in Fig.2 and the original main design parameters are presented in Table 1.

The toroidal component of the magnetic field on JET is generated by 32 large D-shaped coils with copper windings, which are equally spaced around the machine. The primary winding (inner poloidal field coils) of the transformer, used to induce the plasma current which generates the poloidal component of the field (Fig.3), is situated

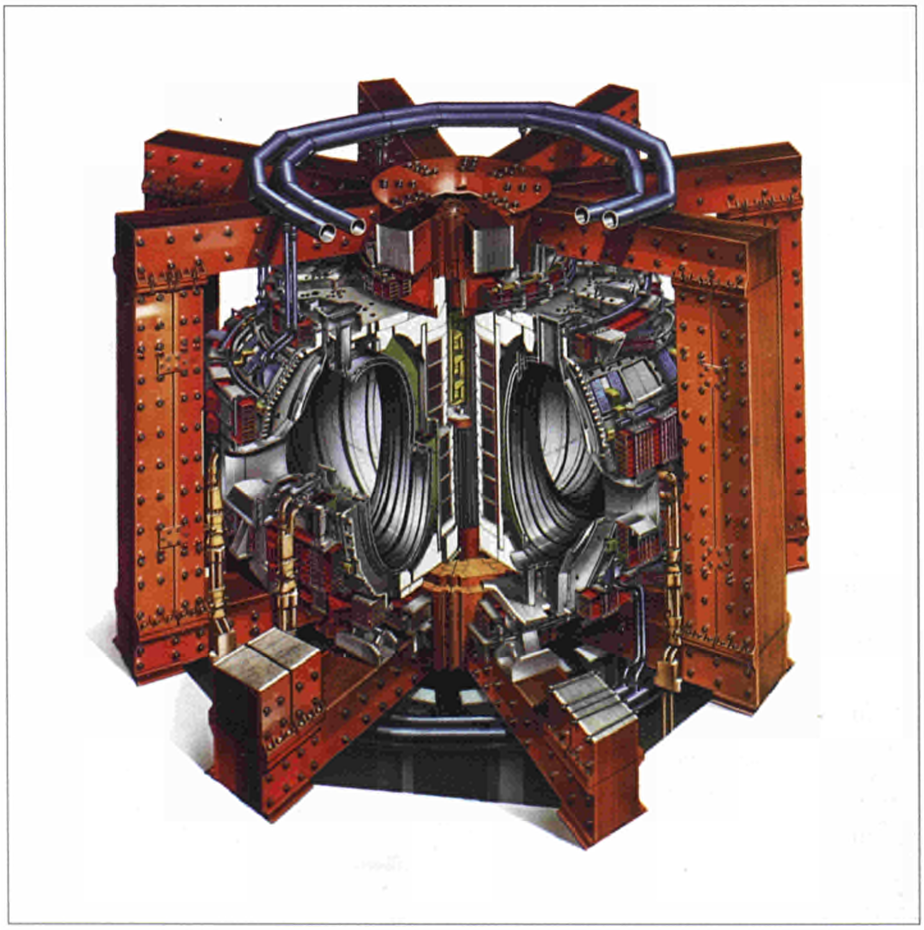


Fig.2: Technical illustration of the JET Apparatus

PARAMETER	SIZE
PLASMA MINOR RADIUS:	
HORIZONTAL	1.25m
VERTICAL	2.10m
PLASMA MAJOR RADIUS	2.96m
FLAT-TOP PULSE LENGTH	20s
WEIGHT OF THE IRON CORE	2800t
TOROIDAL FIELD COIL POWER (PEAK ON 13s RISE)	380MW
TOROIDAL MAGNETIC FIELD AT PLASMA CENTRE	3.45T
PLASMA CURRENT:	
CIRCULAR PLASMA	3.2MA
D-SHAPE PLASMA	4.8MA
VOLT-SECONDS TO DRIVE PLASMA CURRENT	34Vs
ADDITIONAL HEATING POWER	25MW

Table 1: Original JET parameters

at the centre of the machine. Coupling between the primary winding and the toroidal plasma, acting as the single turn secondary, is provided by the massive eight limbed transformer core. Around the outside of the machine, but within the confines of the transformer limbs, is the set of six field coils (outer poloidal field coils) used for positioning, shaping and stabilising the position of the plasma inside the vessel.

During operation large forces are produced due to interactions between the currents and magnetic fields. These forces are constrained by the mechanical structure which encloses the central components of the machine. The use of transformer action for producing the large plasma current means that the JET machine operates in a pulsed mode. Pulses can be produced at a maximum rate of about one every twenty minutes, and each one can last for up to 60 seconds in duration. The plasma is enclosed within the doughnut shaped vacuum vessel which has a major radius of 2.96m and a D-shaped cross-section of 4.2m by 2.5m. The amount of gas introduced into the vessel for an experimental pulse amounts to less than one tenth of a gramme.

Magnetic Field Configuration

The tokamak magnetic field configuration is built up from three components. The first of these is produced by a set of coils around the minor circumference. These coils produce the toroidal magnetic field around the major axis of the machine. The second component (poloidal field) is produced by a large current caused to flow through the plasma by transformer action. The combination of these produces a helical magnetic field which keeps the plasma away from the vessel walls. The final component is generated by a set of hoop coils, which is used to shape and stabilise the position of the plasma.

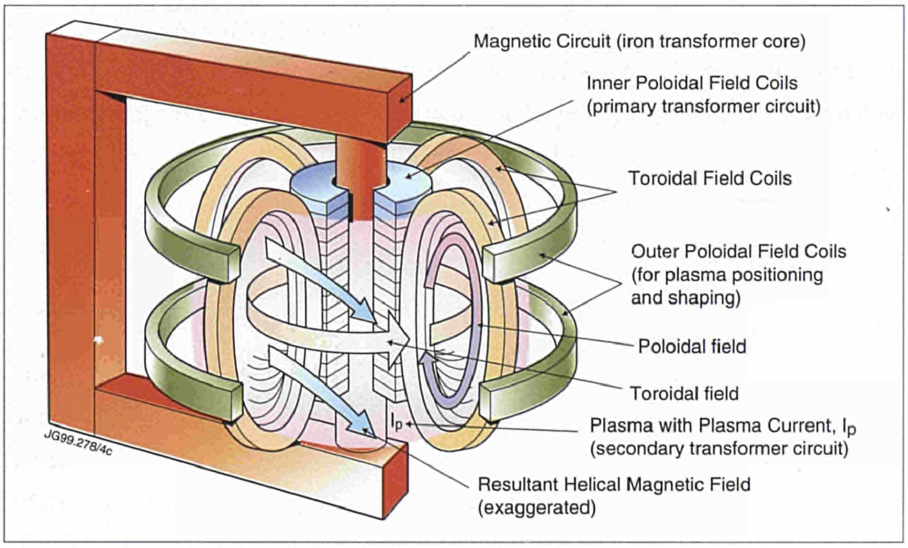


Fig.3: Tokamak magnetic field configuration

Power Supplies

The electric power to the JET device during an experimental pulse is counted in hundreds of megawatts.

An agreement with the Generating Boards allows up to 575MW of pulse power to be taken directly from the 400kV grid, which after transformation down to 33kV is fed to the JET loads.

Two flywheel generators are used to provide the peak power for the toroidal magnetic field coils and ohmic heating circuit. Each of the generators has a rotor 9m in diameter weighing 775 tonnes. Between pulses, 8.8MW pony motors are used to increase the speed of rotation. When power is required for a JET pulse, the rotor windings are energised and the rotational energy of the flywheel is converted into electrical energy. On slowing down from the maximum speed of 225rpm to half speed, the generators can each deliver 2.6GJ of energy with a peak power output of 400MW.

The construction phase of the Project, from 1978 to 1983, was completed successfully within the scheduled period and within 8% of the projected cost of 184.6 MioECU at January 1977 values. The first plasma pulse was achieved on 25 June 1983 with a plasma current of 17000A lasting for about one tenth of a second. This first phase of operation was carried out using only the large plasma current to heat the gas. In 1985, the first additional heating system, employing radio frequency heating, came into operation and during 1991 reached 22MW of power into the plasma. The neutral beam heating system was brought into operation in 1986, and exceeded its design capability in 1988, with 21.6MW of power injected into the torus.

Experiments have been carried out mainly using hydrogen or deuterium plasmas. However, during 1991, experiments were performed with helium-3 and helium-4 and a preliminary experiment was performed using 10% tritium in deuterium. The production of energy in the megawatt range in a controlled fusion device was achieved for the first time in the world. The JET Programme then turned to the effective control of plasma impurities in operating conditions close to those of the Next Step. This required the construction of divertor coils, target structure and cryopump inside the vacuum vessel. Operations resumed in 1994 to study the central problems of the ITER divertor (efficient dissipation of the exhausted power, control of particle fluxes and effective impurity screening) were studied in the operating mode forseen for ITER with a series of divertors and other modes of high fusion performance were also developed. During 1997 a series of experiments (DTE1) was undertaken with deuterium-tritium plasmas so that abundant fusion reactions occurred. The alpha particles liberated from the reactions produced significant heating of the plasma. During this phase, the machine structure became radioactive to the extent that the in-vessel work required to install the third in the series of divertors was carried out during 1998 using remote handling systems.

Controlled Thermonuclear Fusion: A Key Action in the Nuclear Energy Programme of Euratom

Objective, Strategy and Priorities

The long-term objective of the fusion activities, embracing all the research activities undertaken in the Member States (plus Switzerland and other Associated States which have joined the programme) aimed at harnessing fusion, is the joint creation of prototype reactors for power stations to meet the needs of society: operational safety, environmental compatibility, economic viability. The proposed strategy to achieve this long-term objective includes the development of an experimental reactor (the Next Step) followed by a demonstration reactor (DEMO), accompanied by physics and technology R&D activities, also involving European industry. In the context of this strategy, construction of an experimental reactor is necessary and, in the light of progress to date, seems technically feasible during the next decade. This should take place within the framework of international co-operation, such as the International Thermonuclear Experimental Reactor (ITER). For the period 1998-

2002, the "key action" on fusion should enhance the Community's preparedness, from a scientific, technical, financial and organisational point of view, to decide on and support such a future experimental reactor. The contribution of fusion to safe and clean base-load electricity generation will be investigated in the wider context of studies on the socioeconomic aspects of fusion. The mobility and training of scientific and technical personnel, the dissemination of results and the diffusion of information to the public will be an integral part of this key action.

This strategy entails three main lines:

- Next-step activities: fusion physics and technology activities to develop the capacity to construct and operate an experimental reactor;
- Concept improvements: structured physics activities to improve basic concepts of fusion devices, towards preparing the Next Step and the conceptual definition of a demonstration reactor, DEMO;
- Long-term technology: structured technology activities towards preparing, in the longer term, for DEMO and then a prototype reactor.

1998 Achievements

European fusion activities remained concentrated on the most successful toroidal magnetic confinement line, the tokamak, and on a few promising lines akin to it. In addition, in the context of a keep-in-touch activity, coordination of the national civil research activities on inertial confinement and possible alternative concepts was ensured.

Next Step Activities

The programme has continued to focus its activities on the preparation for a long-pulse burning fusion plasma device, particularly in the frame of the Engineering Design Activities (EDA) of ITER, the overall programmatic objective of which is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes. The ITER-EDA is carried out by a Joint Central Team (JCT) located in three internationally staffed Joint Work Sites in Garching (EU), Naka (Japan) and San Diego (US, until the end of 1998) and by three (plus the US until the beginning of 1999) Home Teams (HT).

Efficient collaboration has been achieved between the ITER JCT and Home teams, which has successfully delivered the products requested of them:

- a complete, fully integrated design for the ITER machine is available;
- the major validating technology R&D projects are now in their concluding stages for the purpose of confirming performance and understanding operating margins;
- the safety and reliability analyses have shown that ITER can be built and safely and reliably operated and would indeed demonstrate the safety and environmental potential of fusion as an energy source;
- cost studies from industries throughout the the parties confirm that the total estimated costs have remained within the targets set at the start of the EDA.

Conditions for Fusion

Fusion reactions can only take place if the nuclei are brought close to one another. However, all nuclei carry a positive charge and therefore repel each other. By heating the gaseous fuels to very high temperatures, sufficient energy can be given to the nuclei that the repulsive force can be overcome and they fuse together. In the deuterium-tritium reaction, temperatures in excess of 100 million degrees Kelvin are required - several times hotter than the centre of the sun. Below 100 million degrees, the deuterium-tritium reaction rate falls off very rapidly: to one-tenth at 50 million degrees, and 20,000 times lower at 10 million degrees.

A reactor must obtain more energy from the fusion reactions than is put in to heat the fuels and run the system. Reactor power output depends on the square of the number (n_i) of nuclei per unit volume (density) and the volume of gas.

Power losses must also be kept to a minimum acceptable level by holding the hot gases in thermal isolation from their surroundings. The effectiveness of this isolation can be measured by the energy confinement time (τ_E) - the time taken for the system to cool down once all external forms of heating are switched off.

In a fusion reactor the values of temperature, density and energy confinement time must be such that their product ($n_i \tau_E T_i$), exceeds the figure of $5 \times 10^{21} m^{-3} skeV$. Typical values for the parameters that must be attained simultaneously for a reactor are:

Central ion temperature, T_i
10-20keV
Central ion density, n_i
$2.5 \times 10^{20} m^{-3}$
Energy confinement time, τ_E
1-2s

The temperature is expressed as the average energy of the nuclei (1keV is approximately equal to 10 million degrees K).

> **Heating**
>
> *Initial production and heating of the plasma is produced by the large electric current flowing in the plasma itself (ohmic heating) used to generate the poloidal magnetic field.*
>
> *The heating effect of this current is reduced as the plasma gets hotter as the electrical resistance of the plasma decreases with increasing temperature. Therefore, it is necessary to provide additional means of heating if the temperatures needed for a reactor are to be reached.*
>
> *Two main additional heating methods are in general use:*
>
> *(1) Neutral Beam Heating:*
> *In this method, a beam of charged hydrogen or deuterium ions is accelerated to high energies and directed towards the plasma. As charged particles cannot cross the magnetic field confining the plasma, the beam must be neutralised. The resulting neutral atoms cross the magnetic field and give up their energy through collisions to the plasma, thereby raising its temperature.*
>
> *(2) Radio Frequency Heating:*
> *Energy can be absorbed by the plasma from high power radio-frequency waves. The frequency of operation is chosen to be close to that at which the ions or electrons orbit or gyrate in the magnetic field.*

Following the presentation of the ITER Final Design Report (FDR) in January 1998, the ITER Parties reconfirmed the feasibility of the design, its quality and the fact that it stayed within the original cost estimate. Due to financial considerations, the ITER Council charged the JCT to address a Reduced Technical Objectives/ Reduced Cost version of the device: for this purpose, a Special Working Group was set up with the task to propose technical guidelines for possible changes (detailed technical objectives, overall margins, ..) as compared to ITER-FDR and to provide information on broader concepts as a basis for the justification of these guidelines. Concerning the ITER-EDA Agreement, initially foreseen to expire by July 1998, a 3 year extension was agreed by three ITER parties (EU, Japan and Russia) while the fourth one (US) committed itself unilaterally to one year only.

In 1998, the work of the (European) ITER Home Central Team continued to be co-ordinated by the NET (Next European Torus) Team in the framework of the NET Agreement which expired by the end of the year (the European contribution to ITER from 1999 onwards will be carried out in the frame of the new European Fusion Development Agreement). The major part of the work on JET and in the Associations has been directed towards key areas relevant to the Next Step. A series of "urgent ITER Physics Tasks" was undertaken on the ITER-like tokamaks JET, ASDEX-Upgrade, Compass-D and the other medium-sized tokamaks, focusing on confinement scaling in order to increase confidence in the predictions for ITER. In the first part of 1998, JET was in shutdown in order to replace its previous divertor by the "gas box" configuration (Mark IIGB): for the first time, modifications of the (radioactive) interior of the JET device were successfully achieved by means of remote handling techniques. Operation of JET restarted in June 1998 and first results confirmed the expectations for a more closed divertor.

In the Associations, during 1998, the following improvements and upgrades have been proposed or decided as priority actions: tangential neutral beam injection and reactive power compensation for the ASDEX-Upgrade tokamak (Association Euratom-IPP); 2MW neutral beam injection in the TJ-II stellerator (Association Euratom-CIEMAT); advanced FOM diagnostics for TEXTOR-94 (jointly exploited by the trilateral Euregio cluster, Associations Euratom Belgian State, FOM, FZJ); ECRH studies using gyrotrons and developments for a free electron maser for use on TEXTOR-94 (FOM). On ASDEX Upgrade, operation continued with the so-called Lyra-divertor. Quasi-stationary H-mode (CDH) operation with large radiated power fraction and good power and particle exhaust was achieved. Radiative power limits of more than 80% (JET 65%) could be obtained. Tungsten as divertor coating was investigated in ASDEX-Upgrade in parallel with studies of limiter materials, ranging from Silicon to refractive metals in FTU showing advantages for high Z materials with respect to low core impurities and high density limits. Limits of edge density and its scaling with plasma size and heating power were studied on the above devices as well as, in collaboration with JET, impurity release mechanisms for impurity control. On TORE SUPRA plasma control for ergodic divertor operation with highly radiating plasmas and low core impurity content was a key focus of the

1998 programme. "Wind-tunnel" confinement studies on TCV on the impact of plasma elongation and shaping provided further improvement of the scaling database for the Next Step. Theoretical models and codes for studying the accessible operational space and regimes as well as control algorithms were further developed in collaborations of several Associations supporting the physics arguments for ITER design choices. Disruption mitigation and operational control were studied on the smaller devices (COMPASS-D, RTP, and ISTTOK) which are particularly suited for these studies but also e.g. on TCV and ASDEX-Upgrade (impurity injection). Error field studies on ASDEX-Upgrade and COMPASS-D showed weaker dependence on size than inferred from earlier work. Plasma engineering developments concerned developments of high-power windows for ECRH (Associations Euratom FZK, CIEMAT, and UKAEA) and 118-167GHz gyrotrons (Association Euratom-FZK reaching 1.2MW, 0.5ms 140-165GHz, Suisse, CEA, and industry), for 118GHz the nominal performance (0.5MW, 5s) was demonstrated. The prototype free electron maser (Association Euratom-FOM) has reached its first milestone (pulses of 0.7MW and 10μs, tuneable over the range 130-260GHz). For ICRH power densities of 18MW/m^2 were reached on TORE SUPRA and for Lower Hybrid heating and current drive launcher concepts were studied at the Associations Euratom-CEA and ENEA. Development of neutral beam injection sources demonstrated the ITER specification of 22MA/cm^2 (Association Euratom-CEA in collaboration with Japan) and progressed in the development of ion RF sources (Associations Euratom-IPP, CEA, and DCU). Diagnostics were developed and implemented on all larger devices, with a strong involvement of the Associations EURATOM-IST, DCU, FOM, NFR, RISO and TEKES.

Concept Improvements

Research on concept improvements is essential for extending the possible modes of operation of the Next Step and, in the longer term, for the definition of DEMO. On ASDEX Upgrade, quasi-stationary (6s pulse length) discharges were obtained with negative shear and using Divertor II. This considerable progress was linked to the exploitation of bootstrap currents and the generation of internal transport barriers (which could also be seen in the electron temperature profile by high resolution Thomson scattering on RTP). This work links closely to the exploration of advanced enhanced performance regimes and stationary operation in the Next Step. Contributions are provided by JET, the specialised devices (TORE SUPRA, ASDEX-Upgrade, TEXTOR, FTU, TCV, COMPASS, START, RTP, and ISTTOK) and in the accompanying theoretical and computational programmes. The successful low aspect ratio physics and spherical tokamak studies (β>40%) in START were concluded. This tokamak is being replaced by a larger one, MAST (Mega-Ampere Spherical Tokamak) for which commissioning was approached by the end of 1998.

The toroidal confinement data basis is complemented through contributions from stellarators and reversed field pinches (W7-AS, TJ-II, RFX, and EXTRAP-T2). Like the tokamaks these devices also serve for fundamental fusion physics studies, for the development of diagnostics, for innovative studies and for the training of young professionals and the smaller ones also for the preparation of collaboration on larger devices. Work on these devices is accompanied by theoretical, numerical or diagnostic activities with active incorporation of University research in many places.

The development of the Stellarator physics has been pursued at Madrid (Association Euratom-CIEMAT) where the TJ-II flexible stellarator started scientific experiments by successfully obtaining bean-shaped plasmas. In Wendelstein 7-AS (Association Euratom-IPP, Garching) 5.5keV (T_e) plasmas were obtained with neoclassical confinement; the approach of the theoretical beta limit was demonstrated with NB heating; the expansion of the accessible plasma density range studied for ECRH and the project for the assessment of the magnetic island divertor for Wendelstein 7-X continued. For this project in Greifswald (Association Euratom-IPP) civil engineering works proceeded as foreseen (buildings up to the roof by the end of August); the series production of the advanced conductor (following its successful testing) was launched; the cryostat module was assembled and the demonstration coil moved to the Toska facility (FZK) for testing. Contributions to the toroidal confinement data base were also provided by the reversed field pinch: work on RFX (ENEA/CNR) and EXTRAP-T2 (NFR) concentrated on issues of achieving high plasma performance operation (1.2MA operation has been reached) and improvement of confinement by assisting inductive poloidal current drive and spontaneous single helicity mode operation was attained. Finally, the keep-in-touch activity in inertial confinement including the co-ordination of European civilian activities in this field continued.

Long-term Technology

The effort in long-term technology in the Associations was pursued in the Associations, the Joint Research Centre and industry. Progress for 1998 can be reported on the European Blanket Project blanket: for the two specific (water-cooled lithium-lead and helium-cooled pebble bed) blanket concepts, the detailed design documents and test programmes (developed for blanket module testing in ITER) were completed; good results have been achieved in all the main technical issues, including fabrication techniques and functional materials (beryllium, ceramic breeders) behaviour in pile and out of pile; for structural materials, a contract was placed for the production of a first batch of reduced activation ferritic martensitic steel (delivery by end 1998). For power reactors, it was concluded that the reference structural material was ferritic martensitic steels; for more advanced materials, European efforts should be focused on SiCf/SiC, with keep-in-touch activities on other possible materials. On safety and environment, work has addressed issues such as improved containment concepts, cumulative production of activated materials and its possible reduction as well as the impact of these constraints on the economic aspects of a fusion power plant in order to define boundary conditions for initiating a Power Plant Conceptual Study. In Socio-Economic Research on Fusion (SERF), long-term scenarios have been developed which include fusion as a source of electricity and plant availability and volumic power density have been identified as important factors for production costs.

Involvement of Industry in the Programme

European industry continues to play a key role in the EU Fusion Programme. Areas of involvement include the supply of components, scientific equipment and materials as well as services for the construction and exploitation of Fusion Facilities in the EU as well as for the EU contributions to the detailed engineering design of ITER.

Implementation

All magnetic fusion R&D is fully integrated into a single Community action which is represented as a single body in its relations with other fusion programmes throughout the world. The European Commission - assisted by the Consultative Committee for the Fusion Programme (CCFP) which was replaced (end 1998) by the Consultative Committee for the Euratom specific research and training programme in the field of nuclear energy-Fusion (CCE-FU), composed of national representatives - is responsible for implementation of the key action on Controlled Thermonuclear Fusion. The action is implemented within the framework of: agreements of association with Member States of the European Union (and Associated States participating in the action) or organisations in the Member States for activities in physics, plasma engineering and technology; other contracts of limited duration (in particular with organisations in Member States without Association); the JET Joint Undertaking (until end 1999); the NET Agreement which was replaced (end 1998) by the European Fusion Development Agreement (EFDA, incorporating technology activities in the Associations and European industry, the collective use of the JET facilities for the period beyond 1999, as well as the European contribution to international collaborations such as ITER); and industrial contracts. Through the multipartite Agreement for "Promotion of Staff Mobility", the mobility of scientists and engineers was developed (300 to 400 secondments per year). In coordination with the "Human Capital and Mobility" programme, fellowships were awarded (10 to 15 per year). Nevertheless, in view of the decreasing number of physics students in some countries and considering the loss of a larger number of professional staff from JET which started in 1998 and continues in 1999, increased active measures for maintaining the necessary professional staff potential in the coming years are needed.

Dissemination of information and exploitation of results was performed through laboratory reports, publications in scientific journals, workshops and conferences. The itinerant fusion exhibition, run by the "Fusion EXPO" consortium (till end 1998), was displayed during long periods on the occasion of conferences/fairs

(Rome, Barcelone, Terrassa, Prague); another, smaller exhibition was presented during short periods in different places (Washington DC, Marseilles, Helsinki, Toulouse, Lisbon and 7 towns in the UK); also, 3-D immersive visualisation systems ("virtual reality") were developed for education purposes.

The Community financial participation amounts to about 25% of the running expenditure of the Associations, 45% of capital cost of projects having been awarded priority status by the CCFP, and 80% of JET expenditure. The overall expenditure on fusion research in Europe amounts to 450-500MioECU per annum, of which about 200MioECU come from the Community budget. About 2,000 professional scientists and engineers are currently engaged in fusion R&D in Europe. In its Report, the external Monitoring Panel for 1998 expresses its global satisfaction and considers that "the whole fusion programme is a very convincing example of continuously growing and well implemented successful European cooperation".

Fusion R&D in the Fifth Euratom Framework Programme

The 5th Framework Programme - FP 5 with an overall budget of 14,960MioECU - defines the Community activities within the EC and Euratom treaties in research, technological development and demonstration for the period 1998-2002. Within FP 5, an amount of 1,260MioECU is allocated to the Euratom Framework Programme which includes both thematic and horizontal aspects and covers the area of controlled thermonuclear fusion and energy systems related to nuclear fission, as well as that of industrial and medical uses of radiation and natural sources of radiation.

Within the Euratom Framework Programme, 979MioECU are allocated to the nuclear energy programme, the aim of which is to help exploit the full potential of nuclear energy, both fission and fusion, in a sustainable manner, by making current technologies even safer and more economical, and by exploring promising new concepts. Within the nuclear energy programme, 788MioECU are allotted to the key action on controlled thermonuclear fusion, the aim of which is to further develop the necessary basis for a decision on and the possible construction of an experimental reactor, as well as basic concepts and technologies required in the longer term.

European and International Collaboration

The integrated nature of European fusion activities has led to extensive collaborations. All Associations have undertaken work for, or in collaboration with, other Associations; also, they were partners in JET and NET, and carried out work for them through various contracts and notifications. Across Europe there exists a genuine scientific and technical community of large and small laboratories directed towards a common programmatic objective.

Internationally, the most important collaboration was the ITER EDA under the auspices of the International Atomic Energy Agency (IAEA, Vienna). Also, eight Implementing Agreements in the frame of the International Energy Agency (IEA, Paris) have continued to serve as the frame for collaborations to pool expertise and joint scientific interests. Bilateral or multilateral agreements for collaborations between European and non-European laboratories have assisted the exchange of information, common developments and the definition of complementary scientific investigations.

Large International Tokamaks

On 4th April 1997, the US tokamak, TFTR, produced its last plasma after its excellent fusion power programme with 50:50 D-T fuelled plasmas that had started in 1993. A fusion power of 10.7MW over an effective time of 0.4s with a fusion efficiency Q_{DT} of 0.27 had been produced.

Over this period, TFTR produced about 1090 D-T plasmas using 100g of tritium and producing 1.6GJ of D-T fusion energy. These discharges had significant populations of 3.5MeV alpha particles (the charged D-T fusion product). TFTR research focussed on alpha particle confinement, alpha particle driven instability modes and alpha particle heating studies. Also, apart from the so-called "Super-shot" regime, other operating regimes were explored. In particular, high beta poloidal (β_p) and negative central magnetic shear regimes with very high fusion performance were obtained. It was shown that in the relatively quiescent phases of these discharges, the alpha particles behaved classically and no anomalous losses occurred. The effect of sawteeth and ELMs on alpha particles were also studied. The principal limitation to the TFTR fusion power production was the disruptive stability limit. Secondary limitations were the confinement time and limiter power handling capability.

High-performance experiments with the aim of establishing a physics base for advanced steady state tokamak reactors have been carried out in the Japanese JT-60U using two approaches: high β_p H-mode and reversed magnetic shear mode discharges. In both types of discharge, an internal transport barrier built up inside the plasma, which yielded very high performance with neoclassical transport coefficients but with L-mode confinement at the edge which prevented the density build-up that occurs in ELM-free H-modes that have the transport barrier at the edge. In the reversed shear discharge, the barrier built up at the q_{min}~2 surface. This discharge reached the highest fusion performance with an equivalent Q_{DT} of 1.25 with plasma parameters of $n_e(0) = 8.5\times10^{19}m^{-3}$ and $T_i(0) \approx 16keV$. The discharges were very dynamic and volatile to MHD instabilities, but could, in principle, be controlled, although no steady state was achieved in JT-60U. Further experiments are foreseen with the newly installed negative ion Neutral Beam injector of 10MW.

JET broke all fusion records in 1997, not only in the highest fusion power but also in fusion energy in a quasi steady state discharge, promising steady state

Disruptions

There is a maximum value of density which can be contained with a given plasma current. If this value is exceeded a disruption occurs when the plasma confinement is suddenly destroyed and the plasma current falls to zero in a short period of time. Under these conditions high mechanical and thermal stresses are produced on the machine structure. Disruptions are thought to be caused by instabilities mostly developing on the magnetic surface where q=2.

Sawteeth

Perturbations on the q=1 magnetic surface can result in the formation of large fluctuations in the central temperature and density. These fluctuations have been termed 'sawteeth'. They are also associated with the expulsion of energetic ions from the central region of the plasma. Understanding this process is important as the alpha particles produced from deuterium-tritium fusion reactions might be lost before they can produce any effective heating of the plasma.

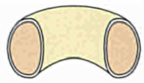
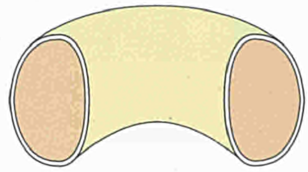
		TFTR	JET	ITER
				
Minor radius	a	0.85m	1.25m	2.8m
Major radius	R	2.5m	2.96m	8.1m
Elongation	κ	1.1	1.8	1.6
Toroidal field	B	5.6T	3.8T	5.7T
Input power	P	48MW	36MW	100MW
Fusion factor	Q_{DT}	0.3	1.1	30 – Ignition
Plasma current	I	3MA	7MA	21MA

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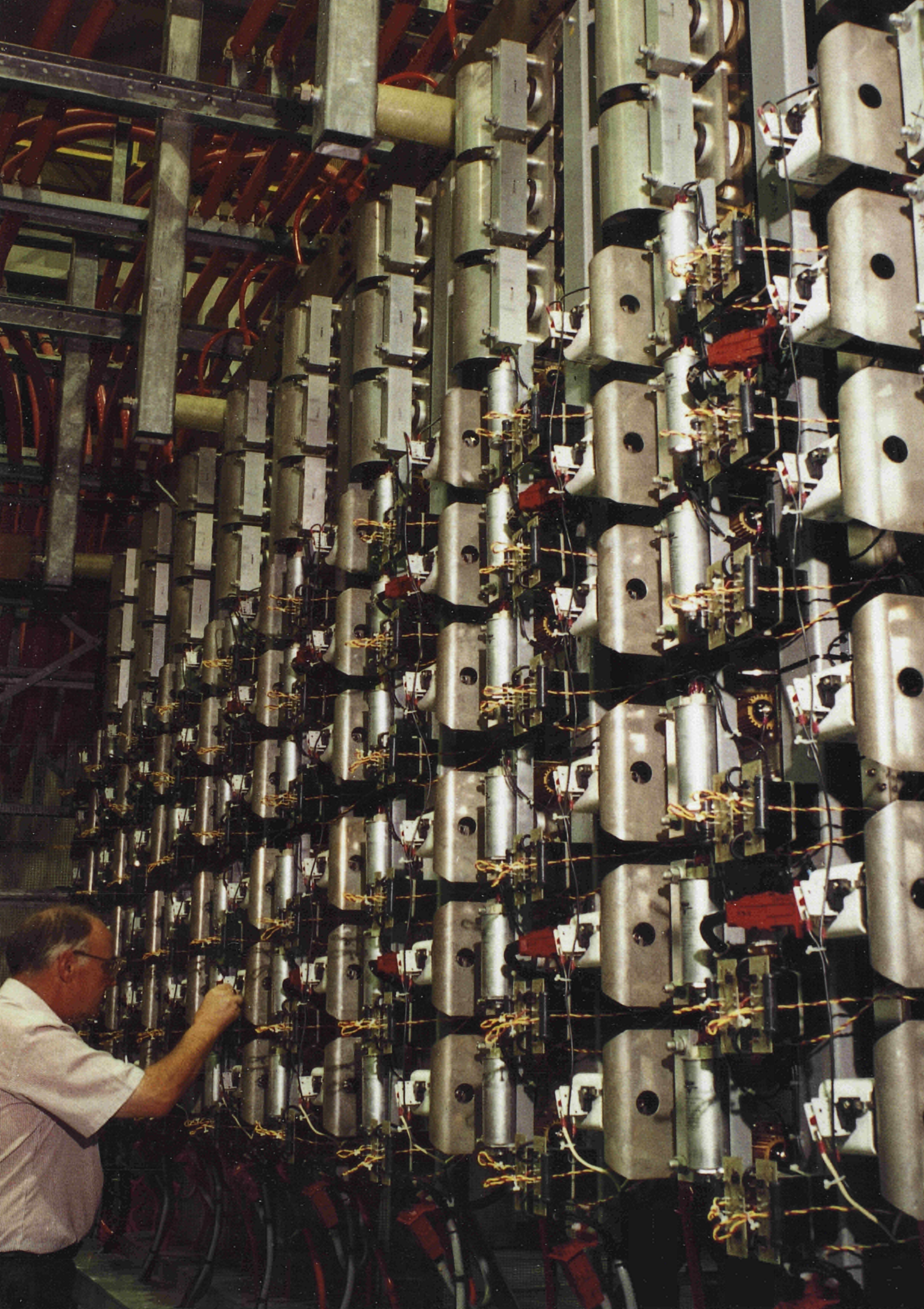
Fig.4: Parameters of three large tokamak designs

operation for a machine like ITER. The record fusion power was produced in a non-steady state hot ion H-mode with a transport barrier at the edge, that led to continuously increasing density and fusion power until the good confinement period was terminated by an Edge Localised Mode (ELM) instability. A record value of 16.1MW was reached at a Q_{DT} close to unity.

By modifying the configuration, an ELMy discharge was produced that had no density build-up and achieved steady state over a period of 4s (as long as the additional heating lasted). No problems of heat loading of the wall or target plates was encountered, which is a major achievement of the new divertor (Mark II) installed in JET in 1996. A total of 21.7MJ of fusion energy was produced in a single discharge. Since, in this type of operating regime, JET is essentially under-powered, the temperatures ($T_e \sim T_i$) were only ~7keV and thus the fusion power was only ~5MW. The fusion Q_{DT} was ~0.2; a clear improvement could be expected with a doubling of the input power.

The ITER Design Activity (EDA) has continued to make good progress and the achievements in the larger tokamaks (Fig.4) have become even more relevant.



Technical Status of JET

Introduction

Following the highly successful series of experiments using the Deuterium-Tritium (D-T) fuel mixture of a reactor (DTE1) in late 1997, JET started 1998 with a month of operations to complete ITER urgent physics studies in hydrogen and deuterium which the JET Council had agreed should be undertaken before the third stage of the JET divertor programme.

At the beginning of February a four month shutdown commenced for the exchange, by Remote Handling (RH) without manned intervention in the vessel, of the Mark IIA divertor target structure for a second target structure, the Gas Box divertor (Mark IIGB). This RemoteTile Exchange (RTE) shutdown was highly successful and provided a clear demonstration of RH as a method of maintenance, repair and upgrading of fusion devices. All the in-vessel work was accomplished in the time planned, all the RH equipment operated without failure, and all new components fitted without significant interface problems.

The primary purpose of the RTE was to remove all 144 Mark IIA divertor modules and to replace them with the 192 Mark IIGB divertor modules. A number of related or dependent tasks were also identified; various first wall protective tiles and diagnostics systems were removed and replaced, surfaces of the tiles were vacuum cleaned and the position and shape of the divertor structure was measured using a remotely deployed 3-dimensional photogrammetry system. In total, 38 different major tasks were planned and successfully executed during the shutdown.

During all this work particular emphasis was placed on safety. Careful planning resulted in low exposure of the workforce to radiation. Most individuals received doses of less than 0.1mSv, and the highest dose was 0.4mSv, significantly lower than in some previous shutdowns. The tritium emanating from the JET vessel was closely controlled using specially designed Contamination Enclosures and Ventilation Systems, in conjunction with the Exhaust Detritiation (ED) System of the Active Gas Handling System (AGHS). Exposure to tritium and beryllium contamination in the form of dust and flakes from the vessel was controlled in the same way. The success of these measures meant that the tritium levels in the Torus Hall were extremely low and caused no access difficulties, and that the discharge of liquids, particulates and gas were all kept well below the Authorised Discharge Levels.

Of the 20g of tritium inventory at the start of DTE1, 16g were removed from the vacuum vessel and accounted for in detail, with 12.5g being recovered to uranium beds. About 1g was removed with the Mark IIA divertor target tiles and about a further 0.5g with dust/flakes, all to separate storage. About 2.5g still remained in the vessel at the end of the RTE.

The RTE was completed as planned at the end of May. The vessel pumpdown proceeded with only minor problems, and the quality of the vacuum obtained was better than after previous shutdowns because no personnel had entered the vessel. The first plasma pulse was obtained as scheduled in early July, and the machine conditions enabled a 2MA/2.5T X-point discharge with a 10s current flat top to be obtained already in the fourth plasma pulse. This had never been achieved so rapidly after a major shutdown.

A power outage in August planned by National Grid to refurbish their power distribution system was used to re-install a number of diagnostic systems onto the machine. An unexpected power cut just prior to the outage resulted in the cooling of the machine, which in turn caused a crack and leak to occur on the Octant 4 Middle Port Adaptor. The leak was successfully repaired by re-welding the cracked weld on the lip where the leak had occurred, and operations restarted as planned at the end of August.

The experimental campaign with the Mark IIGB divertor commenced under Task Force structure in early September and will continue into 1999.

Installation work associated with the upgrade of the Toroidal Field Static Units for operation of JET at toroidal fields of up to 4T was also completed during 1998 and three 4T pulses with plasma were successfully run towards the end of the year.

The following sections detail notable technical achievements during 1998.

Technical Achievements

Remote Handling

Since the Mark II divertor was expected to become active during its use with D–T plasmas, JET had incorporated an important feature in its design - it was engineered to allow replacement of the divertor target structure by full Remote Handling (RH) techniques. Such techniques need to be well established before routine repair and maintenance of fusion power reactors can be envisaged and JET is the only fusion device which was designed from the outset with RH in mind.

In 1998, JET carried out major work using the RH equipment developed over the years. The experience gained at JET is invaluable for the conceptual design and realisation of a next step fusion device. It has shown that RH, when included as one of the basic design requirements from the start of the conceptual design, is a viable technology. The experience extends from the basic philosophy of the approach to RH, to the overall design requirements of the fusion device and to the design details of each and every component which may require RH. The JET experience also extends to the important areas of the organisation and management of a project which successfully integrates engineering aspects (including the RH requirements) into the physics and operational requirements of the device. These include not only the concepts and implementation of the hardware (including standardisation and documentation), but also the operational, maintenance and repair procedures; the facilities required for mock-up and the training of personnel; the methodology for failure recovery and its implementation; the control of hardware and software reliability; the spares policy; the planning and management of shutdowns; and the facilities and procedures developed to ensure the control of radiation exposure and contamination.

The Remote Tile Exchange Shutdown

The major technical activity of the year was the RTE. This was the first fully remote shutdown at JET and was successfully completed during a 15 week period from February to May 1998.

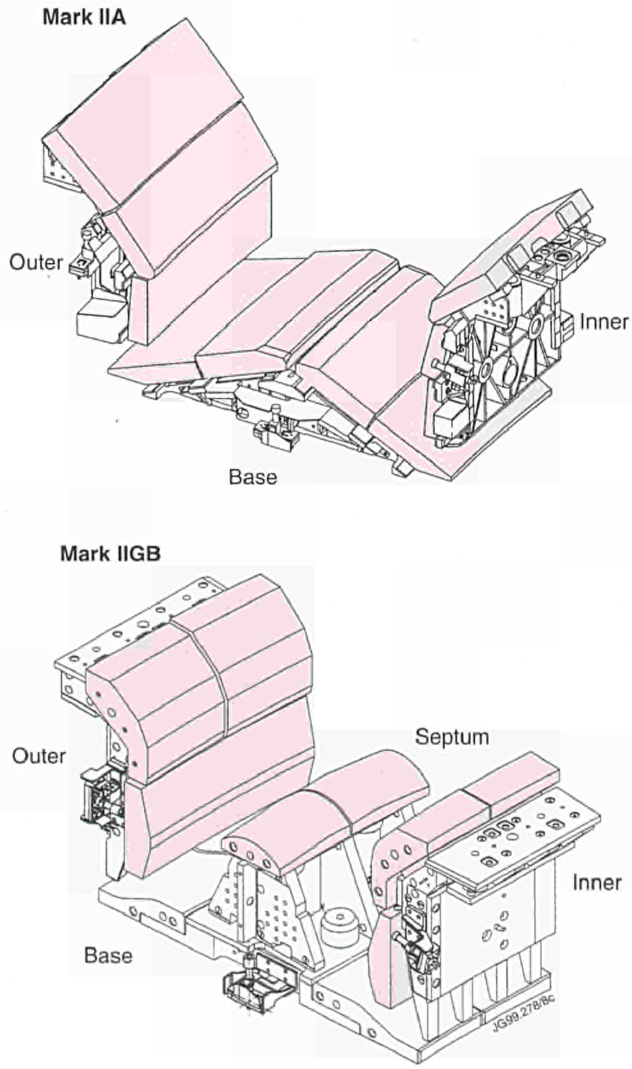


Fig.5: Mark IIA and Mark IIGB divertor modules

The work planned for the shutdown included:

- the fully remote removal of the 144 modules of the Mark IIA divertor and the remote installation of the 196 Mark IIGB divertor base, outer and inner carriers (Fig.5);
- the vacuum cleaning of the in-vessel components and the collection of dust and flakes from the divertor region for future analysis;
- the removal and re-installation of a number of divertor diagnostics; and
- the first remote, high precision (0.3mm accuracy) dimensional survey of the divertor support structure using digital photogrammetry.

The flexible approach which had been adopted in preparing for the RTE also enabled a number of unexpected and unplanned tasks to be undertaken, including:

- seven pairs of poloidal limiter tiles, which had shown the first indications of cracking, were removed and replaced remotely;
- a diagnostic wave guide was found to be displaced by 40mm from the expected position and could not be removed by the established procedure. Using the manipulator it was possible to deflect the wave guide, free the RH bolt, remove the diagnostic and remove the trapped tile carriers. The displaced wave guide support was surveyed using digital photogrammetry and the results used to manufacture a new wave guide which was then installed;
- two diagnostic windows on the bottom of the vacuum vessel were covered with carbon flakes and dust and required cleaning. Using the servomanipulator a 2.5m long, 11mm diameter stainless steel tube was passed though the 12mm wide slot in the divertor support structure. A vacuum cleaner was then attached to the tube and all the debris was removed successfully.

The work was based on the RH philosophy chosen at the start of the JET Project and used the tools developed since. The remote in-vessel work was executed by operators using the Mascot servo-manipulator positioned inside the torus on the

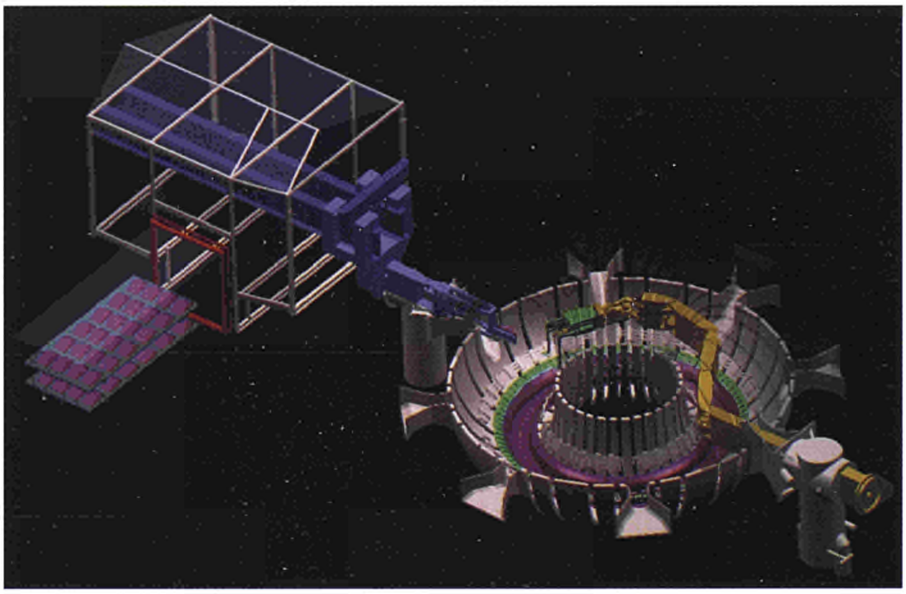


Fig.6: Overall remote handling methodology

end of the JET Articulated Boom (Fig.6). This articulated boom, housed within a specially designed contamination control enclosure sealed from the torus, entered the torus at the Octant 5 main horizontal port.

The components of the Mark IIA divertor were unbolted and removed from the supporting structure with the help of the manipulator and transported by the boom to Octant 1, directly opposite the main boom entry port in Octant 5. The components were then transferred to an end effector attached to a second shorter boom (of otherwise identical design to the main boom) which removed the components from the vessel and manoeuvred them, without manned intervention, onto trolleys for storage in a removable ISO container. The ISO container was attached to the Tile Carrier Transfer Facility (TCTF), a contamination control enclosure located at Octant 1 and housing the second short boom (Fig.6). The two contamination control enclosures, as well as the ISO containers, were kept at a depression relative to the surrounding Torus Hall and ventilated at a rate of 10-20 air changes per hour by the Exhaust Detritiation (ED) System of the AGHS.

DTE1 Tritium Recovery

The Active Gas Handling System (AGHS) is a full gas reprocessing plant, which collects gas from the torus, removes impurities from hydrogen, isotopically separates the hydrogen gas into streams of protium, deuterium and tritium, stores the deuterium and tritium in U-beds for re-use, and injects deuterium and tritium back into the torus. Isotope separation makes use of cryo-distillation and gas chromatography. The system is located in a separate building with its own ventilation system and is connected to the JET machine via 100m long pumping lines and transfer lines. A schematic of the system is shown in Fig.7. It was designed for a maximum daily throughput of up to 5 moles of tritium, 15 moles of deuterium and 150 moles of protium. It was installed in compliance with a strict quality assurance programme and went through an extensive phase of inactive testing. Tritium commissioning was performed in two steps. Trace tritium commissioning with about 0.8g was performed with a tritium-hydrogen gas mixture. Full tritium commissioning with about 3g of tritium tested the complete process using all sub-systems and showed the system was ready for full tritium operation (DTE1 in 1997).

DTE1 ended in November 1997 with about 11g of tritium retained in the torus after the regeneration of all cryopumps. An extended campaign of tritium recovery resulted in the reduction of the in-vessel inventory to 6.2g (corresponding to 17% of the tritium introduced into the vessel during DTE1) by the start of the RTE shutdown in February 1998. This was in itself of considerable technical interest for a Next Step machine and was essential for minimising the in-vessel tritium concentration during the RTE.

Most of this tritium was bound in co-deposited layers of carbon and hydrogen isotopes which adhered mainly to the cooler surfaces on the inner side of the divertor or fell off in the form of 40-50mm thick flakes. Much of the co-deposited

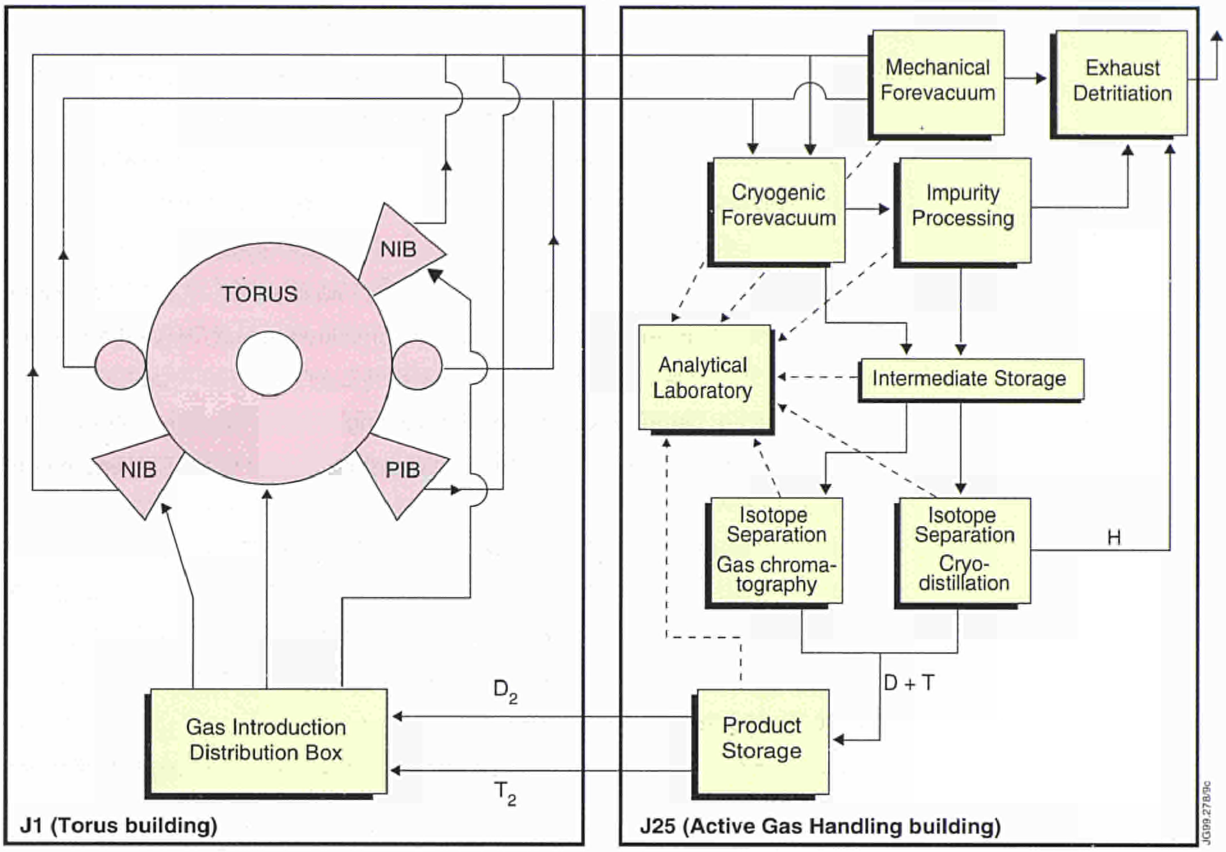


Fig.7: Schematic of the Active Gas Handling System

tritium was removed during the RTE shutdown either by brushing and vacuum cleaning or with the carriers as they were removed from the vessel. The co-deposited layers and flakes slowly off-gas in the presence of the humid air pumped through the enclosures in which they were stored (tritium off-gassing rates of 0.6GBq/hr were measured for one divertor module after removal from the vessel).

After the recovery of about 60g of carbon flakes and dust (containing ≈0.5g of tritium) from the torus, the residual in-vessel inventory at the end of the shutdown was estimated to be 2.5g. This is deeply entrenched within the torus and is being recovered only at a very low level during subsequent operations (about 8mg per week). Never the less, many of the systems necessary for DTE1 were still required to operate throughout 1998. In particular, the AGHS and its associated ED System were fundamental to the safe and environmentally acceptable performance required for the RTE and subsequent plasma operations. The integrity of interspaces on the torus is continuously monitored and, during interventions, these continue to show tritium levels orders of magnitude above that allowable for personnel exposure. Techniques, equipment and controls appropriate for working safely with these levels of contamination are routinely applied and the total dose received by staff remains very low.

Discharges to the environment, both in gaseous and liquid form, have at all times remained more than an order of magnitude below the site approved levels.

Preparations for the 1999 Shutdown

In the foreseeable future, access to the vacuum vessel will be accomplished either fully remotely or with a mixture of remote and personnel access. The TCTF is being modified to support personnel wearing full pressurised suits to enter the vessel, and will supply all standard and emergency services required, as well as all requirements for remote work.

The installation of the inboard pellet launch, planned for June 1999, will be carried out mostly using RH equipment and will include the first RH welding carried out at JET. A new suite of RH tooling has been defined. Over 25 new tools have been designed and are being procured. The RH welding of small support rails onto the torus wall requires detailed development; its feasibility using the JET RH equipment has already been proven.

Remote photogrammetry surveying is being developed further and integrated into CATIA as well as the manufacturing cycle. Following the RH welding of the support rails, a survey will determine the precise three-dimensional rail positions so that the pellet flight tubes, which will use these as attachments, can be manufactured exactly for the support rail positions. Measuring, analysing and transferring the data will require less than a week between completing the survey and installing the first pellet flight tube.

Health Physics, Safety and the Environment

The Director is responsible for safety and is required by the JET Statutes to undertake all organisational measures to satisfy relevant safety requirements. JET continues to meet all the requirements of relevant UK and EC legislation and, in accordance with the Host Support Agreement, JET complies with the safety regulations of the Host Organisation. Responsibilities for Safety and Health Physics are discharged by the Health Physics and Safety Sections, which are part of the Safety and Environment Unit within the Directorate.

Health Physics

Health Physics provides a complete radiological protection and occupational hygiene service to the Project, including advice on radioactive and hazardous materials handling, dosimetry, radioactive discharge and environmental monitoring, beryllium analysis and exposure record keeping.

The RTE dominated the year, together with operations in the tritium and beryllium handling areas. DTE1 had left levels of tritium in the torus which, after clean-up at the start of the year, was estimated to be more than 2000TBq absorbed on vessel components. A controlled sequence of purging of the torus volume reduced these concentrations to a few GBq/m^3, allowing the opening of the torus containment. Personnel entries to the TCTF and Boom enclosure were made in full-pressurised suits to guard against airborne tritium and particulate forms of tritiated dust and beryllium. The tritiated Mark IIA divertor modules were removed and replaced by new Mark IIGB divertor modules. Tritium doses to suited workers were very low due to the high level of protection. The TCTF and Boom enclosures were later decontaminated, allowing entry in respirator protection. Health Physics was required to advise on radiological protection measures, and to assess and monitor tritium and radiation levels in the workplace.

An extensive programme of ex-vessel work on the diagnostics and Neutral Beam systems also took place during the RTE. Permeated tritium was found in many diagnostic volumes and machine interspaces, necessitating ventilation controls to minimise exposure during maintenance. A large number of air and surface contamination measurements were taken and samples of coolant and exposed materials analysed.

At the start of the RTE, the residual dose rates ex-vessel were about 600μSv/hr on the main ports and 30μSv/hr on the mechanical structure. Access control kept doses to radiation workers very low, and by the end of the year of the 500 persons monitored, the highest radiation dose accrued from all radiation work was 0.5mSv (JET limit = 5mSv/year). The highest individual external radiation dose was 0.4mSv, and the highest individual tritium dose was about 0.1mSv. The collective tritium dose was 0.0021man.Sv (0.00146man.Sv in 1997), the sum of all doses was 0.035man.Sv (0.072man.Sv in 1997), the reduction being explained in part by the fully remote in-vessel operations.

The AGHS continued to process and collect tritium from the torus. Tritium concentrations as high as 1.3TBq/ℓ were observed in the water collected from operation of the ED system, and stringent precautions were in place for drum-filling operations. Tritium exposures to operations staff in the AGHS remained negligible.

Surveys of operational areas showed that workplace contamination controls were very effective. A large environmental monitoring programme, covering radioactivity in soil, air, rainwater, groundwater, riverwater, milk and crops has also been in place. Discharges of radioactivity for the year were a small fraction of the UK Environment Agency authorised limits, and tritium and other radioactivity levels in the environment were insignificant.

The measurement of beryllium exposures in the beryllium controlled areas continued during the year. A total of 5300 personal air sample measurements were carried out, and all exposures were well below the 2μg/m^3 maximum exposure limit specified in the UK Control of Substances Hazardous to Health Regulations. More than 22,000 surface contamination and liquid samples were also analysed in the Beryllium Analysis Laboratory.

Safety

A general safety service provides safety-related training, monitoring, co-ordination and planning of statutory inspections, while also ensuring that there is an awareness of any legal requirements or important changes to existing legislation.

Safety-related training followed the normal pattern for basic courses on 30 different topics with a total of 1464 attendees. Safety Induction continues to be the route for ensuring all new staff are initially made aware of the safety culture at JET. Site emergency training and table top exercises have also been held in preparation for a full exercise during 1999.

Throughout the year, there were 51 accidents reported to the Safety Section; all were minor with a total of 19 days lost time. Three of these accidents were required to be reported to the HSE as they resulted in more than three days off work. There were two Incident Safety Review Panels. No injuries occurred. The implementation of the recommendations made by these Review Panels is monitored and reported at the regular JET Safety Working Group meetings which have representatives from all staff groups.

Heating, Current Drive, Fuelling and Exhaust Systems

Neutral Beam Heating

The injection of high energy neutral beams is currently the primary method of heating plasmas to the temperatures necessary for fusion, and has proven itself in D-T plasmas. The basic configuration of two Neutral Beam (NB) injectors (Fig.8 shows the eight beam-lines of one NB injector) was arranged so that all 16 beam-lines were made compatible with tritium and the AGHS was set up to supply the injectors with deuterium and/or tritium. During DTE1, eight beam-lines supplied with deuterium (Octant No.4) were operated at 80kV, 55A (13.6MW maximum) and eight beam-lines supplied with tritium (Octant No. 8) were operated at 160kV, 30A (12MW maximum).

Operation prior to the RTE continued from the beginning of January until 1 February 1998. Both NB injectors were operated in deuterium during this period. Although the last tritium operation with the Octant No.8 injector had taken place in November 1997, small quantities of tritium continued to be recovered from both NB injectors during 1998. The NB systems were maintained during the RTE, and re-commissioning, with some improvements to their protection systems, commenced in July and included, in particular, those safety interlock and protection systems which feature in the Safety Case documentation for D-T operation.

The restart commissioning was interrupted, however, by a failure of a lip-weld on the Middle Port Adapter (MPA) which couples the Rotary High Vacuum Valve (RHVV) of the Octant No.4 injector to the torus vacuum vessel, causing a torus vacuum leak. This was the second failure of its kind on this MPA, but it was possible to effect the repair by in situ welding, in contrast to the previous failure where a temporary repair using silicone rubber had been necessary.

After recovery from the MPA repair, re-commissioning of both NB injectors was completed in September and routine operation continued until Christmas. Limitations arising from beam transmission and beam-line component power loading on the

Neutral Beam Heating

The two JET neutral beam systems have been designed for long (~10s) beam pulses. They have the unique feature that each injector consists of eight beam sources in a single integrated beam-line system connected to the torus. The first beam sources were designed to operate at accelerating voltages up to 80kV and in 1990 one system was substituted with units capable of operating up to 140kV. In addition, this box was also converted to operate with helium (^{3}He and ^{4}He) beams during 1990. In the D-T phase, one unit was converted for operation with tritium at 160kV.

Each system is connected to the torus by a long narrow duct through which up to 12MW of power can be directed.

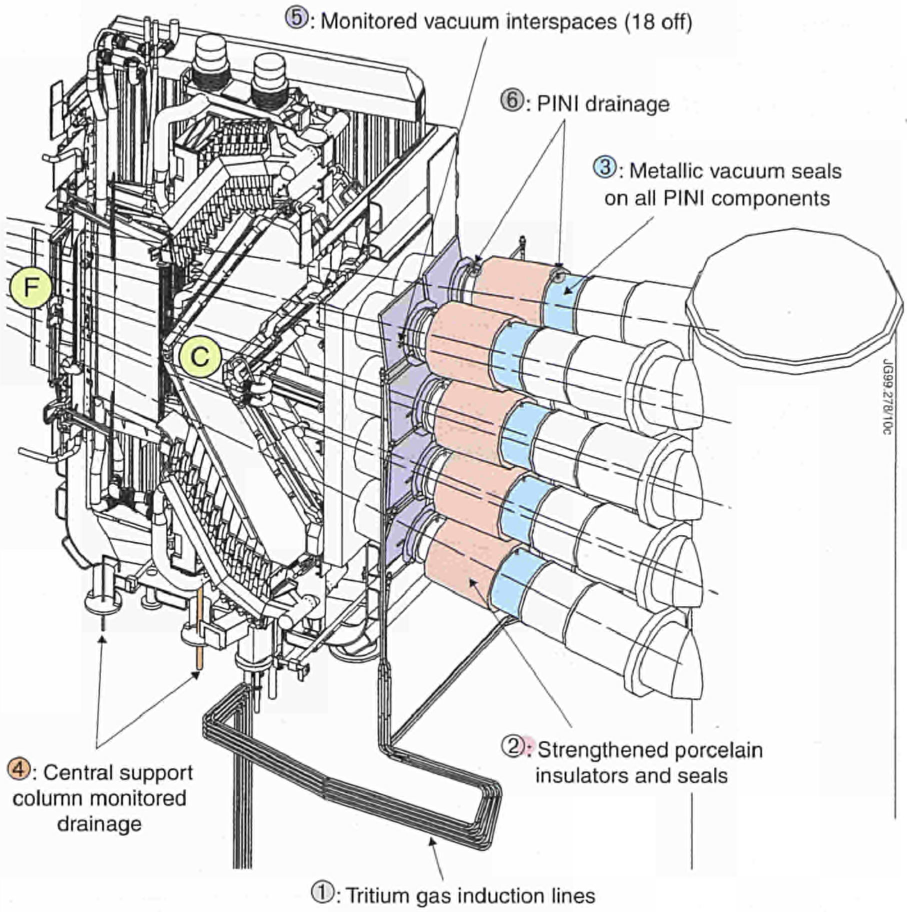


Fig.8: Neutral Beam injector cutaway showing principle components

80kV NB injector restricted the maximum achievable power during September-December. As is normal in the first few months of operation following a major shutdown, the number of pulses with high power NB heating (>15MW) is lower than for a similar period towards the end of an experimental campaign. Nevertheless, it is notable that during 1998 the historical trend of increasing proportion of JET discharges with significant levels of NB heating has continued, in all power bands except the highest (>15MW); the maximum power achieved was about 18.7MW (Fig.9).

Radio Frequency Heating

The Ion Cyclotron Resonance Frequency (ICRF) heating system is used for high power centralised heating of the plasma, with increased emphasis on Fast Wave Current Drive with the latest antennae. The localisation depends mainly on the magnetic field and is insensitive to parameters such as density and temperature. Wide band operation (23-57MHz) allows variation in both the choice of minority ion species heated (H or ^{3}He in deuterium plasmas, D in D-T plasmas) and the localised position of the heating.

The latest ICRF antennae (Fig.10) have been optimised to the geometry of the divertor plasmas. Their location in the torus has been revised to give four arrays of two adjacent antenna. Each array has four RF conductors or straps, which provide

Radio Frequency Heating

Ion Cyclotron Resonance Frequency (ICRF) heating has been chosen for JET and the wide operating frequency band (23-57MHz) allows the system to be operated with the various mixtures of ion species required in the different phases of the scientific programme and to choose the location where the heating in the plasma occurs.

The ICRF heating system has been designed in eight identical modular units. Each unit is composed of a tandem amplifier chain, a network of coaxial transmission lines and matching elements and finally an antenna located in the vacuum vessel on the outer wall. The eight RF generators produce a maximum output power of 32MW. The net power coupled to the plasma has reached 22.7MW, compared with the theoretical limit of 24MW.

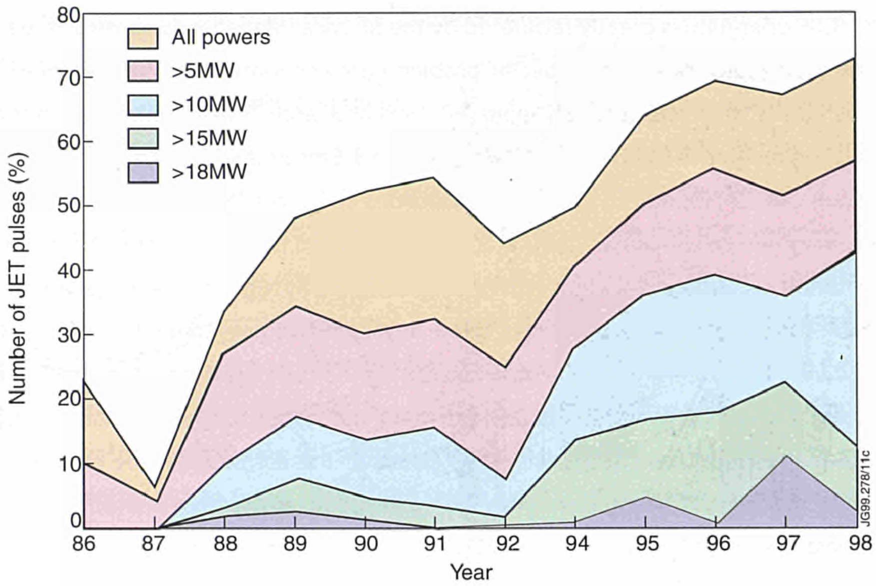


Fig.9: Neutral Beam heating powers delivered to JET plasmas during 1986-98, expressed as a fraction of JET pulses

an enhanced radiated spectrum. Variation in the relative phase of the RF currents in the straps allows this spectrum to be varied for both heating and current drive experiments.

Ion cyclotron resonance frequency heating is one of the main heating methods envisaged for ITER. In JET, the system has been exploited over its full frequency range and ICRF heating has been used, either alone or in combination with NB heating, in all the major experiments with the Mark II divertor. It also played a key role during DTE1 when ICRF specific experiments were also carried out to explore some of the heating scenarios foreseen for future reactors. ICRF is now routinely used for various experiments with the Mark IIGB divertor configuration.

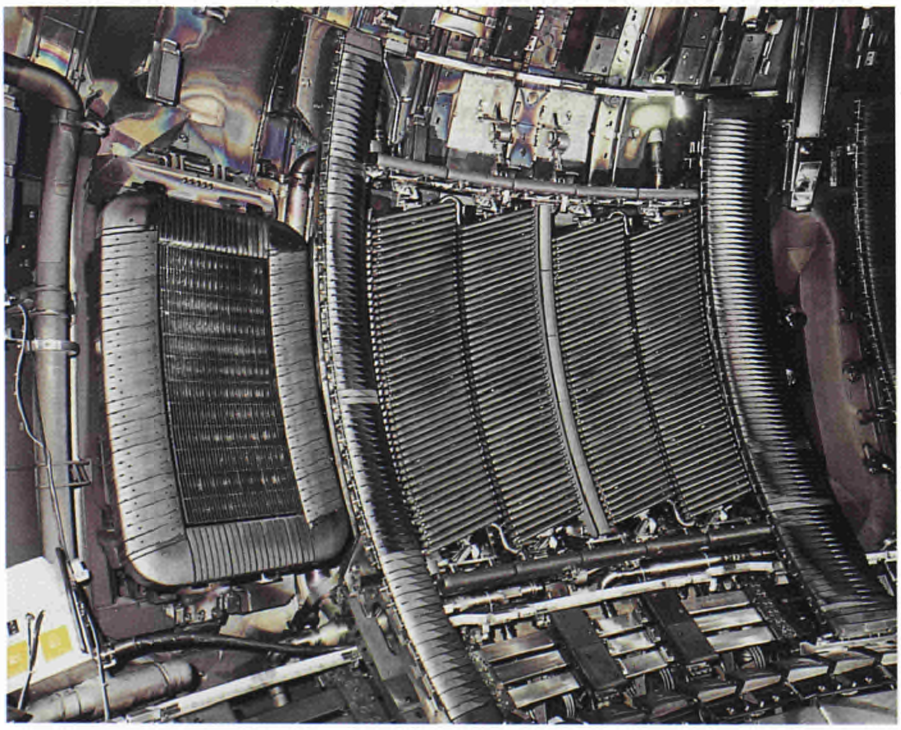


Fig.10: One module of the Ion Cyclotron Resonance Frequency heating antennae (on the right) together with the Lower Hybrid Current Drive launcher (on the left)

ICRF operation is greatly facilitated by the RF Local Manager to control in real-time the coupled power, but specific problems are encountered in the presence of Type I ELMs which cause a very rapid (≈0.1ms) and large (≈ few Ω) increase in the coupling resistance followed by a decrease on a 3-5ms time scale. The RF matching system cannot respond to such large excursions on such a fast time scale, and the resulting mis-match causes generator trips. This is the main reason for the power limitation in combined heating experiments in the ELMy regime. A new system, the Wide Band Matching system, has been developed to overcome this problem. Following the promising results obtained during the commissioning of a prototype system, the completion of the Wide Band Matching system for the remaining three antenna modules has started with the release of the contract for the remaining twelve mechanical tuning elements (Sliding Impedance assemblies) which are the longest delivery items (Fig.11).

Lower Hybrid Current Drive

The Lower Hybrid Current Drive (LHCD) system (Fig.10), operates at 3.7GHz and is capable of driving a significant fraction of the toroidal current in the plasma. This is achieved by launching an RF wave predominately in one toroidal direction. This wave accelerates the high energy electrons in the plasma and so drives a current. It may be used to stabilise sawtooth oscillations, thereby increasing central electron temperature. It is this system for controlling the plasma current profile, which is

Fig.11: First prototype Sliding Impedance assembly installed in the Torus Hall

considered to be the main tool for developing the so-called advanced tokamak scenarios.

During 1998, the LHCD system has been used routinely during operations with the Mark IIGB divertor in optimised shear experiments. Control of the current profile has been explored in the early and high performance phases of such discharges by applying LHCD together with high power NB and ICRF heating. The coupling of the LH waves is sensitive to ELMs which determine the edge conditions in plasmas which combine an Internal Transport Barrier (ITB) with an edge transport barrier in an ELMy H-mode. The optimisation of coupling conditions and the design of new improved launcher structures will be facilitated by a new 2D coupling code implemented at JET during the year. The scenario modelling capabilities have been further enhanced and upgrades of the LHCD plant control systems have improved the reliability of the LHCD system.

Pellet Fuelling

During 1998, the centrifugal pellet injection system was brought online for the first time, with strings of pellets being successfully injected (Fig.12). This required detailed development of the extruder system in particular, the successful demonstration of which was the product of a concerted effort over an extended period.

Helium Exhaust

The Pumped Divertor (PD) cryopump was installed equipped with an Argon Frosting (AF) system which can distribute a spray of argon gas onto the Supercritical Helium (ScHe) cooled tubes of the toroidal cryopump. The purpose of this AF system is to enable helium pumping by cryo-trapping on the argon frost, a process which is well

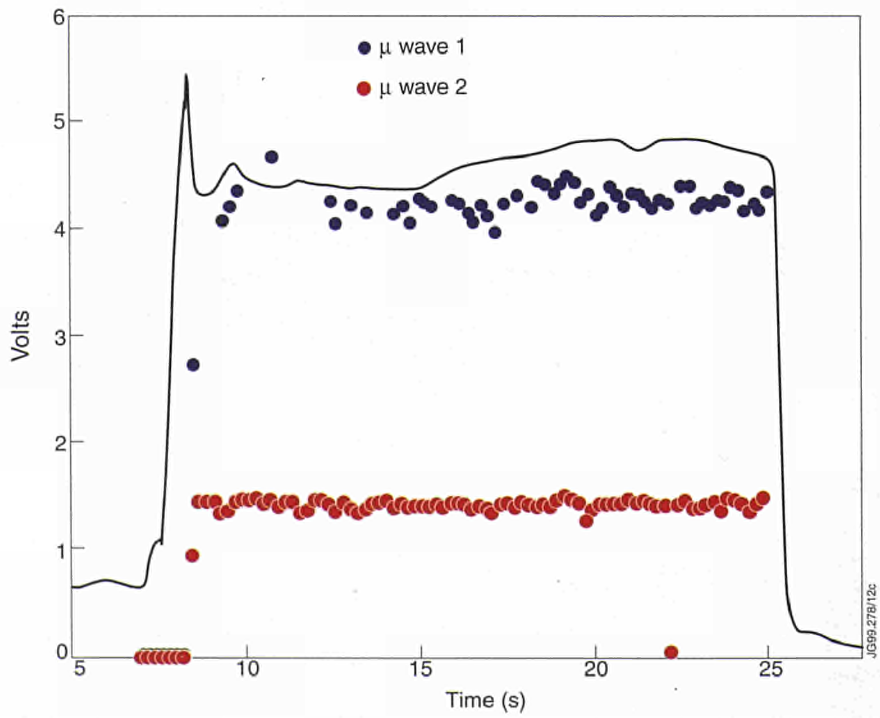


Fig.12: The injection of a long pulse of deuterium ice pellets. The pellets are detected by the μ wave signals. A good pellet string is produced soon after the extruder pressure is raised (solid trace)

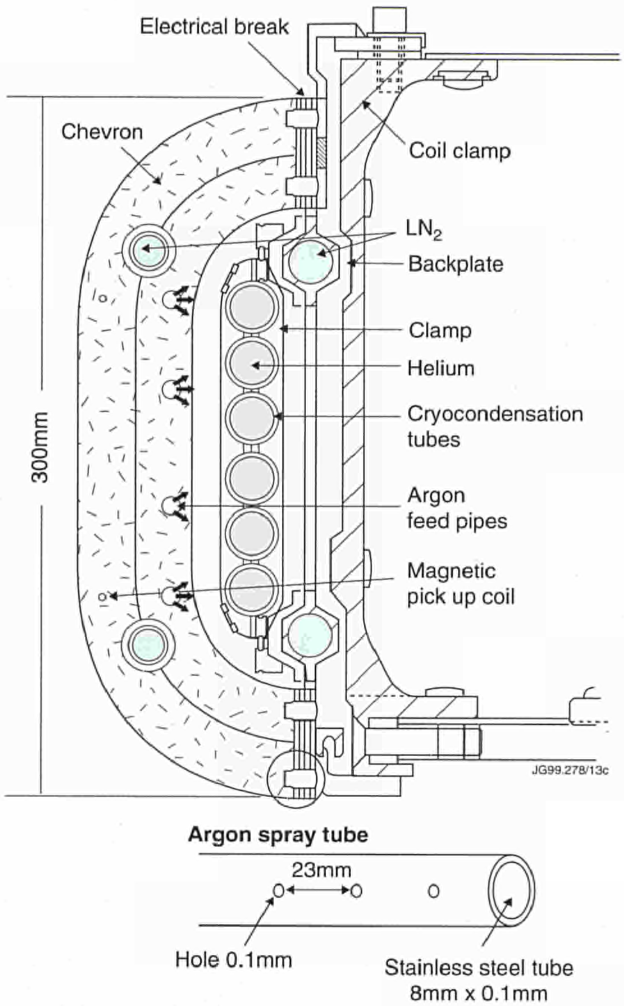


Fig.13: Poloidal cross section through pumped divertor cryopump module showing position of argon spray tubes

known and has been used previously to provide pumping for helium NB injection on JET. The position of the argon spray tubes in the PD cryopump is shown in Fig.13.

The AF system was commissioned in 1994 with the Mark I divertor and it was found that the pumping achieved for helium was about 85% of the pumping speed for deuterium. However, it proved impossible to run plasmas immediately after argon frosting.

With the more closed Mark IIGB divertor, it was decided to re-commission the AF system, to characterise it more carefully and to establish whether or not argon contamination would still be a problem in post-frosting plasmas.

The AF PD cryopump proved to be very successful, allowing discharges to be run immediately after an argon frosting without disruption whilst the frost layer was still pumping strongly. A 30 barℓ load of frost on the pump (equivalent to about 4μm frost layer uniformly distributed on the helium panels) proved to give sufficient pumping for 3-4 plasma pulses in a series of helium transport experiments.

Diagnostics Systems

The status of JET's diagnostic systems at the end of 1998 is summarised in Table 2 and their general layout in the machine is shown in Fig.14. The staged introduction of the diagnostic systems onto JET has proceeded from the start of the operation

SYSTEM	DIAGNOSTIC	PURPOSE	ASSOCIATION
KB1	Bolometer cameras	Time and space resolved and total radiated power	IPP
KB3G	In-vessel divertor bolometer	Time and space resolved radiated power	JET
KB4	In-vessel main plasma bolometers	Time and space resolved radiated power	JET
KC1	Magnetic diagnostics	Plasma current, loop volts, plasma position, shape of flux surfaces, diamagnetic loop, fast MHD	JET
KC1D	Magnetic pickup coils	Magnetic data for equilibrium reconstruction and control	JET
KC1F	Fast magnetic data	MHD analysis	JET
KD1D	Calorimetry of divertor target	Power balance of divertor plasma	JET
KE3	LIDAR Thomson scattering	T_e and n_e profiles in core plasma	JET and Stuttgart University
KE4*	Fast Ion and alpha-particle diagnostic	Space and time resolved velocity distribution of alpha particles and fast ions	JET
KE9D	Divertor LIDAR Thomson scattering	T_e and n_e profiles in X-point plasma	JET
KF1	High energy neutral particle analyser	Ion energy distribution up to 3.5MeV (ICRF minority and fusion products)	St Petersburg
KG1	Multichannel far infrared interferometer	$\int n_e d\ell$ on four vertical chords and four horizontal chords – electron density	CEA
KG3	O-mode microwave reflectometer	n_e profiles and fluctuations	JET and FOM
KG4	Polarimeter	$\int n_e B_p d\ell$ on four vertical chords and four horizontal chords– poloidal magnetic field	JET and CEA
KG6D	Divertor microwave interferometer	$\int n_e d\ell$ on sightline across the divertor plasma	JET
KG7D	Divertor microwave comb reflectometer	Peak n_e on sightline across divertor plasma	JET and CFN IST
KG8A	E-mode reflectometer	Measurement of n_e fluctuations and profiles in edge and SOL	JET and CFN IST
KG8B	Correlation reflectometer	Density fluctuations, electrostatic turbulence	JET
KH1	Hard X-ray monitors	Runaway electrons and disruptions	JET
KH2	X-ray pulse height spectrometer	Monitor of T_e, impurities and LH fast electrons	JET
KJ3	Compact, re-entrant soft X-ray camera	MHD instabilities, mode identification, plasma shapes and impurity transport	JET
KJ4	Compact, in-vessel soft X-ray camera	MHD instabilities, mode identification, plasma shapes and impurity transport	JET
KJ5	Active phase, soft X-ray cameras	MHD instabilities and vertical position sensing, DT compatible	JET
KJ6	Compact VUV camera	Divertor view in VUV	JET
KK1	Electron cyclotron emission spatial scan	$T_e(r,t)$ with scan time of a few milliseconds	NPL, UKAEA and JET
KK2	Electron cyclotron emission fast system	$T_e(r,t)$ on microsecond time scale	FOM
KK3	Electron cyclotron emission heterodyne	$T_e(r,t)$ with high spatial resolution	JET
KK4D*	Electron cyclotron absorption	n_eT_e profile on sightline across divertor plasma	JET
KL1	CCD viewing and recording	Viewing main and divertor plasmas	JET
KL1E	Endoscopes	To allow an unrestricted view of the divertor in the visible and IR	JET
KL2	Impurity flux camera	Impurity influx from the divertor targets with high spatial resolution	JET
KL3.2	Infra-red camera (2 dim)	Divertor tile temperature profiles with high dynamic range	JET
KL6	Colour view of divertor tiles	Colourimetry – used for erosion/redeposition measurements	JET
KM2	14MeV neutron spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distribution	UKAEA
KM3U	2.4MeV time-of-flight neutron spectrometer	Neutron spectra in D-D discharges, ion temperatures and energy distributions	JET and NFR
KM5	14MeV time-of-flight neutron spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distribution	NFR
KM7	Time-resolved neutron yield monitor	Triton burnup studies	JET and UKAEA

* These systems have been put into a non-operational state

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SYSTEM	DIAGNOSTIC	PURPOSE	ASSOCIATION
KM9	14 MeV Neutron spectrometer	Neutron spectra in D-T discharges, ion temperature and energy distribution	NFR
KN1	Time-resolved neutron yield monitor	Time resolved neutron flux	UKAEA
KN2	Neutron activation	Absolute fluxes of neutrons	UKAEA
KN3	Neutron yield profile monitor and FEB	Spatial and time resolved profiles of neutron flux and fast electron Bremsstrahlung	JET and UKAEA
KN4	Delayed neutron activation	Absolute fluxes of neutrons	MoI
KR2	Active phase, neutral particle analyser	Ion distribution function, T(r) and H/D/T flux ratios	ENEA
KS3	H-alpha and visible light monitors	Ionisation rate, Z_{eff}, impurity fluxes from wall and divertor	JET
KS4	Charge exchange recombination spectroscopy	Fully ionized light impurity concentration, T_i and rotation velocities	JET
KS5	Charge exchange recombination spectroscopy	As KS4 plus ion temperature profiles	JET
KS6	Bragg rotor X-ray spectroscopy	Monitor of low and medium Z impurity radiation	UKAEA
KS7	Edge charge exchange	Multichannel measurement of edge poloidal rotation, ion temperature and impurity density	UKAEA
KS8	Polarisation resolved passive spectroscopy	Radially located source measurements from Zeeman splitting of lines	JET
KS9	Motional Stark effect diagnostic	Uses polarisation of Stark components of beam emission to measure pitch angle of magnetic field	JET, UKAEA, PPPL
KT1	VUV spatial scan	Time and space resolved impurity radiation	JET
KT2	VUV broadband spectroscopy	Impurity survey	UKAEA
KT3D	Divertor spectroscopy	Divertor sources in near UV and visible	JET
KT4	Grazing incidence XUV broadband spectroscopy	Impurity survey	UKAEA
KT5P	Divertor gas analysis using Penning gauge	Analysis of divertor exhaust gases	JET
KT6D	Poloidal view, visible spectroscopy of divertor plasma using periscopes	Impurity influx, 2D emissivity profile of spectral lines	JET
KT7D	VUV and XUV spectroscopy of divertor plasma	Impurity influx, ionization dynamics, electron temperature and density	JET
KX1	High resolution X-ray crystal spectroscopy	Ion temperature, rotation and Ni concentration	ENEA
KX2	X-ray crystal spectroscopy	Ion temperature and plasma rotation	JET, Leicester University
KY3	Plasma boundary probes (2 drives: A & B)	Vertical drives for reciprocating Langmuir and surface collector probes, RFA and fluctuation probes	JET and UKAEA
KY4D	Langmuir probes in divertor target tiles and limiters	n_e and T_e at the divertor and limiters, power flux	JET
KY4F	Langmuir probe fluctuations	Turbulence and transport coefficients	JET, IPP, CIEMAT
KY5D	Fast pressure gauges	Neutral flux in divertor region	JET
KY6	50kV lithium atom beam	Electron density in scrape-off layer and plasma edge	JET
KY7D	Thermal helium beams	n_e and T_e in the divertor plasma (together with KT6D)	JET
KZ3	Laser injected trace elements	Particle transport, τ_p, impurity behaviour	JET
Kα1	Thin foil charge collectors	Escaping fast neutral particles	JET
Kγ5 & 8	Gamma rays	Fast ion distribution	JET
CATS	Data acquisition system	Fast ($\leq$1MHz) data acquisition for several diagnostic systems	JET

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Table 2: Status of JET Diagnostics Systems, December 1998

in June 1983. Operational experience on the existing diagnostics has been good and most systems have operated automatically with minimal manual supervision. The resulting measurements have been of high quality in terms of accuracy and reliability and have provided essential information on plasma behaviour in JET.

During 1998, a large number of diagnostics were either re-introduced after being removed for DTE1 (particularly SOL, divertor and fluctuation measurements) or newly-installed together with the Mark IIGB divertor.

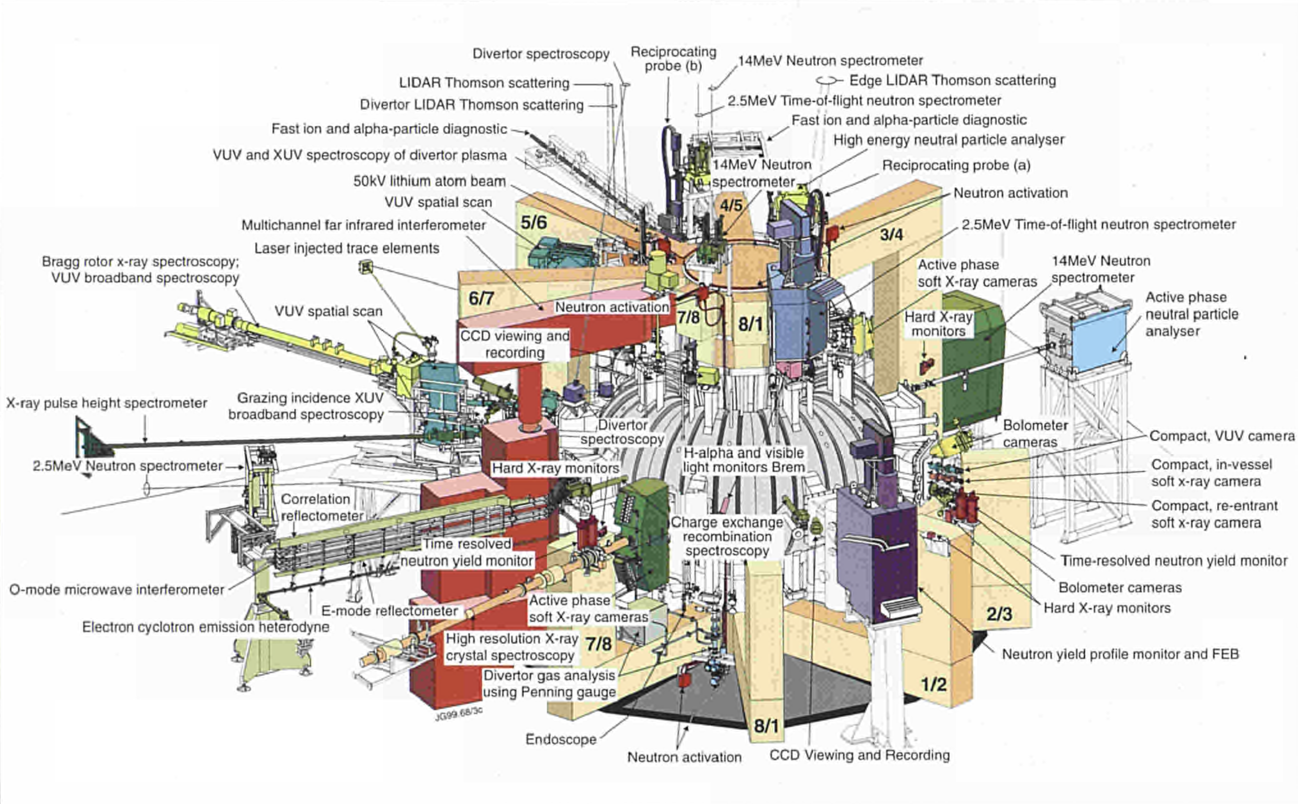


Fig.14: General layout of diagnostics on the machine

Control and Data Management

> **Control and Data Acquisition**
>
> *Due to the high number of components and their distribution throughout a large site, the operation and commissioning of JET is supported by a centralised Control and Data Acquisition System (CODAS). This system is based on a network of minicomputers interfaced to the experiment through distributed front-end instrumentation (including front end micro-processors) and signal conditioning modules. The various components have been logically grouped into subsystems with each one controlled and monitored by a computer. After a pulse, all the information from the subsystem is merged together into a single file on the storage and analysis computer. This file is then transmitted to the IBM mainframe computer for detailed analysis. A summary of information from the JET pulses is held in the JET Central Physics File.*

The JET Control and Data Management System (CODAS) is a fully integrated computer-based system. A network of computers is used for controlling, monitoring, data acquisition and data storage. This network is also used to analyse the data from the tokamak, its power supplies, auxiliary equipment and diagnostic devices. CODAS also provides the following common services: Network Information Services, E-mail, file servers, printing, network monitoring and off-line programme development. These services have grown further and over 120 systems are now in regular use.

JET components and diagnostic devices are grouped into a number of sub-systems. Sub-systems which control/monitor parts of the tokamak and its auxiliary systems are referred to as machine control sub-systems; diagnostic devices are grouped in a similar way into diagnostic sub-systems. Each sub-system is controlled and monitored by one dedicated computer interfaced to the machine and its diagnostics through CAMAC and/or VME instrumentation. Real-time applications are implemented in front-end CAMAC and VME-based processors.

Data collection and transfer to the IBM mainframe has continued to operate well. The amount of data collected per pulse was fairly steady across the year. Figure 15 is a plot of the weekly maximum pulse file size over the last five years.

The mainframe computing service is based on an IBM 9021/821 two-processor mainframe with a vector facility. There are 450 Gigabytes (GB) of disc storage and a further 7200GB of automated cartridge tape storage. The service has been

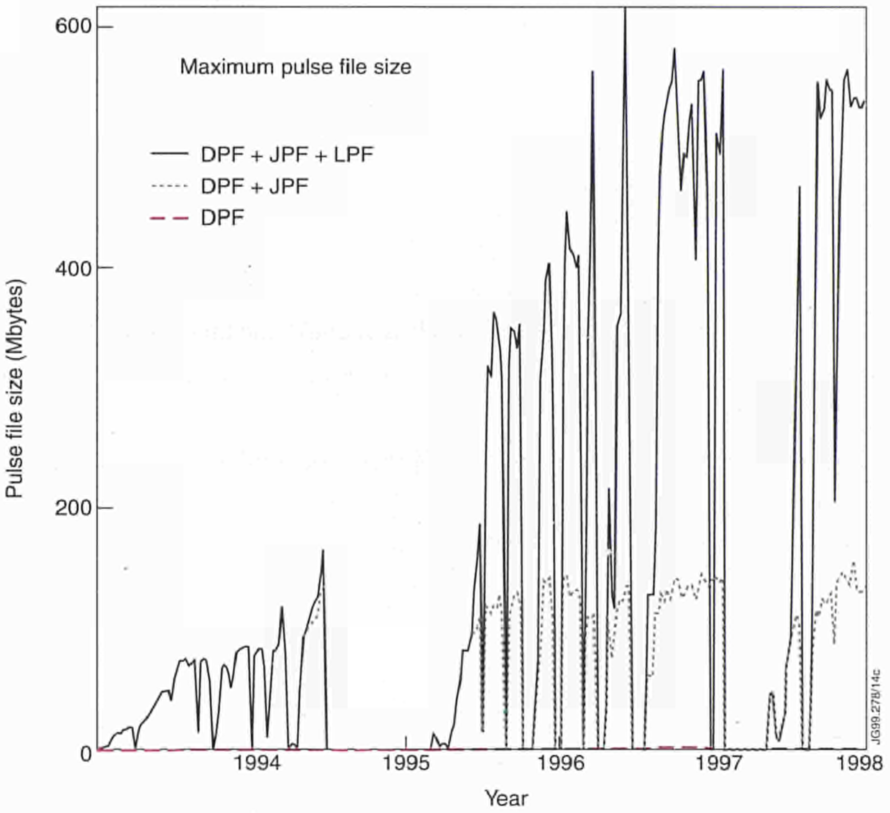


Fig.15: Evolution of the Delayed (DPF), JET (JPF) and Late (LPF) Pulse Files size over the last five years

operating since June 1987, initially based on an IBM 3090/200E dual processor mainframe. This was replaced in February 1990 with an IBM 3090/300J, almost doubling the processing capacity. In August 1997, the central processor complex was replaced over one weekend, with a second user IBM 9021/821 mainframe with 1GB central memory. This gave an immediate factor of three increase in processor speed and an overall doubling of the workload throughput. The software environment was unchanged. Data is transmitted from the CODAS UNIX system to the IBM at speeds of up to 1MB per second ensuring that the data are available for analysis on the mainframe promptly after collection on the CODAS systems. The development of a very sophisticated data archiving and retrieval system based on a cache of 50GB of on-line disc backed by tape storage on the Automatic Tape Library currently accommodates almost 3TB of raw JET data (JPF), which is compressed by a factor of about 2.5 for storage. The total data collected during 1998 was 780GB compared with 982GB in 1997, 524GB in 1996 and less than 200GB in each of the previous two years. The system gives almost instant access to any JPF data that is available on disc (typically about three weeks data production). Data that is less recently accessed is restored automatically from cartridge tape; the average time to access data is less than 3 minutes for any pulse back to 1983.

To provide more power for the more processor-intensive applications that were previously run on the IBM, a network cluster of workstations and purpose-built PCs has been developed since 1994. During 1998, this cluster was enlarged, increasing the overall capacity and reducing turn-around times by a factor of 3.

A large re-arrangement of the CODAS control computer took place during the RTE. Throughout the year work has continued to ensure the readiness of all computer systems and associated software for the year 2000 and to improve remote access to JET experimental data.

Summary of Operations

Operations were dominated during 1998 by the RTE and by the tritiated nature of the machine following DTE1. Other milestones related to the use of the centrifuge pellet injector and the toroidal field upgrade for 4T operation. Pulse conditions were restricted somewhat by the temporary loss of one of the three main 400/33kV transformers which, following extensive repair at the factory, will be returned to JET in January 1999.

During the year a number of incidents affected operations. These included a freon leak in the basement from a divertor pump flange; a drain of in-vessel water cooled circuits and the consequent cool-down of the machine as a result of a faulty flow signal; the inadvertent venting of the pellet centrifuge; site power loss events as a result of supply faults external to JET; and failure of a coupling drive shaft which resulted in misalignment of the Torus Hall shielding beam.

At the beginning of the RTE 6.2g of tritium remained inside the vacuum vessel. This had fallen to about 2.5g by the end of the RTE. Levels continue to fall at the

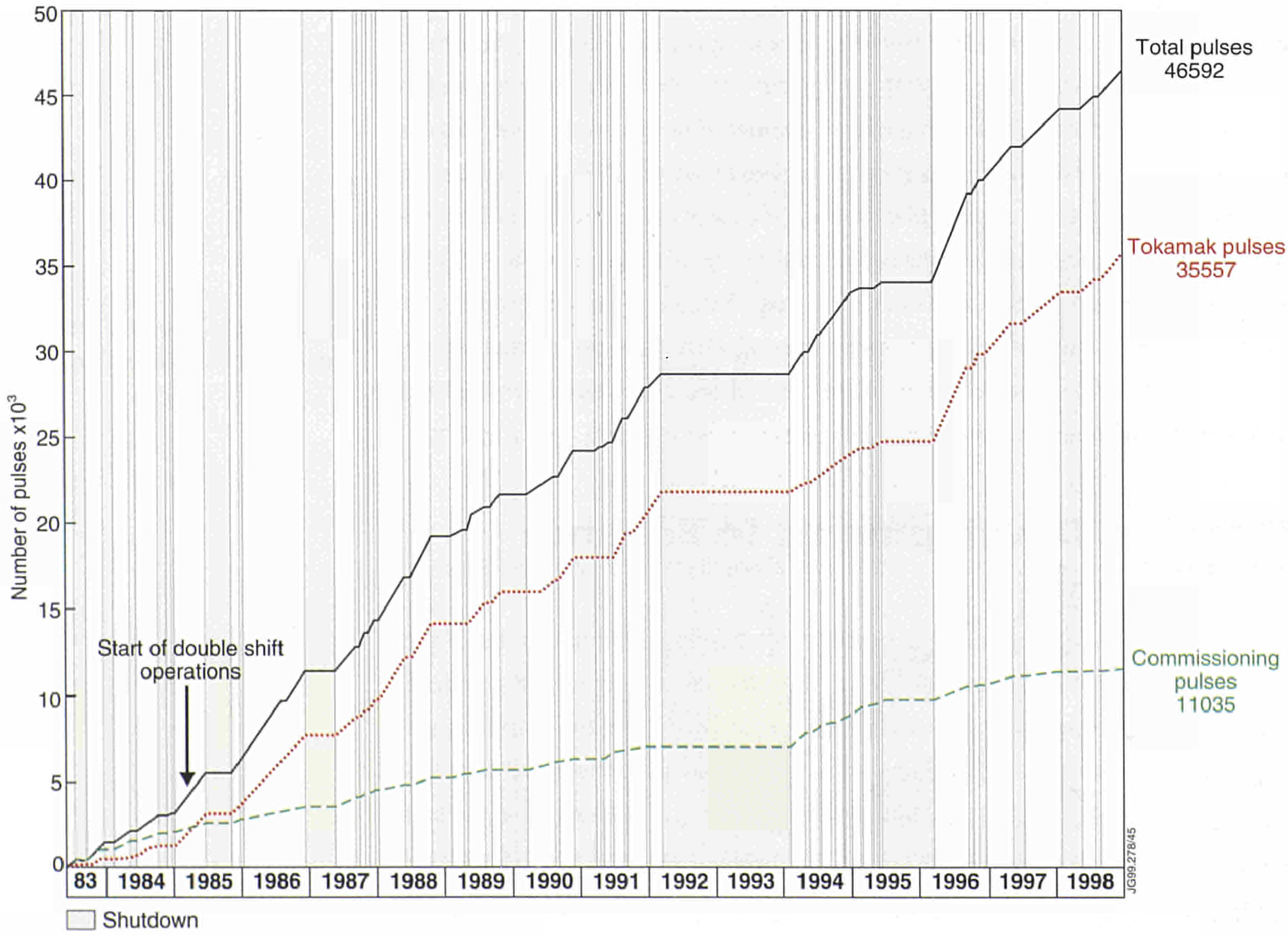


Fig.16: Cumulative total of JET Pulses: 1983-1998

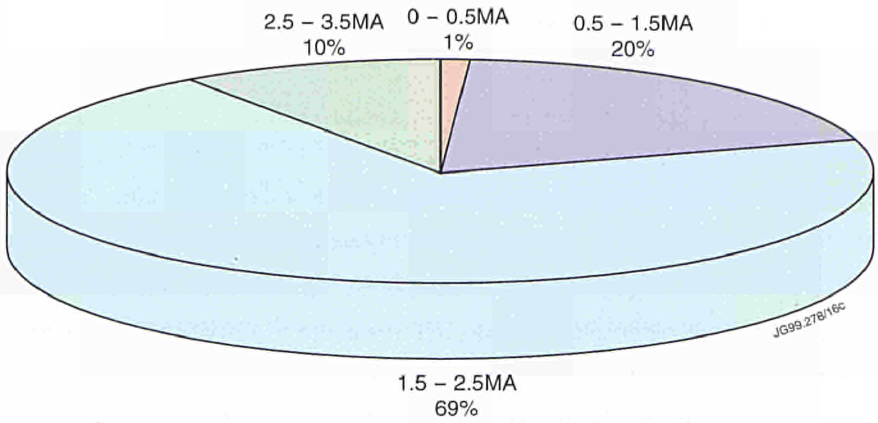


Fig.17: Distribution of pulses in 1998 according to plasma current

rate of 8mg per week, and it is estimated that there was approximately 2g remaining inside the vacuum vessel at the end of the year. Currently, Torus Hall tritium levels are about 0.04DAC and stack discharges remain well within authorisation and site management limits.

The JET machine and its major auxiliaries such as the cooling circuits, NB injectors and many diagnostics are now contaminated with tritium and continue to be treated with precautions similar to those applied during DTE1. In particular, the Torus Hall continues to be treated as a Radiation Controlled area, and the depression system is continuous in operation when the vessel temperature is greater than 150°C; this requires the use of the air locks for access to the area.

Despite a significant loss of staff during the year, the daily pulsing rate for experiments remained constant, the overall number of pulses being lower than in 1997 primarily by the lower number of operational days in 1998. The number of successful pulses in 1998 was 2826, including Task Force Pulses, Restart pulses and technical commissioning pulses. The overall distribution of pulses over the 1983-98 period is shown in Fig.16. An analysis of the distribution of pulses according to plasma current is shown in Fig.17. In comparison with 1997, the percentage of high current pulses is lower, mainly due to the removal of one of the three transformers which limited operational flexibility.

Technical Developments to Enhance Performance

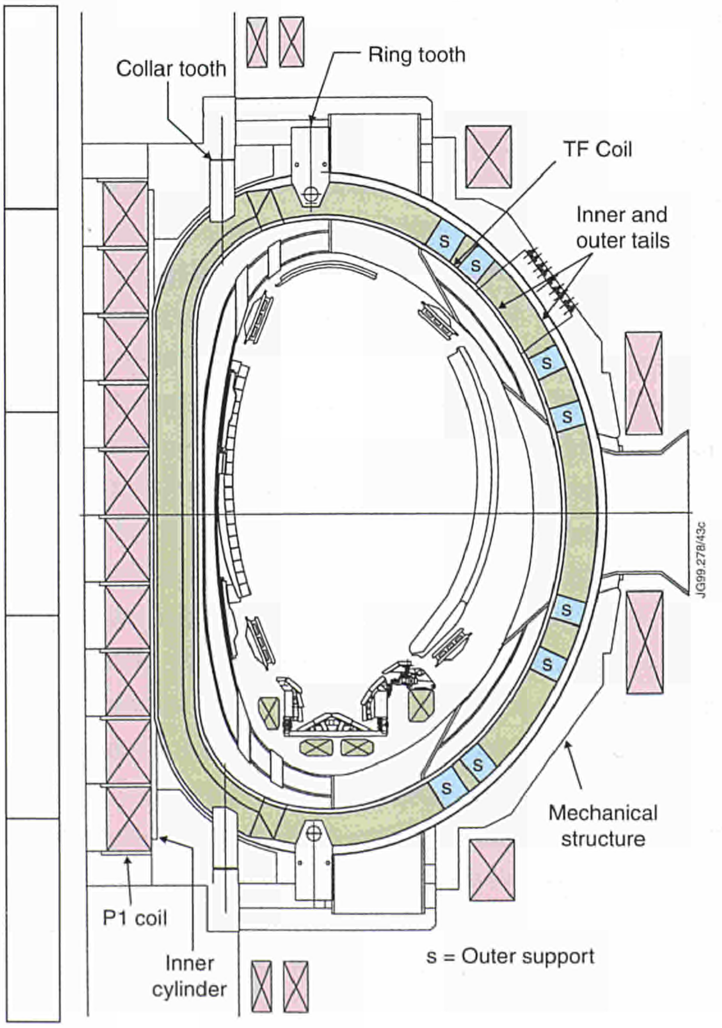
During the year studies continued on possible enhancement options of some of the JET sub-systems. It was considered that the toroidal magnetic field could be increased from the present 3.45 Tesla to a value of about 4 Tesla, the output power of the neutral beam injectors could be improved by increasing the power supplies from 80kV at 60A to 120-140kV at 60A, and the efficiency of shallow pellet fuelling could be increased by injecting pellets from the inboard (high field) side of the torus.

Upgrading of the Toroidal Magnetic Field to 4 Tesla

JET has operated throughout most of its lifetime at a toroidal magnetic field of up to 3.45T. Plasma performance improves with increasing magnetic field and this was demonstrated during DTE1 when, subject to strict controls, the highest performance was achieved at 3.6T. During 1998, the major reassessment of the basic machine (i.e. the toroidal coils, the mechanical structure and the vacuum vessel) continued to prove that the toroidal field could be safely increased to 4T, with a plasma current up to 5.0MA, without replacing or modifying any of the subsystems.

JET has 32 toroidal field copper coils, each made up of two adjacent pancakes with 12 turns each. Each coil is subject to a net inward force which is reacted along the straight section by the inner poloidal coils (P1): both tension and the inward force are proportional to the square of the toroidal field (B_T^2). The lateral forces on the coils, caused by the interaction of the coil current with the poloidal magnetic field, are supported by the mechanical structure in 12 positions along the coil (Fig.18). The areas of main concern are the collar teeth (full support could not be installed due to the lack of space), the ring tooth (due to the limited stress

Fig.18: Cross-section of JET showing toroidal coil supports



capability of the teeth bolts) and the coil "tails" (where the windings cross over from in-going to out-going pancakes). The forces on the mechanical supports of the coils and the stresses on the coils, generally reach maximum values in equilibrium and decay during disruption.

Forces and stresses have been calculated for the reference combination of 4.0T/5MA, for the main operating scenarios, in equilibrium and following a disruption event. Analysis and testing has now demonstrated that stresses arising in all areas of the coils, apart from the coil tails, are safely within the allowable stresses derived from tests on samples cut from the used coil for a range of interesting scenarios. All scenarios are assessed before being approved for operation and protective hardwired limits are maintained for the transverse and in-plane forces on the coils.

The coil tails, rather than the winding itself, support the hoop stress at the cross over. The coil tails carry no current and thus remain cold during the pulse. The resulting thermal stress combines with the mechanical stresses to produce a local concentration of shear stress in the epoxy at the tail tip. The mechanical stress depends on the TF field, whilst the thermal stress depends on the total energy dissipated in the coil. Thus, the increased mechanical stress at 4T can be compensated by reducing flat top duration and thus the energy dissipation. The stress, nonetheless remains close to the allowable. As a result, only a limited number of 4T pulses is presently foreseen, equivalent in fatigue to 10% of the total operation of JET to date. Further analysis and modelling of the tails is continuing.

Another area of concern is the interpancake transition element. Several models have been developed to determine the copper and the butt brazed joint tensile stresses, and the epoxy shear stresses up to 4T. These models gave consistent results, showing acceptable stresses.

Unlike the TF coils, where forces and stresses mainly arise in equilibrium, in the vacuum vessel, major forces and stresses arise as a consequence of plasma disruptions. Therefore, the allowable stresses can be set for a limited number of disruptions. During such events, the vacuum vessel demonstrates essentially two kinds of oscillatory movements: a rolling motion (at about 15Hz) around the toroidal axis and a sideways motion (at about 5Hz). The rolling motion is due to the centre of force being inboard of the vessel vertical supports and scales approximately as the square of the plasma current. Extrapolating the worst case disruptions to date gives a displacement of 6.5mm at 5MA/4T. The sideways motion of the vessel is caused by a net radial force. The maximum force and the consequent displacement scale essentially as $B_T I_p$ and it is transferred from the plasma to the vessel by eddy and halo currents. Extrapolation to 5MA/4T gives a worse case displacement of 15mm.

Detailed modelling of the geometry of the vessel and its supports have been made and used to calculate the stress distribution in critical areas. The most critical area is predicted to be the weld joining the Main Vertical Ports (MVPs) with the outer shell of the vacuum vessel. Fatigue testing of the material and detailed computer analysis have given the relationship between measured displacements, applied loads and number of cycles to failure.

The finite element model used to predict the critical stress has been improved by inclusion of the webs between the shells of the vessel. This stiffens the port, reducing the displacement due the radial force by a factor two, and the peak stress controlled by this displacement by a similar amount. This strongly reduces the fatigue of the port to a level which is not important for the few worst case disruptions which would be allowed.

Design studies have also been carried out into additional supports for the vacuum vessel which would reduce the movement in asymmetric disruptions. In particular, additional dampers could be fitted to allow the vacuum vessel to be locked to the mechanical structure during installation. Dampers using highly viscous material rather than oil have been tested and demonstrated to have the required performance.

During the RTE, the toroidal magnetic field power supplies were upgraded for operation at 4T and, towards the end of the year, three 4T pulses with plasma were run successfully.

Enhancement of the Neutral Beam Heating System

Experiments conducted in the Neutral Beam Test-bed, using a prototype modified accelerator structure have demonstrated the capability of increasing the ion beam current from the present 30A to 60A at 120-140kV. This would lead to an enhancement of injected power, delivering up to 15.4MW to the plasma. While minor modifications would be required to the NB injectors, additional power supplies would be required, since the present supplies are for 60A at 80kV or for 30A at 160kV. In view of costs, it has been decided to consider upgrading the power supplies to 60A at 120-140kV.

An extensive engineering analysis has shown that the PINI Ion Source and the Full Energy Ion dumps, both of which would receive increased power loadings in an upgraded injector, are capable of handling the power without being upgraded themselves. On the other hand, design limits for the Box (or exit beam) Scrapers in the Neutral Injector Box would be exceeded for both power density normal to the surface of the hypervapotron elements (10MWm^{-2}) and intercepted power per PINI (250kW). During 1998, new Box Scrapers, designed to accommodate an injector power of 15.4MW, have been maunfactured for delivery in 1999.

In addition, the high current PINIs, already in use on the Octant No.4 injector (injecting 13MW of deuterium at 80kV), will be refurbished with new components to correct a "cross-eyed" effect beginning to develop in some PINIs. These will be introduced in a staged programme starting in 1999 and, in conjunction with the new Box Scraper, should permit use of the full available power.

Finally, two PINIs will be modified in 1999 by raising their operating voltage to 85kV to permit a better diagnosis of the plasma current profile using the Motional Stark Effect.

High Field Side Pellet Fuelling

One of the main disadvantages of shallow pellet fuelling by strings of deuterium ice pellets at modest velocity (≲500ms^{-1}) is the observed degradation of fuelling efficiency as the heating power applied to the plasma is increased. This is observed in general for pellets launched at the outboard (Low Field Side - LFS) of the plasma. The effect is mainly due to the shallower penetration of the pellets as the plasma temperature is increased. More recently, pellets injected into plasmas in other tokamaks (eg. ASDEX Upgrade, DIII-D) from the High Field Side (HFS) have improved fuelling efficiency even at low pellet injection speeds (about 130ms^{-1}).

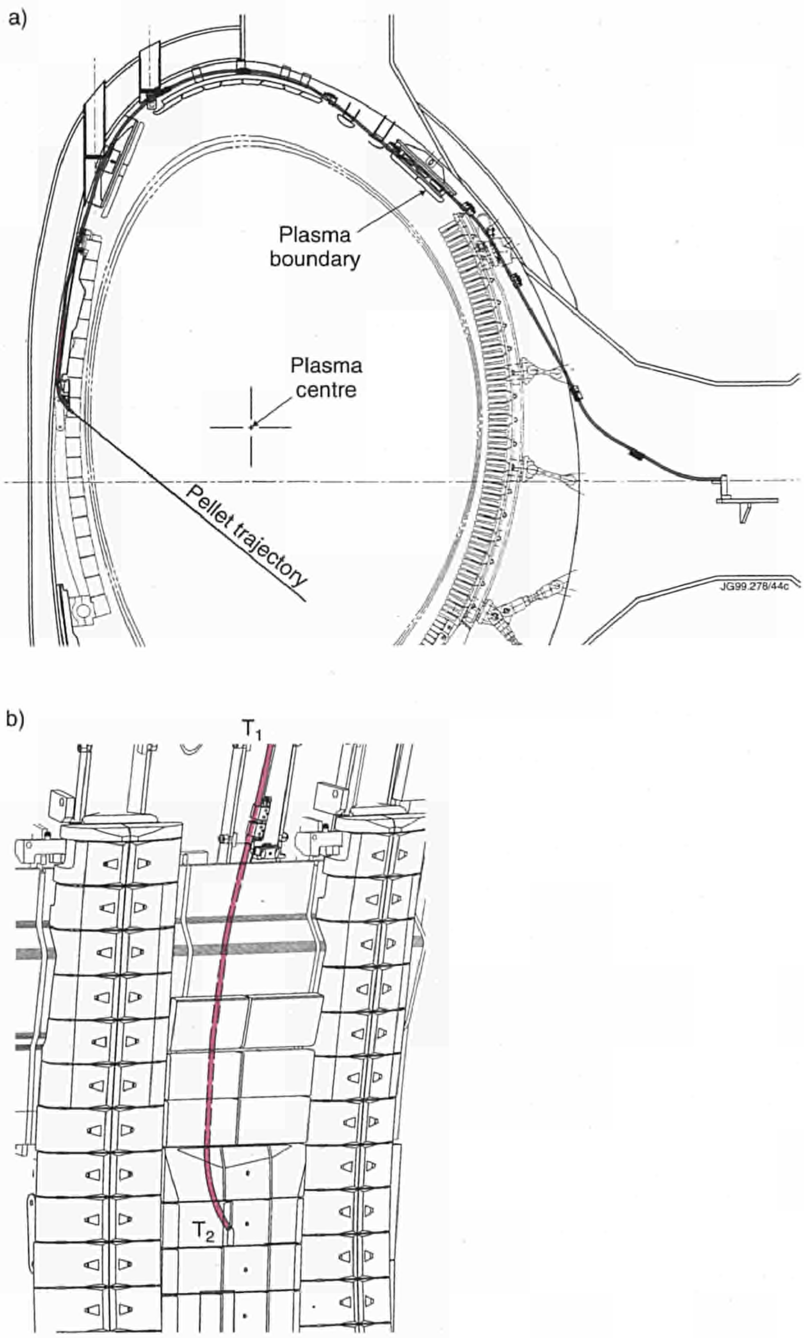
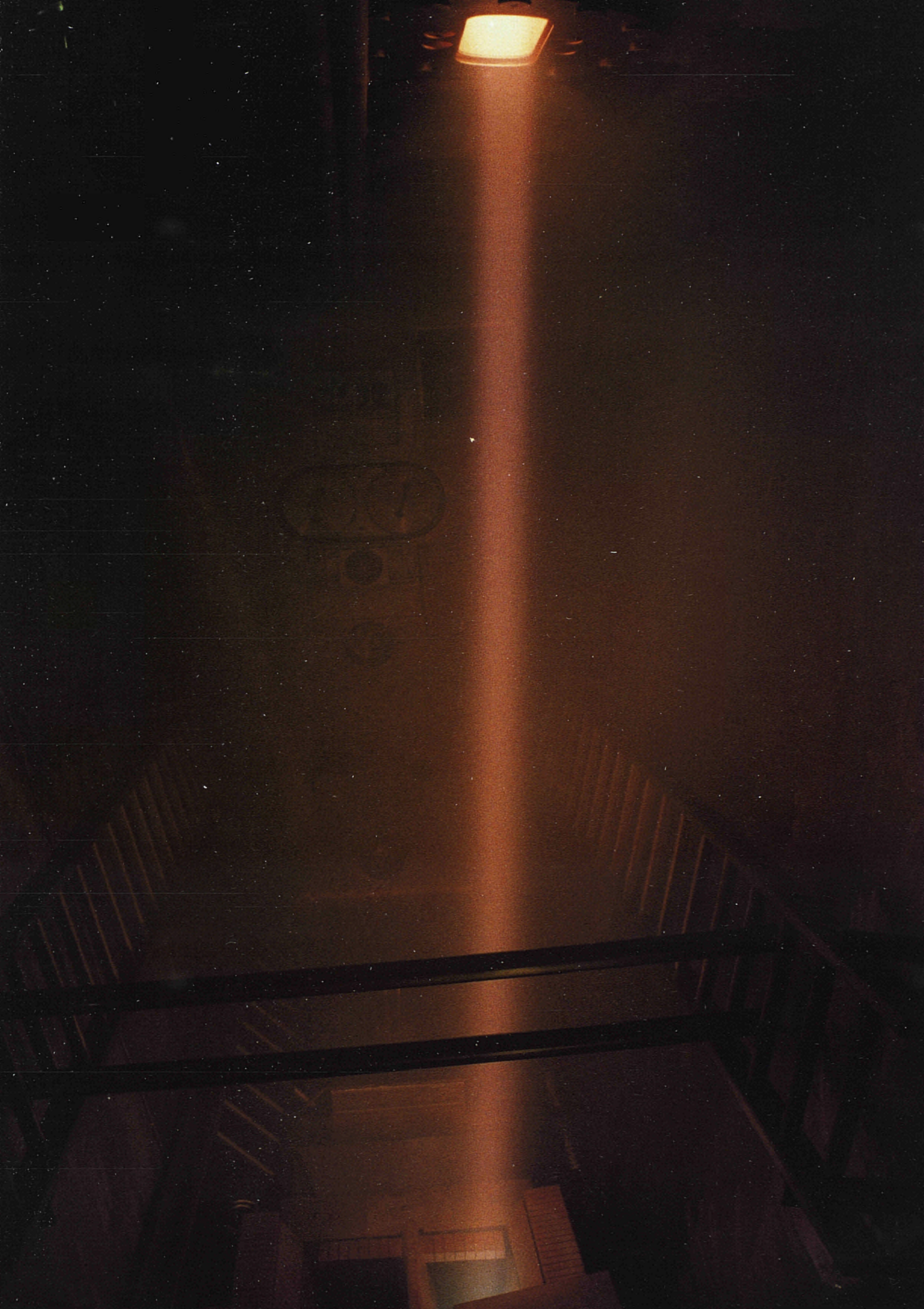


Fig.19: (a) Track layout (shaded) for High Field Side (HFS) Pellet Launch above the midplane. The track shown is 12mm (outside diameter), 10mm (inside diameter) for 4mm pellet injection; (b) Track layout for HFS Pellet Launch above the midplane. The track passes behind protective tiles from T_1 to T_2

Subsequent to the RTE, JET technical effort concentrated on the preparation for the installation of an in-board pellet injection system. The JET Pellet centrifuge will be used as the pellet source and a track will be installed to run poloidally around the torus in-vessel from the main horizontal port on the outer wall to the inner wall, where it will inject the pellets near radially (Fig.19). In addition, a new electro-mechanical pellet selector (part of a new external flight tube) will allow selection between HFS and LFS injection. Radiation levels in the torus require the bulk of the installation to be carried out remotely, although the levels will have dropped sufficiently (350μSv/hr) by the end of the 1999 shutdown to allow manned access for about 1 week for final connection in-vessel. In many respects this is a more challenging operation than the RTE as this work had not been conceived previously and no provision had been made in-vessel for this RH operation. This again represents an important demonstration of a RH technology which could be used for unplanned interventions in future devices.



Scientific Advances during 1998

Introduction

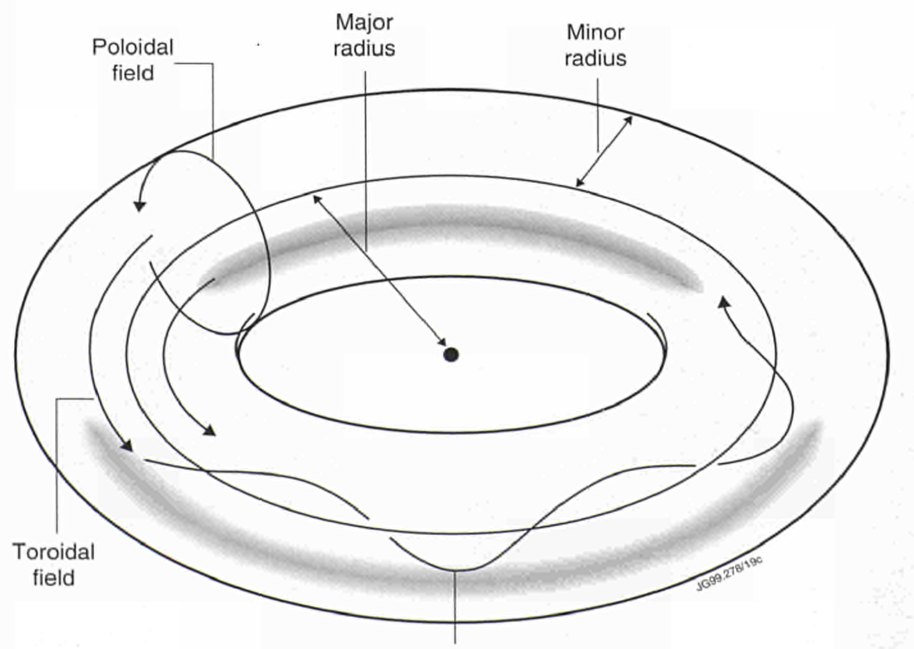
The overall objective of the Project is to study plasma in conditions and with dimensions close to those needed in a fusion reactor. The central values of temperature, density and energy confinement time required for a reactor operating with deuterium and tritium are such that the fusion triple product, ($n_i\tau_E T_i$), must exceed the value of $5x10^{21}m^{-3}$skeV. Typical individual values for these parameters, in a reactor, are central ion density (n_i) of $2.5x10^{20}m^{-3}$, central ion temperature (T_i) of 10-20keV and a global energy confinement time (τ_E) of 1-2 seconds. With ohmic heating alone in JET, temperatures of 3keV and 4keV for the ions and electrons, respectively, densities of $4x10^{19}m^{-3}$ and energy confinement times of 1s are the limits that have been achieved. These parameters were obtained simultaneously during one discharge and resulted in a fusion product of $1.2x10^{20}m^{-3}$keVs. However, higher peak values of electron and ion temperature have been reached using additional radio frequency heating and neutral beam heating and

Magnetic Field Configuration

The toroidal and poloidal magnetic fields combine to form helical magnetic field lines, which define a set of magnetic surfaces. As the strengths of the magnetic fields vary across the minor cross-section of the machine, the pitch of the field lines vary and usually decrease with increasing minor radius. The number of turns a field line must traverse around the major direction of the torus, before closing on itself, is denoted by the safety factor, q. Of special importance are the positions where q is numerically equal to the ratio of small integers, as these regions are specially sensitive to perturbations. Instabilities arising from these perturbations can result in enhanced energy losses.

In addition, the maximum plasma pressure, which can be maintained by a given magnetic field is dependent on the plasma current value. The effectiveness with which the magnetic field confines the plasma is given by β, which is defined as the ratio of plasma pressure to the magnetic field pressure.

JET can be operated with elongated plasma cross-section rather than circular. This enables larger plasma currents to be carried for given values of magnetic field, major radius and minor radius, as well as producing larger values of β.



Resultant helical field (exaggerated pitch) combinations of these methods. Even so, these substantial increases in temperature were associated with a reduction in energy confinement time as the heating power was increased. Thus, gains in plasma temperature have been partly offset by degradation in energy confinement time. The fusion product values obtained have not shown the full gains anticipated over conditions with ohmic heating alone. However, a substantial increase in the values of the fusion product has been achieved, by operating in the so-called magnetic limiter (X-point) configuration. During the 1991/92 campaign, values of 9-10x$10^{20}m^{-3}$skeV were obtained using up to 16MW of additional heating.

Higher values of temperature, density and energy confinement have been obtained individually in separate experiments, but not simultaneously during one discharge. These include peak ion temperatures up to 38keV, energy confinement times up to 1.8s and central densities up to 4x$10^{20}m^{-3}$.

The strategy of JET is to optimise the fusion product by building up a high density, high temperature plasma in the centre of the discharge, while still maintaining an acceptably high confinement time. These conditions should ensure that sufficient alpha particles are produced during deuterium-tritium operation so that their confinement and subsequent heating of the plasma can be studied.

The original scientific programme of JET was divided into four phases. The Ohmic Heating, Phase I, was completed in September 1984 and Phase II - Additional Heating Studies - started early in 1985. By December 1986, the first part, Phase IIA, had been completed. The machine then entered a planned shutdown for extensive modifications and enhancements before the second part of the Additional Heating Studies, Phase IIB, which started in June 1987. The objective of this phase, from mid-1987 until late-1988, was to explore the most promising regimes for energy confinement and high fusion yield and to optimise conditions with full additional heating in the plasma. Experiments were carried out with plasma currents up to 7MA in the material limiter mode and up to 5MA in the magnetic limiter (X-point) mode and with increased radio frequency heating power up to 18MW and neutral beam heating power exceeding 20MW at 80kV.

The ultimate objective was to achieve full performance with all systems operating simultaneously. Phase III of the programme on Full Power Optimisation Studies started in 1989 and was completed in early 1992. In 1991, JET's lifetime was prolonged by four years until the end of 1996. The extension was to allow JET to implement the new Pumped Divertor Phase of operation, the objective of which was to establish effective control of plasma impurities in operating conditions close to those of the Next Step. In mid-1996, the lifetime of the Project was further extended to the end of 1999 to enable significant contributions to be made to the development and demonstration of a viable divertor concept for ITER and to undertake experiments using D-T plasmas in an ITER-like configuration. The centre piece of operations in 1997 was a period of D-T operation (DTE1) during which JET carried out a broad-based series of D-T experiments, setting new world records for fusion power production (16.1MW), fusion energy (22MJ), fusion duration (4MW for about 4s) and Q, the ratio of fusion power produced to input power (0.62, and

Breakeven

This condition is reached when the power produced from fusion reactions is equal to that necessary for maintaining the required temperature and density in the plasma volume.

Ignition

Ignition of a mixture of deuterium and tritium would be reached if the power produced by the alpha particles (20% of the total thermonuclear power) released from the fusion reactions is sufficient to maintain the temperature of the plasma.

Operating Modes

Under normal operating conditions the magnetic surfaces are nested inside each other. The edge of the plasma is defined by the magnetic surface which intersects the limiter. The only magnetic field lines intersecting the walls of the chamber are those beyond the region bounded by the limiters as shown in the diagram on the left. This is termed material limiter operation.

The magnetic field configuration on JET can be modified so that one of the closed surfaces near the limiter is opened up so that it intersects with the vacuum vessel wall. In this configuration, the magnetic separatrix is moved to within the vacuum chamber.

This so-called X-point configuration (or magnetic limiter) can be operated with the two nulls of the separatrix within the vacuum chamber (double null) or with only one inside (single null) as shown in the diagram on the right.

During X-point operation with additional heating, the plasma can behave, with respect to confinement, as though its edge were bounded by limiters. This is called the Low (L)-mode. Under certain circumstances, the plasma can be induced to behave in a different manner which produces better plasma confinement. This is termed the High (H)-mode of operation.

0.95±0.17 if the same plasma conditions could be achieved in steady-state). Following DTE1, the third stage in the divertor programme on JET began with the installation by remote handling of the Gas Box (Mark IIGB) divertor and continued with experiments specifically for ITER. This programme will be pursued before the final phase of full D-T operations in JET.

Main Scientific Results

The main objectives of the 1998 campaign were:

(a) the ITER Urgent Physics Mission, which had the objective of reducing the uncertainties in extrapolating to ITER the steady state ELMy H-mode (the standard mode of operation foreseen for ITER);

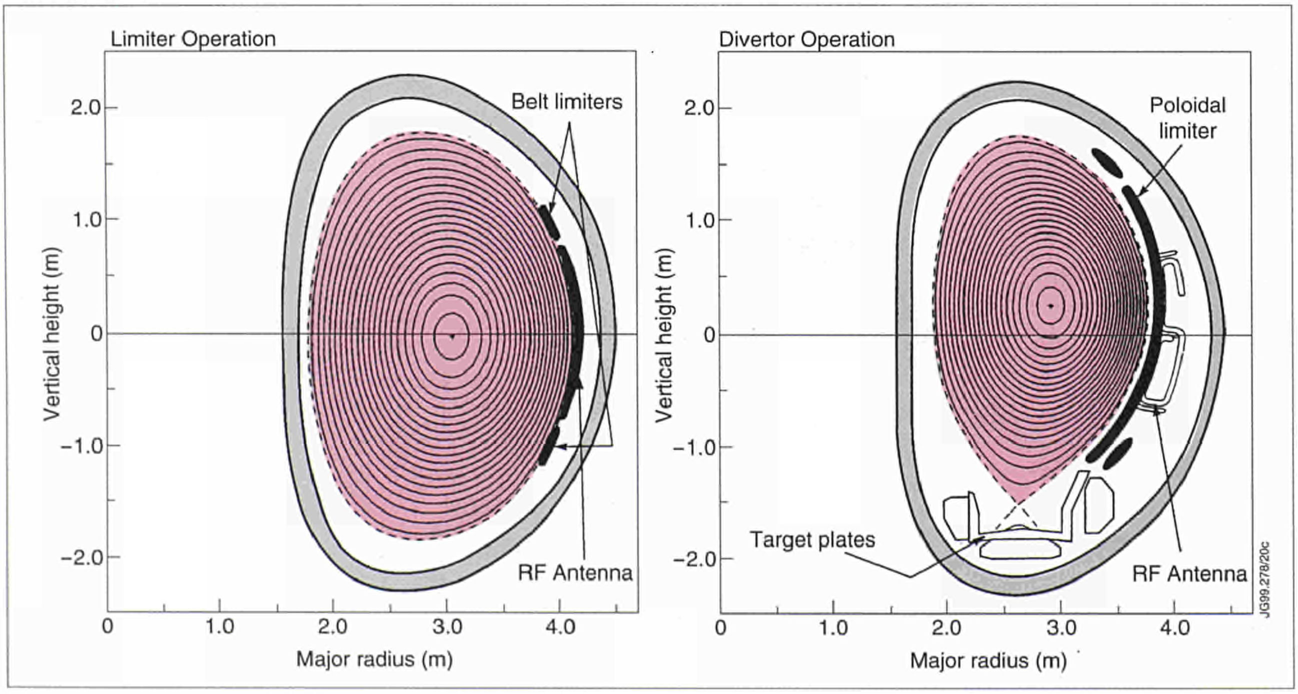
b) the ELMy H-mode Physics Mission for ITER, which had the objectives of characterising the Mark IIGB divertor with the general aim of advancing understanding of the optimum divertor concept for ITER, of studying plasma edge and divertor physics and of studying confinement near and away from boundaries (that is, at high density and high radiated power); and

c) the Performance Optimisation Physics Mission for JET and ITER, which had the objectives of undertaking physics/scaling experiments to improve understanding of Internal Transport Barriers and MHD stability limits, to validate models, to explore routes to quasi steady-state at high performance and to maximise fusion performance.

These are described below.

ITER Urgent Physics Mission

The aim of these experiments was to reduce the uncertainties in extrapolations to ITER by obtaining improved data on confinement, H-mode threshold power,



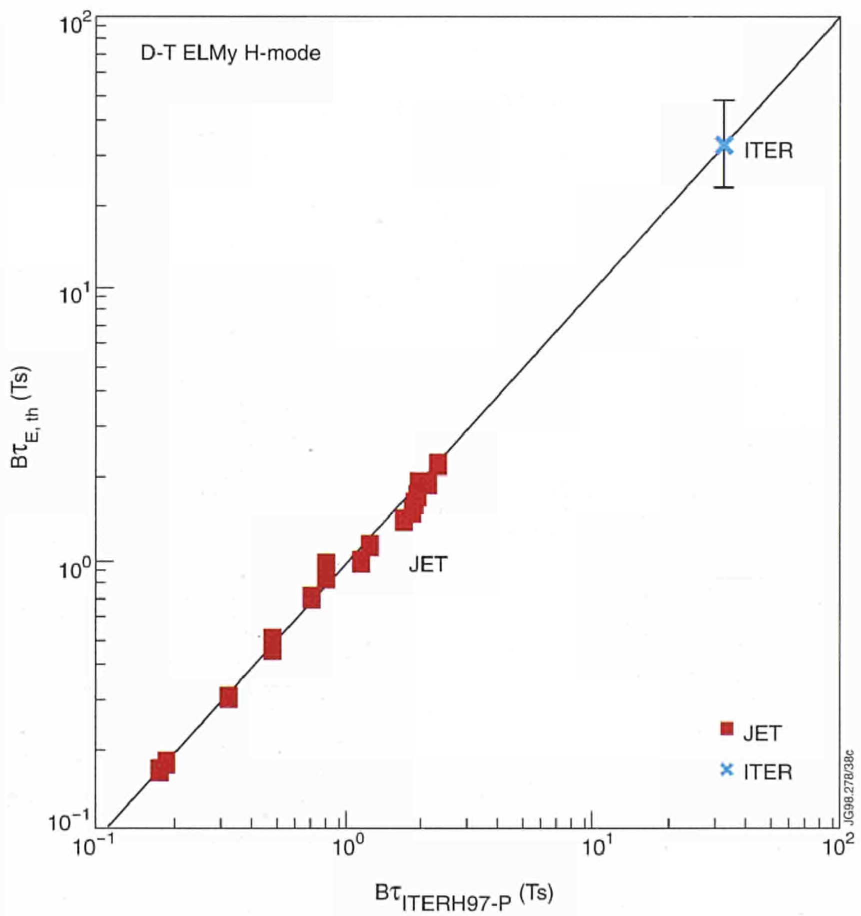
divertor behaviour and stability in ITER-like plasmas in hydrogen and deuterium. Of particular note were the following energy confinement scaling experiments and the studies which aimed at defining a coherent operating scenario for ITER.

Energy Confinement in ELMy H-modes

The global properties of the JET steady-state ELMy H-mode (the standard operating mode forseen for ITER) are well described by the ITERH97-P scaling expression used to predict the confinement time in ITER (Fig.20). Although the form of this scaling is close to that expected from theory (gyro-Bohm), the mass dependence is different. This can be reconciled by separating the global energy (Fig.21) into contributions from the plasma core (Fig.22 shows the expected theoretical gyro-Bohm scaling) and a plasma pedestal (which is determined by the edge temperature and density, is affected by edge radiation and edge stability, and has a different scaling to the core).

Dimensionless Scaling Confinement Studies

Identity experiments carried out in collaboration with ASDEX Upgrade, DIII-D and ALCATOR C-MOD keep all dimensionless parameters (such as the normalised scale size, ρ*, pressure, β, collisionality, ν*, safety factor, q and plasma shape) constant and confirm the validity of this scaling approach to transport.



Energy Confinement

Energy confinement in tokamaks when the plasma is bounded by a material limiter generally degrades as the input power to the plasma increases. The result is that the energy confinement time, τ_E falls approximately as the square root of the input power. This regime is said to exhibit low L-mode confinement. In plasmas with a magnetic limiter (that is with an internal magnetic separatrix or X-point), a transition can occur above a certain threshold input power to a regime in which the energy confinement time is increased by a factor of two or more greater than in the L-mode situation. This has been called high H-mode confinement. However, a similar degradation with input power is observed.

In addition to the improved energy confinement time, enhanced particle confinement is observed and the temperature and density close to the separatrix can increase substantially, resulting in the formation of plasma profiles with an edge 'pedestal'. The precise conditions for the transition into the H-mode vary with plasma parameters. For example, the threshold power for the transition increases at least linearly with the toroidal magnetic field. In recent years, the H-mode transition has also been observed in plasmas with a material limiter, although the power threshold is usually significantly higher than in magnetic limiter (X-point) plasmas.

Fig.20: Experimental data for the normalised thermal energy confinement time ($B\tau_{E,th}$) versus the ITERH97-P scaling

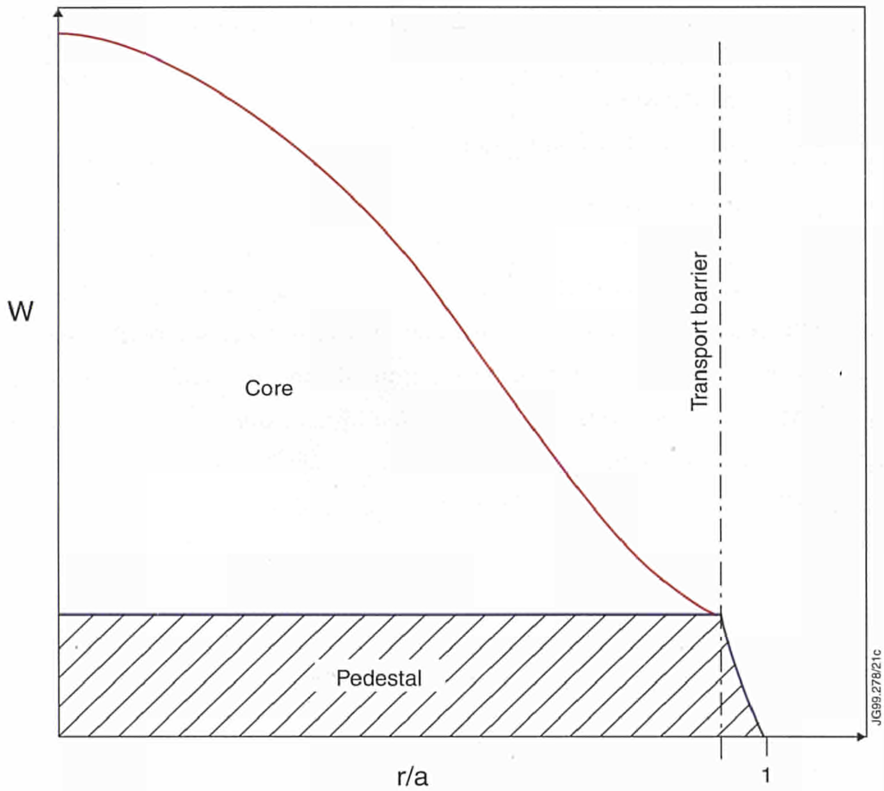


Fig.21: A schematic representation of the stored energy density versus radius. The shaded region is the stored energy in the pedestal and the unshaded region is the stored energy in the core

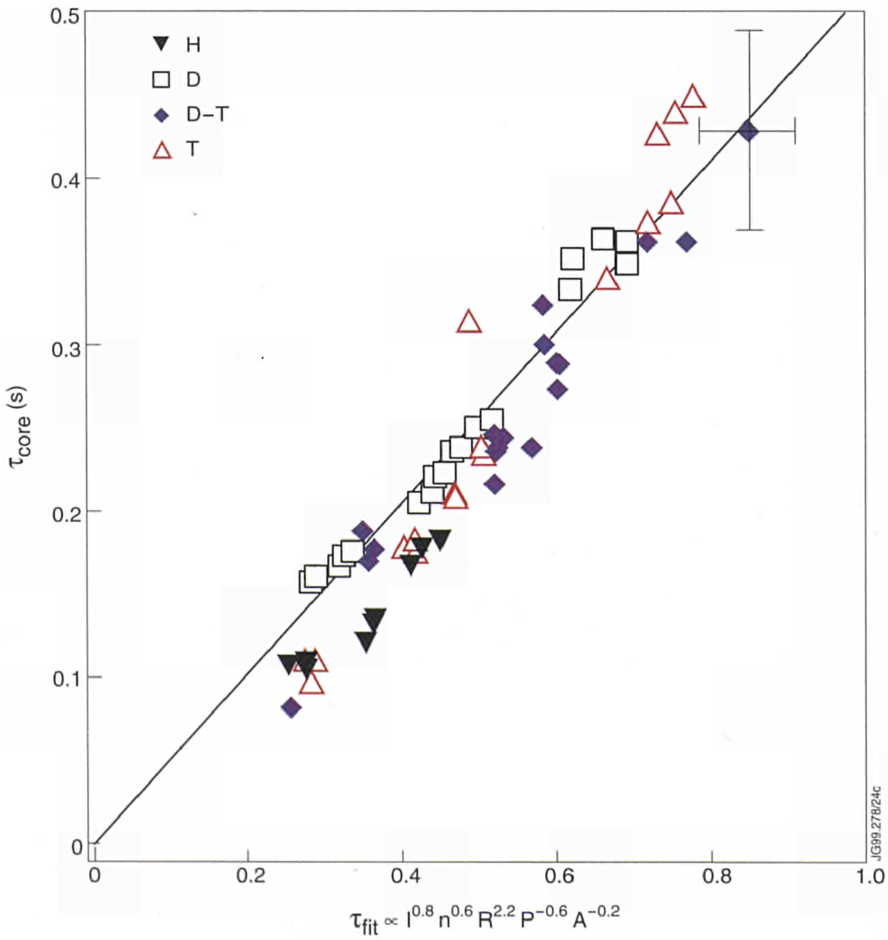


Fig.22: Core energy confinement time versus the pure gyro-Bohm fit

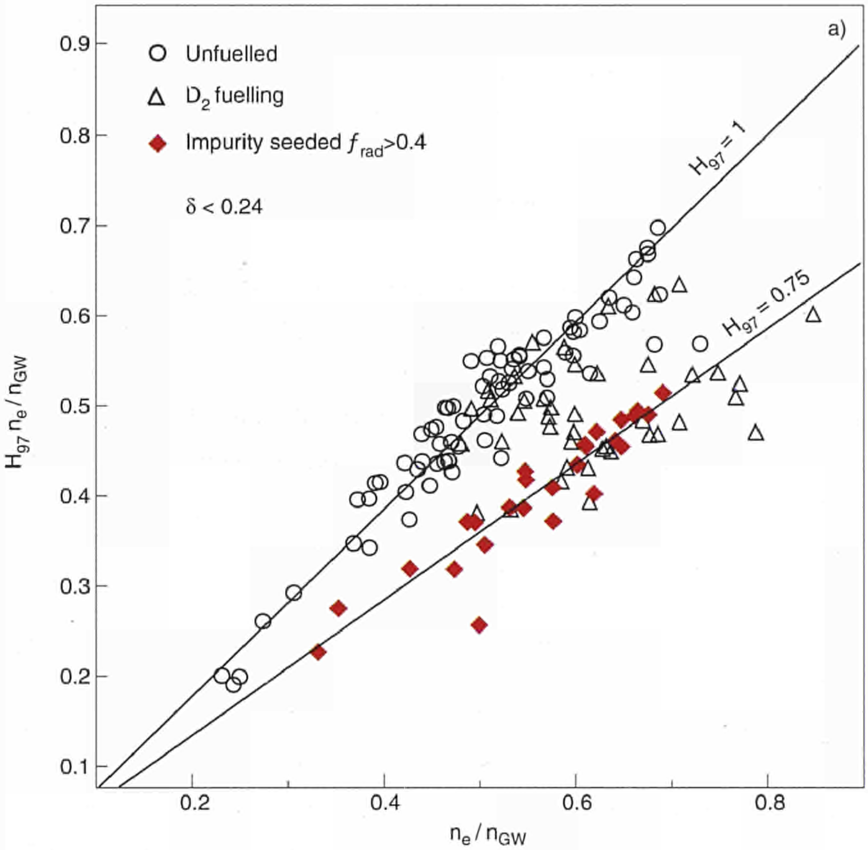


Fig.23(a): Normalised $n_e\tau_E$ versus density normalised to the Greenwald limit, n_{GW}, for unfuelled, impurity seeded and D_2 fuelled H-modes in the Mark I and Mark IIA divertors for 1.9-2.9MA and triangularity $\delta < 0.24$

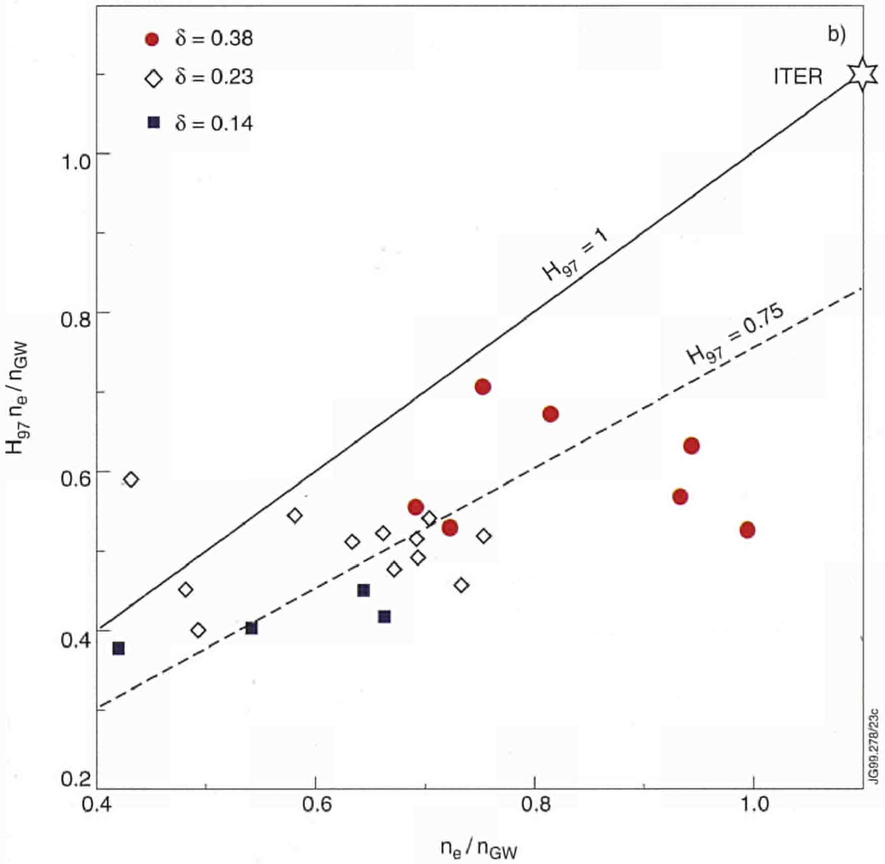


Fig.23(b): Normalised $n_e\tau_E$ versus density normalised to the Greenwald limit, n_{GW}, for a triangularity scan in Mark IIA with deuterium fuelling for identical plasma current and NB heating power

Varying ρ* in JET showed that the same favourable scaling for energy confinement applied to both low and medium β plasmas, that the ν* scaling was weak, and that confinement remained good even with a low q_{95}=2.76. This last result is of particular importance since it should imply good confinement for ITER operating at 24MA (rather than 21MA), thus offering a considerable increase in the overall ignition margin.

ρ* scaling studies were also carried out in highly radiating plasmas using neon as the radiator and keeping q, β and radiated power fraction fixed. While the overall confinement was degraded in comparison with that at lower radiated power fraction, the core plasma appeared to show a favourable (gyro-Bohm) scaling. This result is also consistent with the separation of the global energy into contributions from the plasma core and pedestal.

ELM

An ELM (Edge Localized Mode) is an edge instability which occurs in the high confinement (H-mode) regime. It affects a narrow region in the plasma edge and leads to a loss of particles and energy from the edge on a timescale ≤1 millisecond and therefore is a rapid, but transient, instability. However, ELM's can occur as repetitive instabilities which cause a reduction in the time-averaged energy and particle confinement time.

Towards a Coherent Operating Scenario for ITER

High density, high confinement, high radiated power fraction and small ELMs are key to the ITER design. High density and confinement are required for ignition and a high total radiated power fraction is required to protect the divertor. Three critical issues have received much attention in energy confinement scaling studies: (1) degradation of the energy confinement time, τ_E, as the density approaches an upper limit, n_{GW}, (2) degradation of τ_E with radiated power fraction, f_{rad} and (3) failure of increasing the density above n_{GW} with gas fuelling.

In JET, the best performance is obtained with unfuelled or lightly fuelled ELMy H-modes (Fig.23(a)). Strong gas fuelling produces a relatively small gain in density

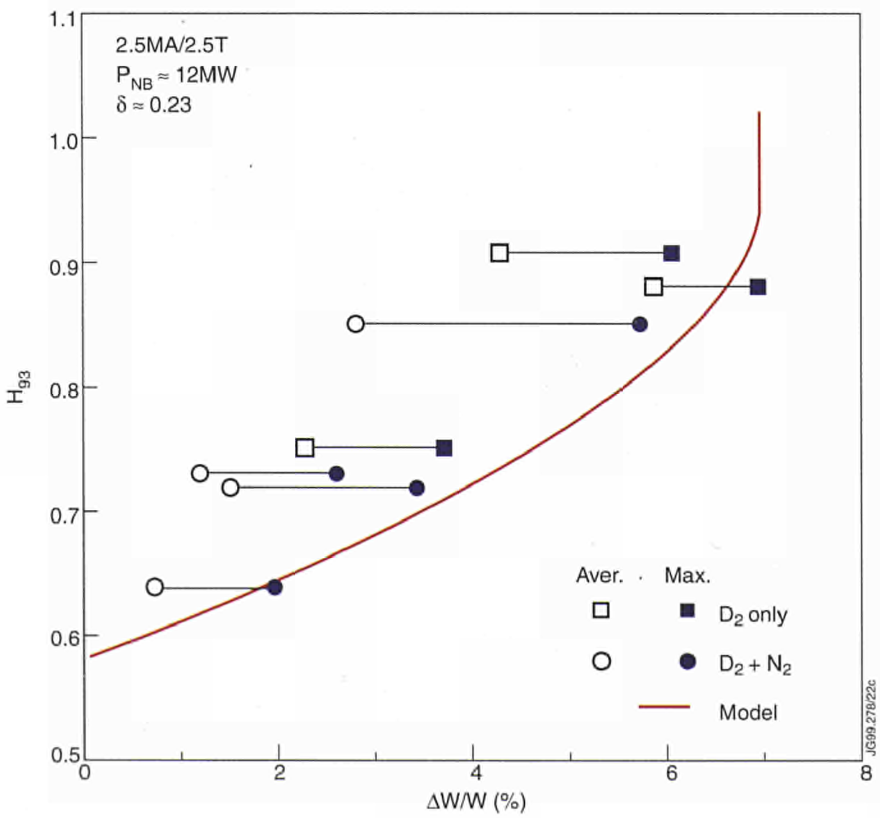


Fig.24: Effect of ELM size (ΔW/W) on the energy confinement time relative to the ITERH93-P scaling (H_{93}). Average and maximum ELM size are compared to a semi-empirical model for ELM pressure cycles

and at the price of reduced energy confinement. Raising the radiated power fraction to achieve low divertor power loading results in a 25% reduction in energy confinement corresponding to a loss in the average pedestal energy. Gas fuelling and/or impurity seeding reduces the ELM amplitude (Fig.24), but there is a trade-off between ELM size and τ_E. To reduce the ELM size below 2% (thought tolerable for ITER) implies a significant loss in energy confinement. The only effective way of increasing fusion performance is by increasing the plasma triangularity. These results (Fig.23(b)) are consistent with the predictions of a semi-empirical model for ELM pressure cycles, the ELM frequency being related to the average pedestal pressure. It is clear again that the scaling of the core and edge contributions to the total energy need separate consideration.

The loss of pedestal energy associated with strong gas fuelling and high radiated power may be acceptable provided the core confinement scaling remains similar to Gyro-Bohm, as indicated by the JET results (Fig.22). The lack of strong temperature profile resilience demonstrated in JET (Fig.25) would also help ITER due to the relatively peaked alpha particle heating profile. However, more work is required on the scaling of radiative regimes and discharges close to the density limit. Dimensionless identity pulses with the ASDEX Upgrade CDH-mode were also carried out to show whether the conventional dimensionless parameters ρ^*, ν^*, β

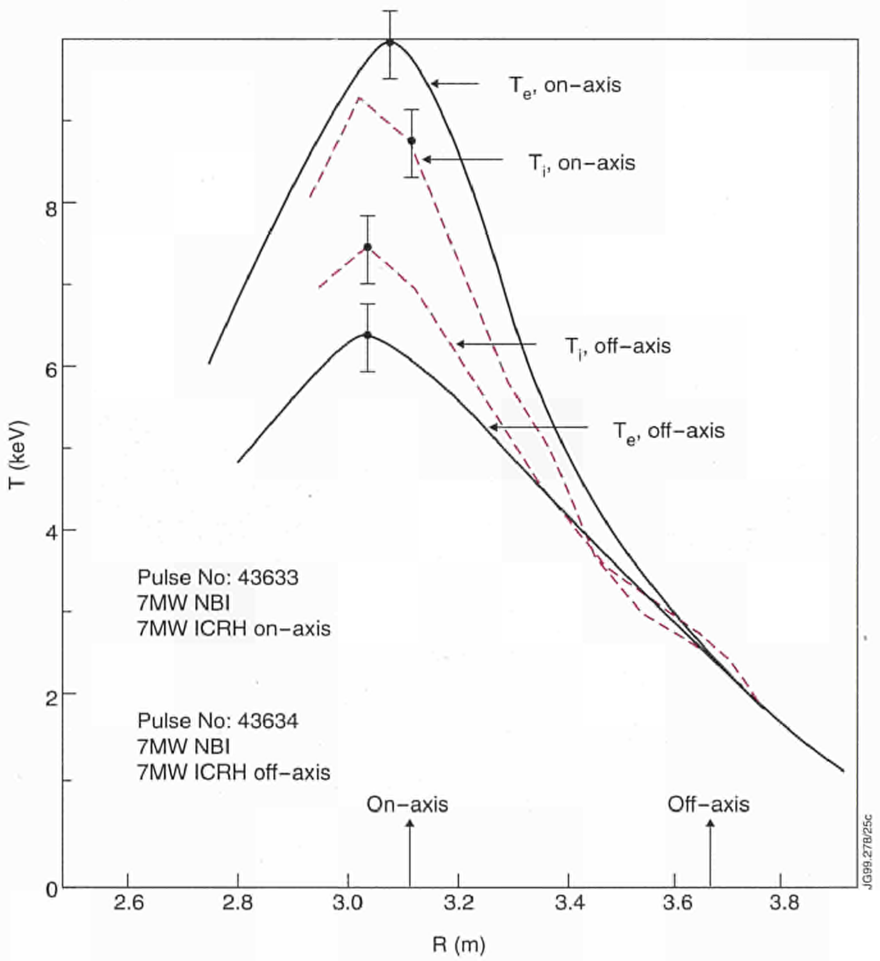


Fig.25: Higher central temperatures are achieved with on-axis ICRF heating (rather than at r/a=0.75) used in combination with NB heating in sawtooth-free ELMy H-mode discharges

Divertor

JET was originally configured as a "limiter tokamak" where the edge of the plasma (the "last closed flux surface" - LCFS) was defined by contact with a material boundary called a limiter, which absorbs the exhaust power of the plasma. Since the edge of the plasma is quite hot, material is eroded by sputtering and the sputtered impurities enter the plasma relatively easily. This enhances radiative losses and dilutes the plasma, which lowers the fusion reaction rate.

The JET vacuum vessel and magnetic field system have been modified to operate in a "divertor" mode. The field configuration includes an "X-point" so that the LCFS (in this case designated the separatrix) bounding the main plasma does not intersect the wall. The power crossing the separatrix is transmitted in a thin layer called the scrape-off layer (SOL) to the divertor at the bottom of the vessel and is absorbed by the divertor "target plates". Divertor operation reduces the impurity content of the main plasma through a combination of effects. The divertor plasma is generally much cooler than the main plasma edge, so that sputtering and erosion are reduced. Moreover, impurities which are produced at the target plate tend to be retained in the divertor area by friction with the plasma streaming towards the divertor plates. In addition to controlling impurity content, divertor operation tends to allow higher SOL temperatures, thus facilitating access to high confinement regimes.

and q_{95} are sufficient for identity in the transport. If not, this would imply that atomic physics processes are important.

ELMy H-Mode Physics Mission for ITER

One of the main goals was to characterise the performance of the Mark IIGB divertor, particularly in the ELMy H-mode regime which is the reference operation scenario for ITER.

This divertor is the most closed to neutral leakage from divertor to main plasma in a series of divertor geometries which have been tested on JET (Fig.26). The various geometries provide a direct experimental test of the improvements expected with a closed divertor, and which form a key ingredient in the design of ITER.

The initial assessment of the Mark IIGB gas box divertor is nearing completion. H-mode performance has been shown to be largely independent of divertor geometry, as with previous divertor geometries on JET. The exhaust of deuterium, impurities and, in particular, helium improves with divertor closure. The septum dividing the two divertor legs has provided some interesting new physics: balanced detachment has been obtained in L-mode discharges; and easier H-mode access has been demonstrated.

Particle Control and Exhaust

All JET divertor configurations have been pumped by a divertor cryopump (Fig.26) which provides an exhaust rate from the vacuum vessel of about $150m^3s^{-1}$. The exhaust of hydrogen isotopes has been shown to improve steadily with increasing divertor closure and this improvement has continued with the Mark IIGB divertor (Fig.27(a)).

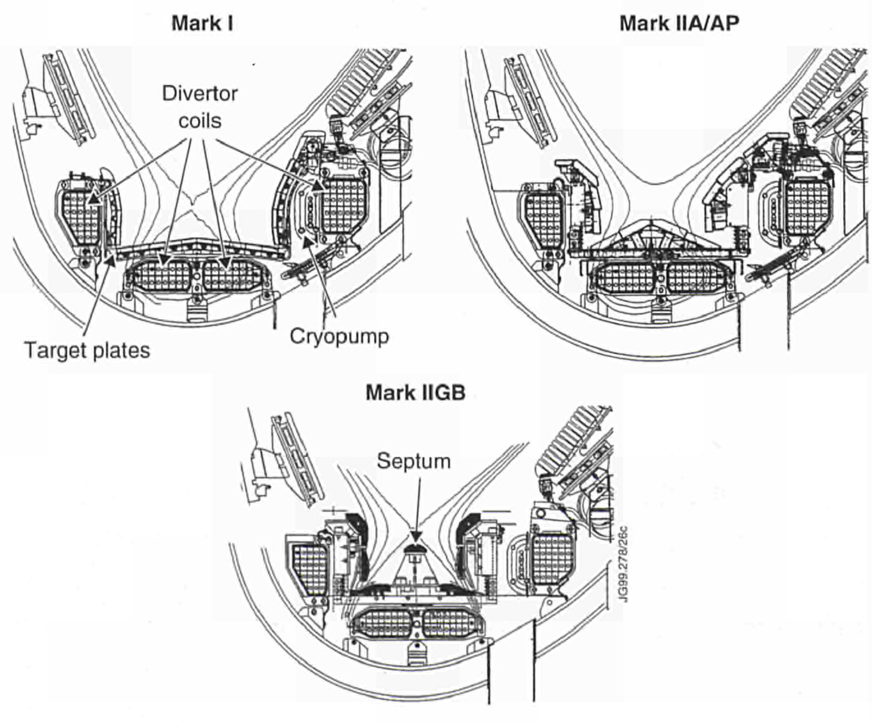


Fig.26: Poloidal cross sections of the Mark I, Mark IIA/AP and Mark IIGB pumped divertors

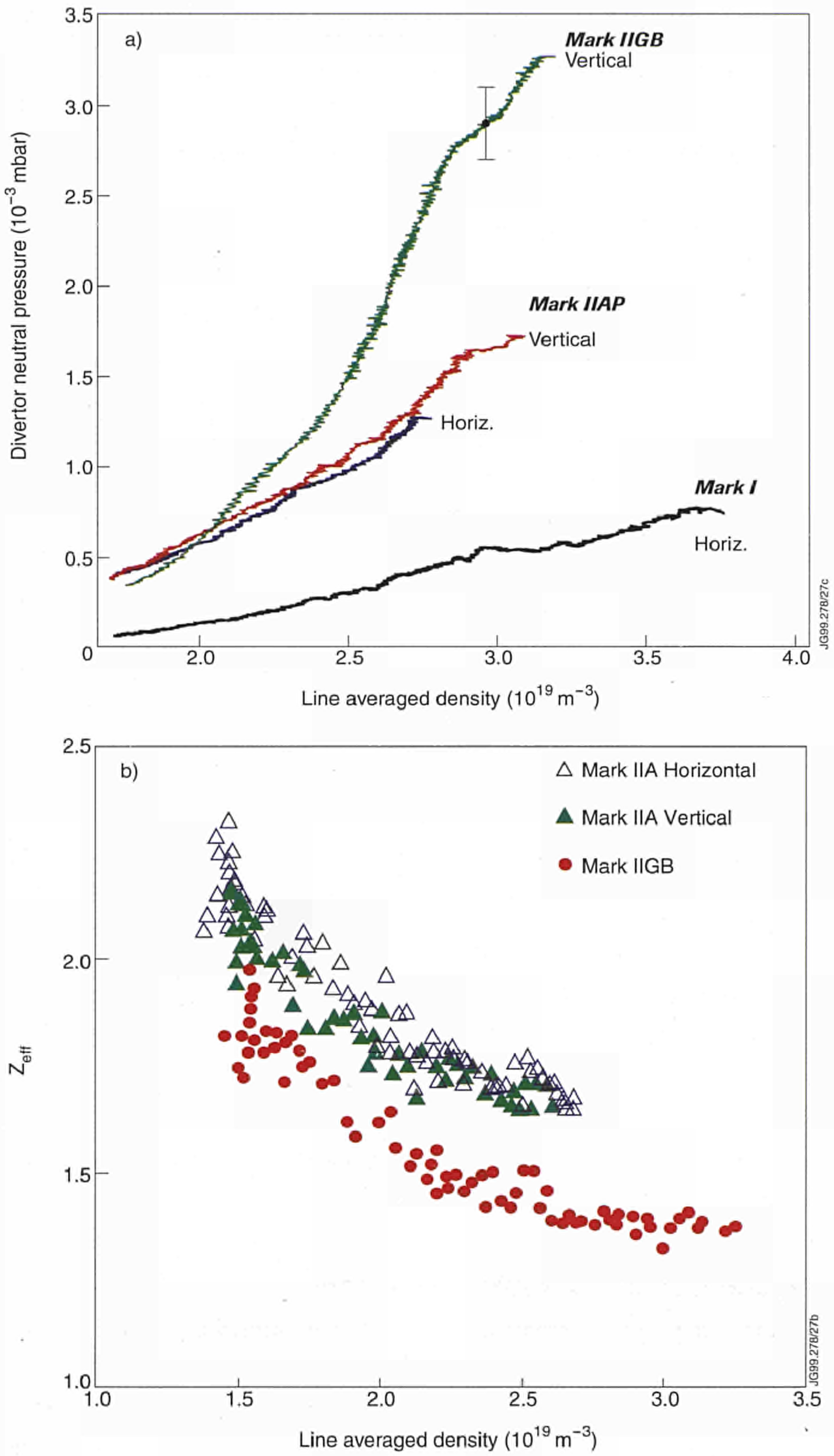


Fig.27: Effect of divertor closure on (a) divertor neutral pressure and (b) bulk plasma impurities (Z_{eff}) in L-mode plasmas

Improved impurity exhaust has also been demonstrated (Fig.27(b)) and, following helium and impurity enrichment studies in 1997/98, helium exhaust studies were completed using argon frosting on the divertor cryopump to pump helium. Helium exhaust is observed with all divertor configurations and is maximised when the divertor strike points are in the corner of the divertor structure, adjacent to the

Impurities

Impurities released from interactions between the plasma and material surfaces can have major effects on plasma behaviour by causing:

(a) increased radiation losses;

(b) dilution of the number of ions available in the plasma between which fusion reactions can occur.

A measure of the overall impurity level is given by Z_{eff} which is defined as the ***average*** *charge carried by the nuclei in the plasma. A pure hydrogen plasma would have Z_{eff} =1 and any impurities in the plasma would cause this value to be increased. In JET, Z_{eff} is generally in the range from 1.2-3.*

Major energy losses can result from two radiation processes:

- *Bremsstrahlung Radiation - radiation is emitted when electrons are decelerated in the electric field of an ion. The amount of radiation emitted increases with Z_{eff}. Bremsstrahlung radiation imposes a fundamental limit to the minimum plasma temperature that must be attained in a fusion reactor;*
- *Line Radiation - heavy impurities will not be fully ionised even in the centre of the plasma and energy can therefore be lost through line radiation.*

Considerable effort is made to keep the level of impurities in the JET plasma to a minimum. The vacuum vessel is baked at 300°C to remove gas particles trapped on the vessel walls which might be released by plasma bombardment and low Z materials (carbon and beryllium) are used to clad plasma facing components.

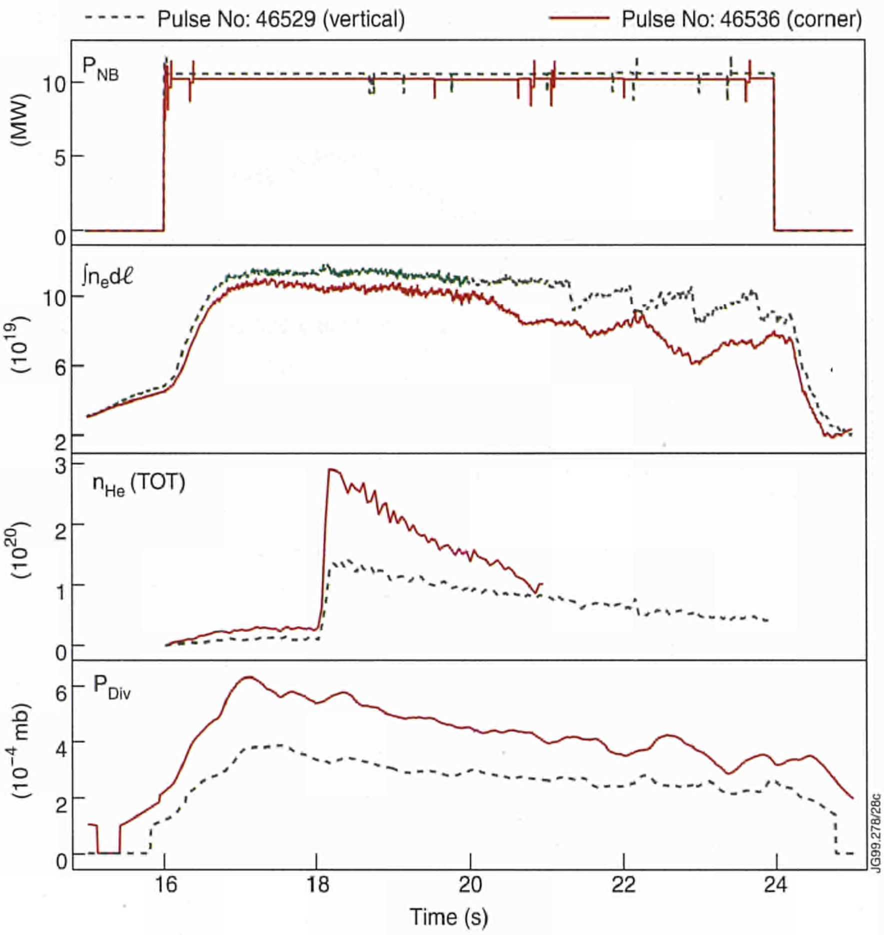


Fig.28: Decay of helium content in the plasma core following a puff of helium into two ELMy H-mode discharges, one in a vertical target configuration and one in a corner configuration. The decay rate of the best ELMy discharges is well within the requirements for helium exhaust in a reactor

pumping ports. The exhaust of helium from two ELMy H-mode discharges, one in a corner configuration and one with the strike points on the vertical targets of the divertor, is shown in Fig.28.

These experiments were technically much more successful than with the Mark I divertor and clear pumping of helium was demonstrated. The ratio of the helium replacement time to the energy confinement time was as low as 4 (for infinite pumping speed) in ELMy H-modes, significantly lower than that needed in a reactor (≤10).

Detachment and Divertor Symmetry

One of the predicted advantages of the Mark IIGB divertor was the more balanced detachment which should be possible by preferentially fuelling into the outer divertor leg. This has been demonstrated in L-mode density limit discharges where inner and outer leg fuelling were compared (Fig.29). With outer fuelling, the particle flux is virtually identical on the inner and outer targets and, at the highest densities, balanced detachment between the legs is achieved. With inner fuelling, as with previous JET experiments using divertors without a septum, the inner divertor plasma detaches first and the outer divertor plasma only detaches at densities just below the density limit. A more balanced detached divertor plasma should lead to less erosion of the divertor in a reactor by reducing the peak particle flux for a given plasma density.

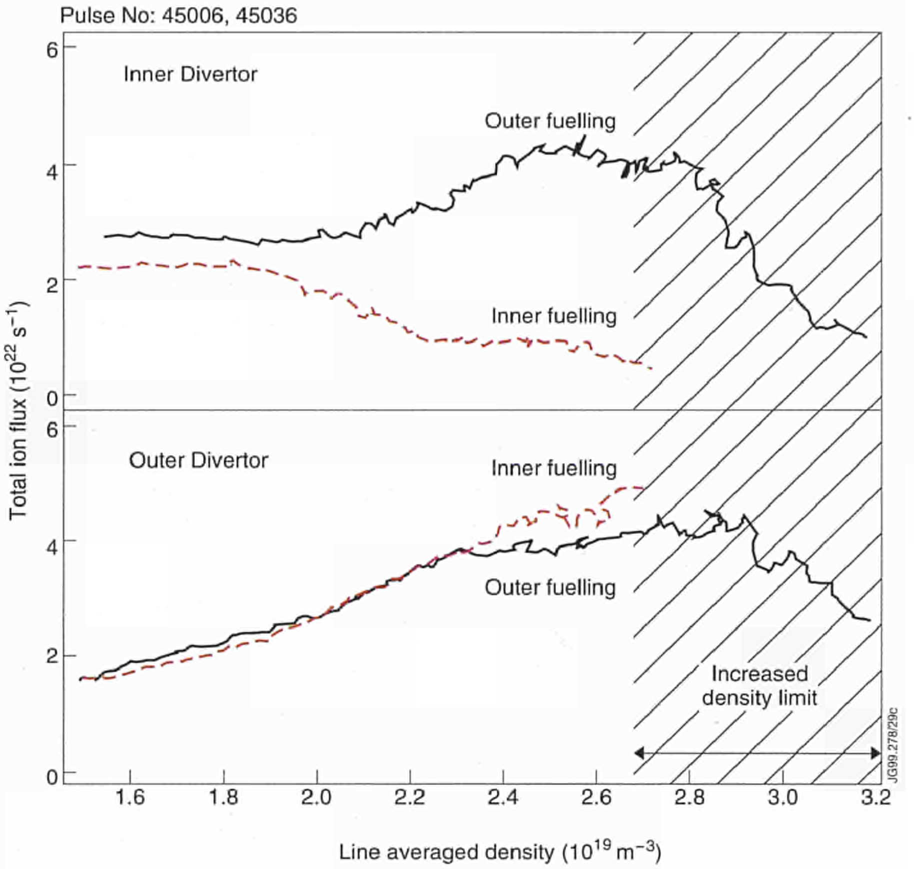


Fig.29: Fuelling with gas injection into the outer leg of the Mark IIGB divertor results in more balanced inner and outer legs and a higher density limit

L-H Threshold Power

Access to the H-mode has been found to be dependent on divertor geometry (Fig.30). The H-mode threshold power appears to be reduced with increasing divertor closure but is higher for vertical target configurations in comparison with horizontal ones. Furthermore, magnetic configurations which are limited on the divertor septum have a significantly lower H-mode threshold than conventional vertical target configurations.

Energy Confinement

On the other hand, energy confinement in ELMy H-mode discharges was found to be largely independent of geometry, although the power needed to produce good confinement had a different parametric dependence to the conventional L-H threshold power. This will have implications for a Next Step device.

More generally, energy confinement did not appear to depend on the method of heating (NB or ICRF) but appeared to depend on the triangularity of the plasma configuration (the character of the ELMs changes with triangularity). High current, high power ELMy H-modes showed sometimes a sudden loss of confinement. This has become more common with the Mark IIGB divertor but could be avoided by controlling the plasma current profile and the gas fuelling rate which, in itself, causes little confinement degradation.

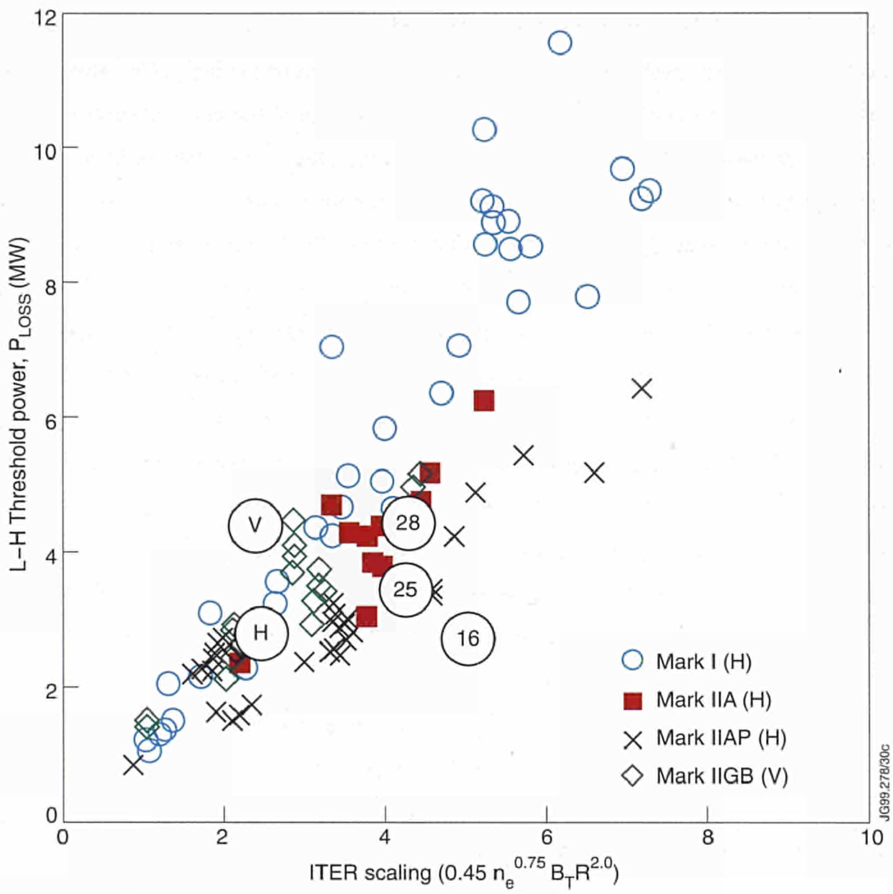


Fig.30: L-H threshold power depends on divertor geometry. It is higher with vertical (V) rather than horizontal (H) targets and lower with greater closure (Mark IIAP rather than Mark I). Proximity to the septum (at 22cms) also decreases the threshold

Scrape-Off Layer and Edge Plasmas

With improved diagnostics, it has been possible to characterise the Scrape-Off Layer (SOL) and edge plasmas better and to address some fundamental questions of edge physics.

Unexpectedly high SOL flows have been measured at the top of JET and their influence on impurity transport is being investigated. SOL ion temperatures have been obtained for the first time and are found to be significantly higher than the electron temperature, something which had been expected from power balance considerations, but had never been proven before on JET. Fluctuation measurements are beginning to allow the exploration of the fundamental causes of edge and SOL transport; this could lead to a physics-based description of this region of the plasma.

Performance Optimisation Mission

The realisation of an economical tokamak reactor that is fully steady-state requires that the entire toroidal plasma current be driven non-inductively without excessive power consumption by external current drive systems. Present estimates for the efficiency of such external systems are quite low and this has led to a significant research effort into regimes which could both reduce the plasma current required for ignition in a reactor and provide a large fraction of that current by the neoclassical bootstrap mechanism.

A significant effort is now being devoted to regimes where heat transport is reduced in the plasma interior by the production of Internal Transport Barriers (ITBs) to further optimise the plasma pressure profile. The principal method found to be effective for producing ITBs has been the control of the plasma current profile. ITBs have been observed mainly in plasmas with low or negative magnetic shear in the plasma interior and may provide a route to a steady-state reactor when combined with an edge transport barrier. Since the core pressure in this scenario is not so dependent on the edge pressure gradient (as is the conventional H-mode), ELMs, which somewhat reduce this gradient, can be used to maintain a constant plasma density.

The optimised shear regime is established after following a particular scenario to optimise the current profile. High power additional heating is applied at the end of a fairly rapid current ramp (0.5MAs^{-1}) which starts at the beginning of the discharge. This method prevents the plasma current from penetrating to the plasma core before the main heating and results in the low or slightly negative central magnetic shear which appears to allow an ITB to be formed during the main heating pulse. Typically, low power heating and current drive using LHCD and ICRF heating are also used before the main heating phase to further slow the diffusion of plasma current and to increase the reproducibility of the discharges (Fig.31). When the current profile is such that the volume within the q=2 surface is reasonably large

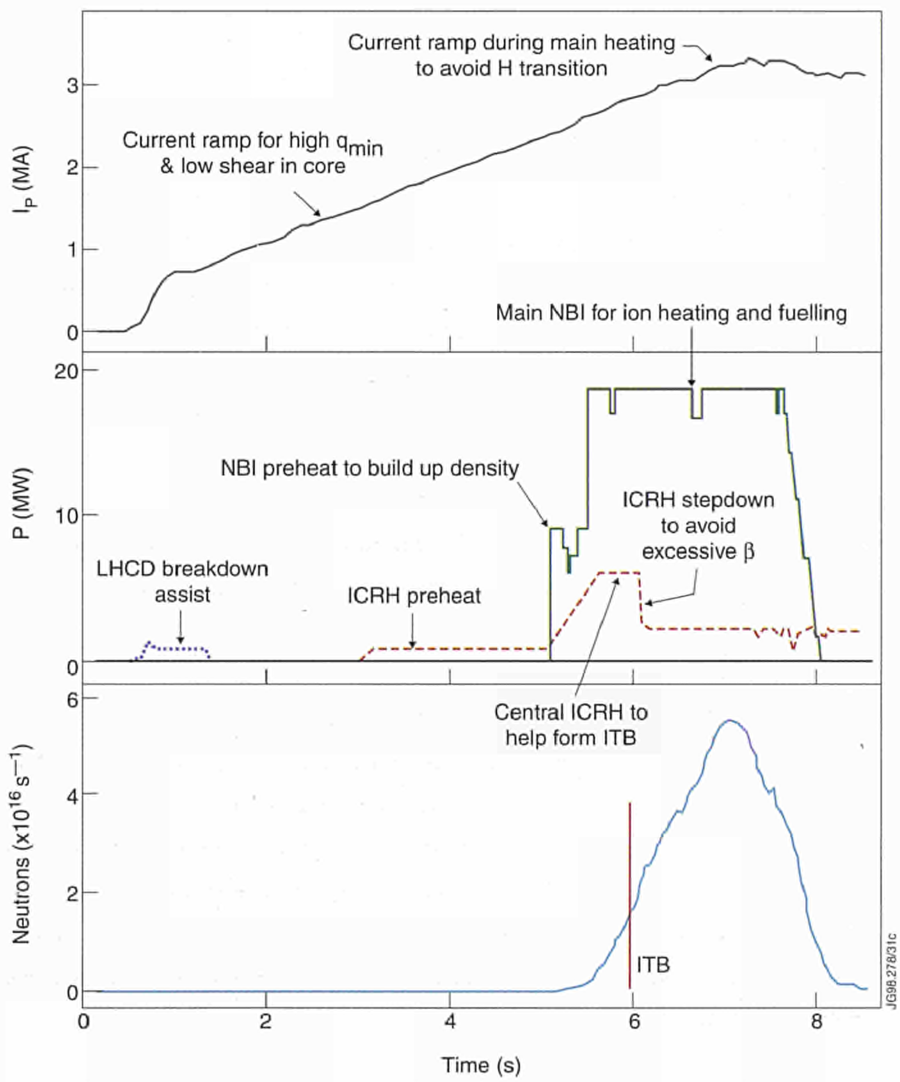


Fig.31: An overview of the heating sequence of a typical optimised shear discharge

(r/a≈0.3-0.4), the full heating power, typically 16-18MW of NB heating together with 6MW of ICRF heating is applied. An ITB can then form, allowing the development of high central pressures (3 bar at 3.45T, and even higher at 3.8T), close to the ideal MHD stability limit for most of the heating pulse, with β_N increasing with time as the ITB moves outwards to ≈2/3 of the plasma radius and the pressure profile becomes less peaked. The highest performance has been achieved with small or slightly reversed central shear and q(0)=1.5-2.

Following the highly successful DTE1 experimental campaign of 1997 during which optimised shear discharges produced the highest deuterium reaction rates and ion temperatures so far in JET, as well as a D-T fusion power of 8MW, the main experimental effort has been directed towards producing ITBs with the Mark IIGB divertor. The L- to H-mode threshold power is lower than with the Mark IIA divertor and scenarios had to be modified to take this into account, particularly the modification of the current profile by the edge bootstrap current due to the H-mode pedestal. Ultimately, transient high performance discharges with a fusion yield about 20% lower than in 1997 were achieved. Furthermore, new techniques which allow the performance of optimised shear plasmas to be increased, in particular towards steady-state, were also developed. Double barrier modes combining Internal and Edge Transport Barriers have been maintained at high performance for up to 6s, which is the present maximum time duration of the high power phase.

Plasma Beta

The economic efficiency of a tokamak reactor is determined, partly, by the maximum plasma pressure which can be contained by the magnetic fields in the device. In particular, the important parameter is the plasma beta β_T, defined as the ratio of plasma pressure to the pressure of the confining magnetic field (β_T is proportional to nT/B_T^2, where n is the plasma density, T the plasma temperature and B_T the toroidal magnetic field). This limit expected theoretically, is the so-called Troyon limit $\beta_T(\%)=2.8I_p(MA)/B_T(T)a(m)$, where I_p is the plasma current and a is the minor radius.

Ion and Electron Internal Transport Barriers

The formation of an ITB is most clearly seen as a very steep gradient in the ion temperature profile. At the same time, the electron density profile becomes very peaked. The location of the ITB tends to move radially outwards during the discharge. Careful analysis of data has shown that steep gradients in the electron temperature profile are also observed as shown in Fig.32. Radial profiles of electron temperature are measured with the ECE diagnostic using an heterodyne radiometer technique with a very good radial space resolution (about 0.03m). From a large variety of optimised shear discharges in both D-D and D-T plasmas, it has been concluded that the development of ITBs follows the same time evolution (i.e. formation, expansion and contraction) at the same radial location for both ions and electrons.

The production of electron ITBs when ion ITBs are triggered further enhances the relevance of these regimes to a reactor in which the main heating will be from alpha particles, which predominantly heat electrons. The physical mechanism which allows an ITB to be triggered is likely to act on all plasma species. It is presently thought that turbulence is stabilised through a combination of shear in the plasma rotation and in the magnetic field; therefore, both electron and ion diffusivities are improved significantly when turbulence is stabilised and ITBs are formed. This is very typical of JET optimised shear scenarios which can be simulated using empirical models in predictive transport codes.

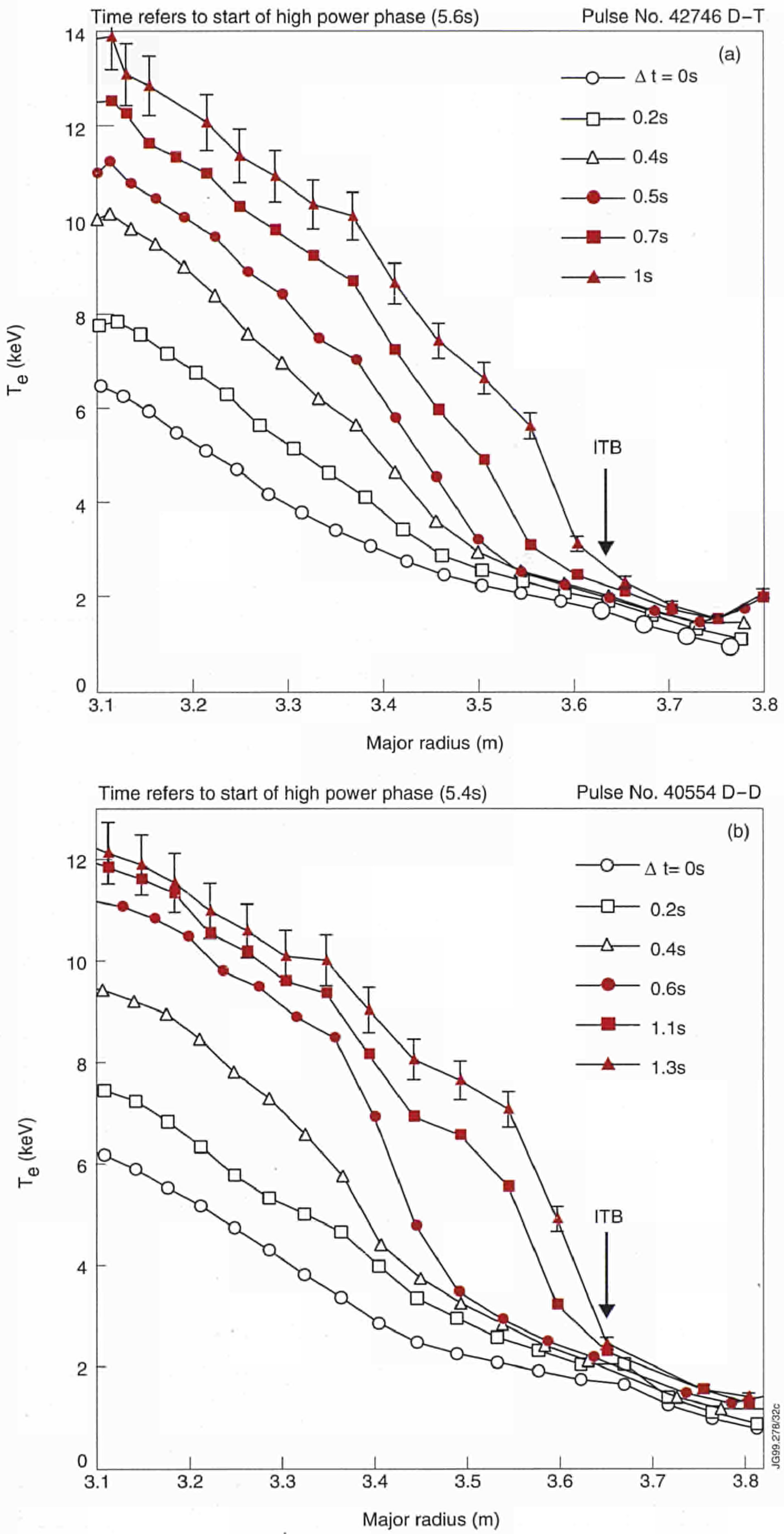


Fig.32: Radial electron temperature profiles at different times after the high power phase in (a) D-T and (b) D-D showing the formation of an electron ITB, here with an L-mode edge

Improved Thermal Insulation with Internal Transport Barriers

The transport analysis code TRANSP has been used to estimate the ion heat diffusivity under a wide variety of conditions. Typical radial profiles for the ion heat diffusivity are shown in Fig.33 both for D-D and D-T discharges. The heat diffusivity decreases in the region of the ITB and reaches values near, or even below, neoclassical values close to the plasma centre; note that error bars are large here. The heat diffusivity is similar in comparable D-D and D-T pulses, which suggests that isotopic effects on the ion, as well as electron, heat transport are as predicted by neoclassical transport theory.

TRANSP has also been used to check the overall data consistency of the D-T optimised shear discharges; the triple fusion product reaches very high values, up to $1.1 \times 10^{21} m^{-3} skeV$, although at ion temperatures which are too high for optimum fusion yield in D-T plasmas.

Steady State Operation

Control of the plasma profiles by using noble gases to radiate in the plasma edge has been instrumental in prolonging optimised shear discharges. In particular, high performance steady-state operation has been obtained with argon as shown in Figs.34 and 35. High confinement and β have been maintained for the full duration of the high power phase (more than 10 times the energy confinement time) with double transport barriers and with very mild ELM activity. Further optimisation using LHCD and off-axis ICRF heating remains to be done. For the discharge shown in Fig.34, radiation is kept at a level which is sufficient to reduce the edge pedestal

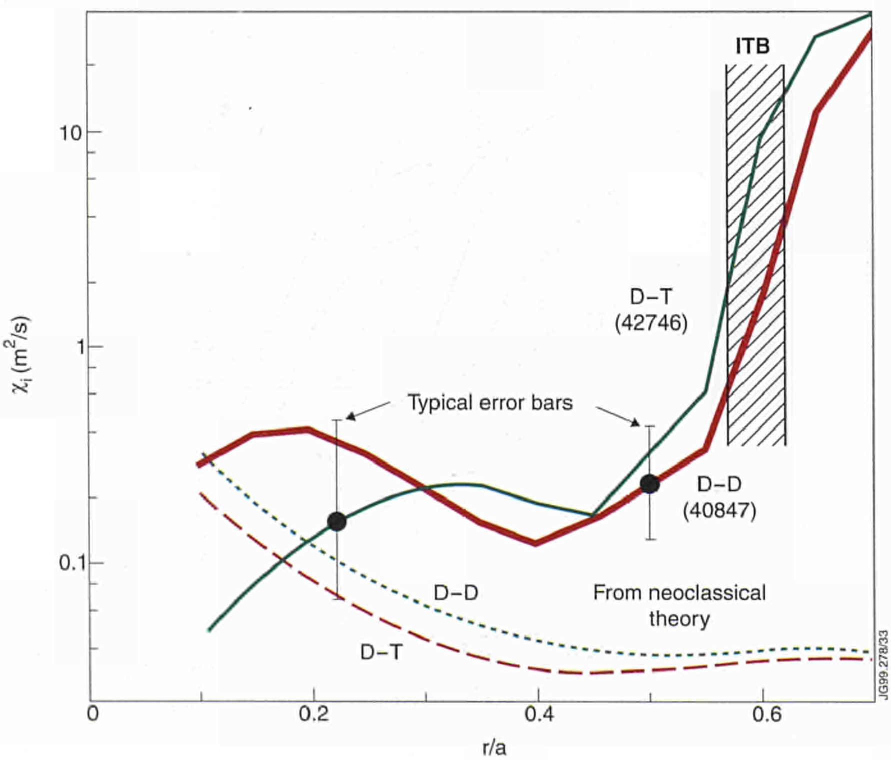


Fig.33: The ion heat diffusivity is low inside the ITB for typical optimised shear pulses in D-D and in D-T

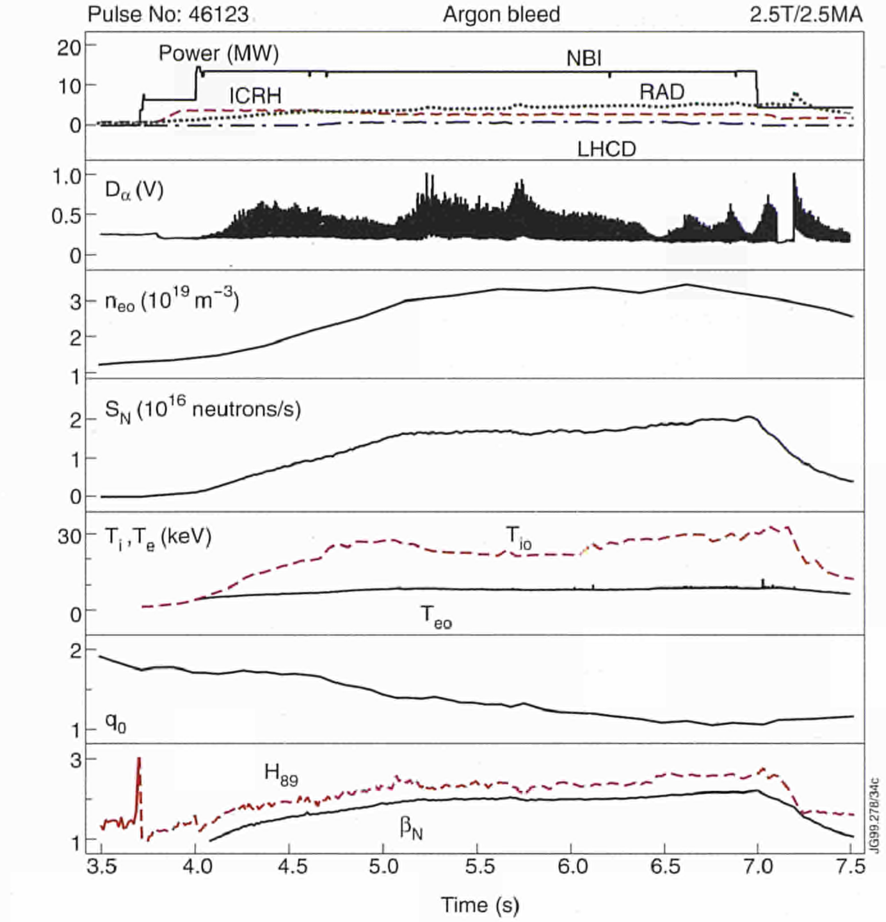


Fig.34: The main plasma parameters for a steady-state optimised shear discharge in which argon is used to control the plasma edge

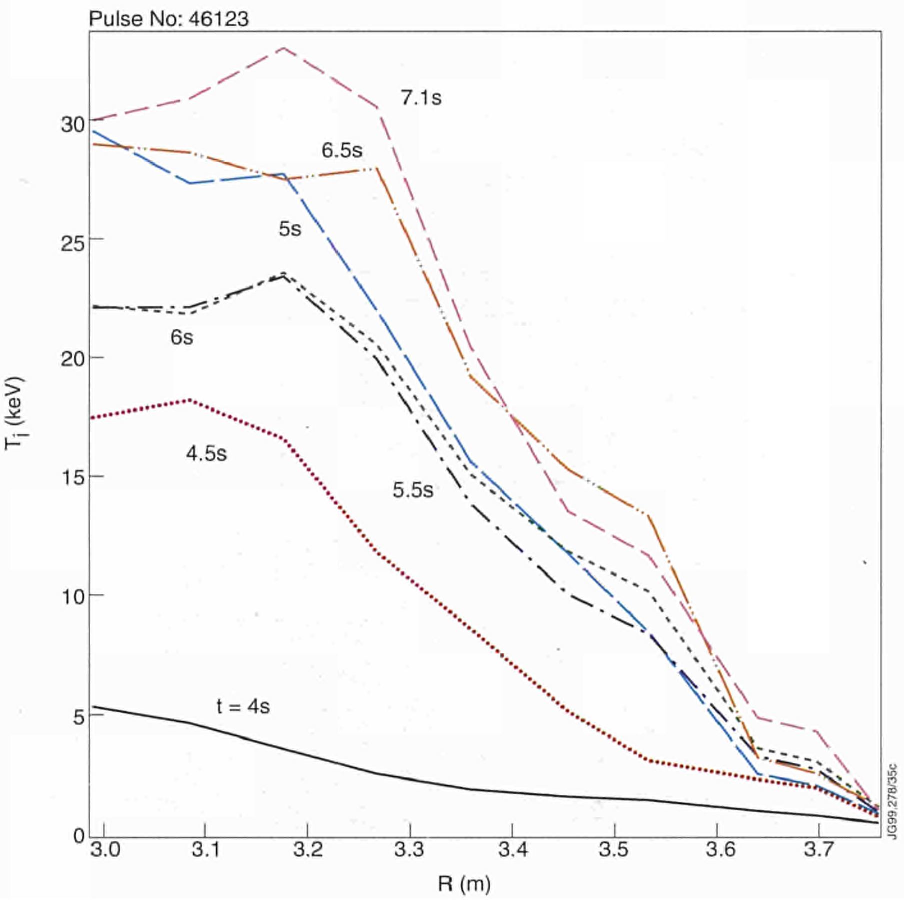


Fig.35: Ion temperature profiles for the optimised shear discharge of Fig.34

but not to restore an L-mode edge. A certain degree of broadening of the pressure profile is achieved, thus avoiding external kink mode induced disruptions. There is also a leverage on the evolution of the q profile; in effect, the q=2 magnetic surface broadens and ITBs are rather broad as seen on Fig.35. The pressure gradients are not very large. As a possible consequence, the central density saturates 2-3s after the start of high power (the plateau of the plasma current starts at 5s). Quasi-stationary conditions have been obtained at 2.5T, 2.5MA, q_{95}=3.3, H_{89}=2.7 and β_N=2.2. The ELMs are very mild and compatible with divertor operation in a reactor. With an argon seeded edge and an ITB, fuel dilution appears not to be a problem and bolometer measurements (Fig. 36) indicate that the radiation stays outside the ITB.

The performance of the argon seeded optimised shear discharges is limited at present by tearing modes (also observed in ELMy H-modes) which appear when the q=3,2 surfaces move into the steep pressure gradient region. Near this limit a 2.5MA/2.5T discharge has been sustained at β_N=2.5 and H_{89}=3 for three energy confinement times and produced an equivalent fusion power of 7MW for a total injected power of 20MW. Further development aims at suppressing the source of the tearing modes by enhanced current profile control.

The potential of the double barrier mode has been studied using the JETTO transport code together with the MISHKA code for MHD stability. The transport model assumes that turbulence is stabilised by a combination of shear in the plasma

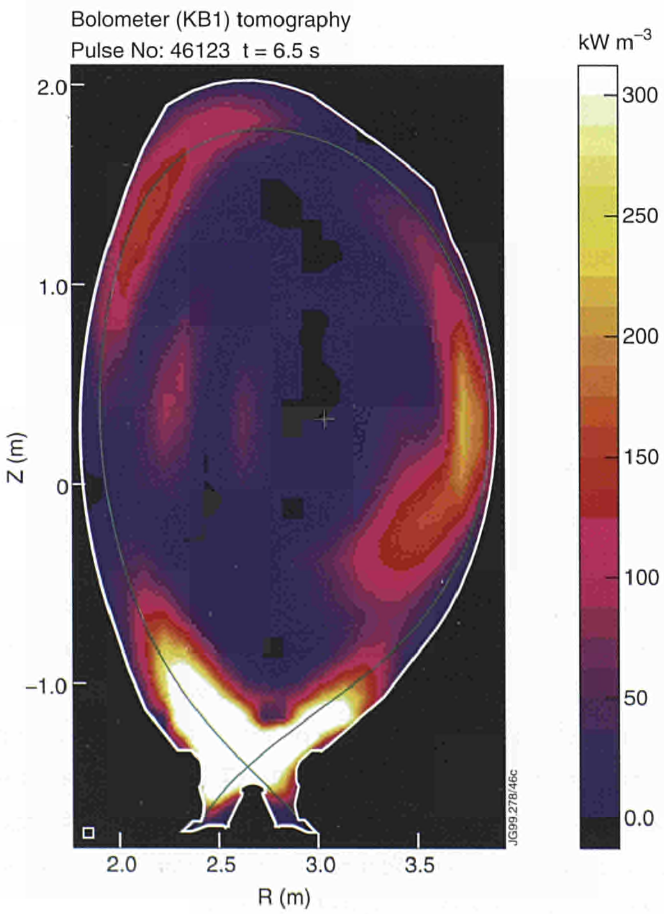


Fig.36: Radiation pattern for the optimised shear discharge of Fig.34 3s after the start of the high power phase

rotation and in the magnetic field. A comprehensive study at Princeton Plasma Physics Laboratory, New Jersey, USA using a full kinetic code with an approximate method evaluating the rotation has confirmed that the growth rate of turbulent modes is lower than the shear flow rate, suggesting significant turbulence suppression.

A systematic MHD analysis has indicated that plasmas with low plasma inductance, high β_N (> 3) and significant bootstrap current fraction (< 70%) could be achieved by a proper tuning of the plasma current profile and partial stabilisation by the vessel wall. Simulation indicates that this effect exists, with the stabilising walls located at 1.3 times the minor radius. Under these conditions, discharges with performance substantially better than achieved during DTE1 could be obtained, but would depend on the particle diffusivity which is still uncertain. The main significance of these high performance discharges is their extra potential for steady-state conditions.

Progress towards a Reactor

Towards the end of 1997 a very significant step towards a fusion reactor was taken with the operation of JET with plasmas made up of mixtures of deuterium and tritium. Several different types of discharges were used; (a) the hot ion H-mode; (b) the optimised shear mode; and (c) the steady state ELMy H-mode. The highest fusion output power was obtained in the hot ion H-mode, where 16.1MW was obtained in a 4MA, 3.6T pulse. The fusion amplification factor, Q (the ratio of fusion power produced to input power) reached 0.62, and 0.95±0.17 if the same plasma conditions could be achieved in steady-state. The fusion triple product, $n_i\ \tau_E\ T_i(0)$, in this discharge was $8.3\times10^{20}\ m^{-3}$ keVs, with an ion temperature of 27keV which is close to the optimum. This type of pulse was repeated on three other occasions and a yield well in excess of 10MW was achieved on each occasion.

The behaviour of the optimised shear pulse with an ITB was found to be more difficult to obtain in D-T than in deuterium, due to the lower L-H power threshold. Nevertheless, an ITB was formed and 8MW of fusion power was obtained for an input power of 20MW. The central ion temperature was 32keV which is somewhat higher than required for optimum performance. The reacting volume was also rather small and the future programme will be directed towards increasing the plasma density and the volume of the good confinement region in this type of discharge.

In the steady state ELMy H-mode, which is the preferred mode of operation for ITER, a steady fusion power output of 4MW was achieved for about 4s giving a total fusion energy output of 22MJ. The Q of this pulse was 0.18.

These three types of pulses are shown on the plot of the fusion triple product ($n_i\tau_E T_i(0)$) versus central ion temperature, $T_i(0)$ (Fig.37). Particular care has to be taken in the interpretation of this plot when the temperature and density profiles, as in the case of the optimised shear pulse, are far from the assumed parabolic shapes of the profiles in the Q_{DT} curves of the figure.

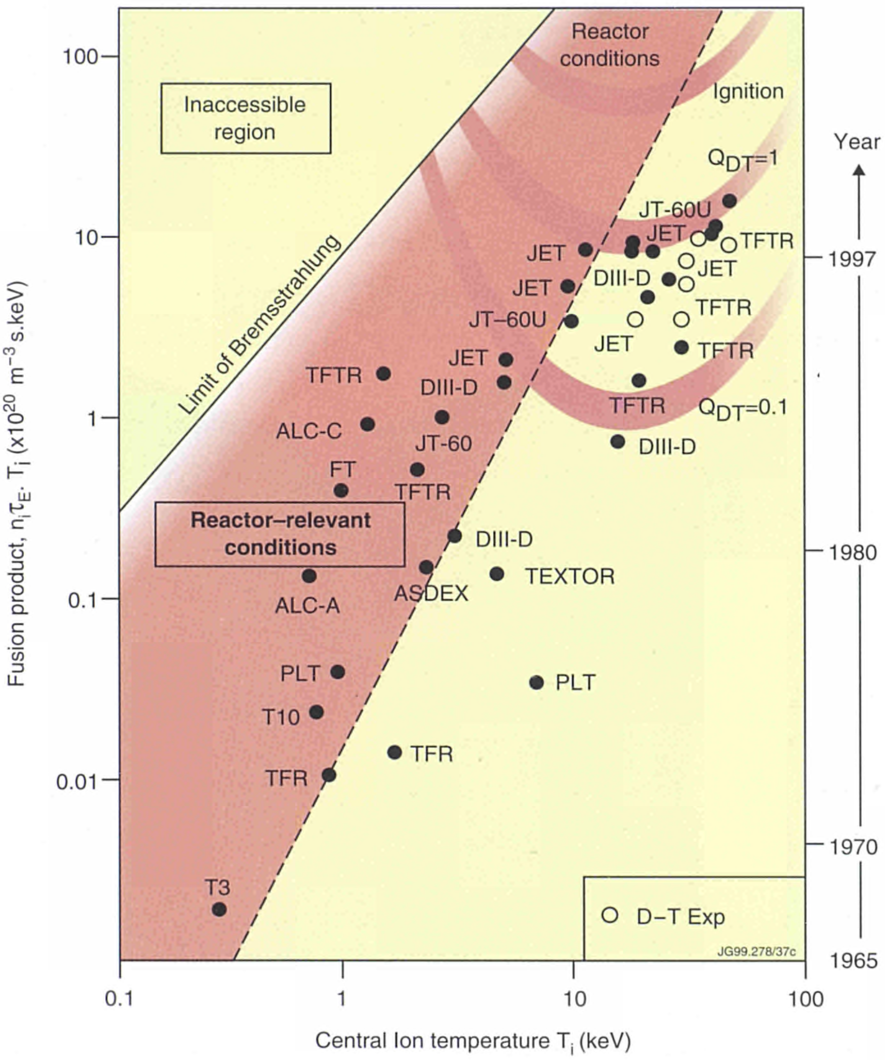


Fig.37: Fusion triple product as a function of central ion temperature, T_i, for a number of tokamaks world-wide


Trailmaster
6m

Programme Overview

Background

In 1978, the original objectives of JET were set out in the JET Design Proposal, EUR-JET-R5, as follows:

> *"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 alpha 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."*

Since the beginning of its experimental campaign in 1983, extensive studies had been made in the first and third areas of work of JET's objectives: reactor relevant temperatures (up to 38keV), densities (up to $4x10^{20}m^{-3}$) and energy confinement times (up to 1.7s) had been achieved in separate discharges. The second area of work had been well covered in the limiter configuration for which JET was originally designed. However, the highest performance JET discharges had been obtained with a "magnetic limiter" (or X-point configuration).The duration of the high performance phase of these discharges exceeded 1.5s; this was achieved by careful design of the targets and specific operation techniques, but was limited, ultimately, by an unacceptably high influx of impurities, characterised by a rapid increase in electron density, effective ionic charge and radiated power (referred to as the "bloom").

The fourth area of work had been started by earlier studies of energetic particles produced as fusion products or by ion cyclotron resonance heating. It was addressed further during 1991 by the first tokamak experiments in deuterium-tritium mixtures. During 1991, the JET Council had approved the policy of a step-wise approach to the introduction of tritium in advance of the full D-T phase of JET operations. As a first such step, JET successfully carried out the preliminary tritium experiment in November 1991, using about 10% tritium in the plasma. A release of fusion energy in the megawatt range in a controlled fusion device had been achieved for the first time in the world.

In the 1991/92 campaign, JET achieved plasma parameters approaching breakeven values for about a second, resulting in large bursts of neutrons. However, in spite of the plasma pulse continuing for many seconds after reaching peak plasma values, the neutron count fell away rapidly as impurities entered the plasma and lowered its performance. This limitation on the time for which the near-breakeven conditions could be maintained was due to the poisoning of the plasma by impurities (the "bloom"). This further emphasised the need to provide a scheme of impurity control suitable for a Next Step device.

In late 1991, the Council of Ministers approved a modification to the JET Statutes, which prolonged its lifetime by four years until 31st December 1996. The extension was to allow JET to implement the new Pumped Divertor Phase of operation, the objective of which was to establish the effective control of plasma impurities in operating conditions close to those of the Next Step. This programme of studies was to be pursued before the final phase of full D-T operations in JET.

During 1993, a large proportion of JET's effort was devoted to shutdown work for the pumped divertor phase of operations, and was successfully completed in January 1994. The first plasma in the Pumped Divertor Characterisation Phase was produced in mid-February and by mid-March successful 2MA diverted plasmas had been established. During 1994, the plasma current was increased to 5MA, the total heating power to 26MW, the stored energy to 11.3MJ and the neutron rate to $4x10^{16} s^{-1}$.

1994 saw significant progress in optimising peak fusion performance and extending operation to the reactor relevant steady-state ELMy H-mode, which was obtained under a variety of conditions (plasma currents up to 4MA, power levels up to 26MW, in the high β_p regime, in discharges with negative central magnetic shear, and at high β_N). The high power handling capability of the Mark I divertor target was demonstrated and the severe impurity influxes (the "bloom"), which previously terminated high performance plasmas, was eliminated. The cryopump reduced recycling, eliminated the effects of wall saturation (observed in previous long pulse operation), allowed effective particle control, and generally allowed higher performance.

The 1995 programme addressed the central problems of the ITER divertor:

efficient dissipation of the exhausted power, control of particle fluxes and effective impurity screening, using both carbon fibre composite and beryllium as the power handling material. During this phase, the plasma current was increased to 6MA (a world record in an X-point configuration), the total heating power to 32MW, plasma stored energy to 13.5MJ and the neutron rate to a new JET record in deuterium of 4.7 x $10^{16}s^{-1}$ (comparable to the best achieved prior to installation of the pumped divertor and achieved even though the plasma volume was 20% smaller).

At the beginning of 1996, JET entered a new Phase of ITER Support, and started the year in shutdown for the installation of the Mark II divertor support structure. This formed the basis for all subsequent divertor work at JET. In addition, the "more-closed" Mark IIA divertor target assembly was installed.

In 1996, the Mark IIA divertor was found to behave as expected. It offered improved power handling over the Mark I divertor, pumped the plasma 2-3 times more rapidly and showed signs of increased neutral recycling in the divertor region. The 1996 experimental campaign then concentrated on specific ITER-relevant issues related to the more closed Mark IIA divertor and, due to their importance for predicting ITER's ignition margin and fusion power output, the scaling of the H-mode threshold power and the energy confinement time. In addition, preparation of high performance scenarios for a further phase of deuterium-tritium operation (DTE1) was a high priority.

In mid-1996, the lifetime of the Project was extended to the end of 1999, to enable the Project to provide further data of direct relevance to ITER. In particular, the Project was expected to contribute significantly to the development and demonstration of a viable divertor concept for ITER and to undertake experiments using D-T plasmas in an ITER like configuration, which should provide a sound basis for the D-T operation of ITER. In addition, the extension would permit key ITER-relevant technology activities to be carried out, including the demonstration of remote handling and tritium handling.

1997 was a year of JET operations, whose centrepiece was DTE1 during which JET carried out a broad-based series of D-T experiments, setting new world records for fusion power production (16.1MW), fusion energy (22MJ), fusion duration (4MW for about 4s) and fusion amplification factor, Q (the ratio of fusion power produced to input power) of 0.62 and 0.95±0.17, if the same plasma conditions could be acheived in steady-state. These experiments also addressed crucial issues of D-T physics and technology for ITER.

Following the tritium clean up experiments at the end of DTE1, a series of ITER Urgent Physics Tasks was undertaken with hydrogen and deuterium plasmas. These tasks focussed on confinement scaling experiments to increase confidence in the predictions for ITER. The third stage in the divertor programme on JET then began with the installation fully by remote handling of the Gas Box (Mark IIGB) divertor during the RTE shutdown. The subsequent experimental campaign concentrated on ELMy H-mode and performance optimisation studies.

Future Plans

The JET Programme was divided into phases governed by the availability of new equipment and fitting within the accepted life of the Project. Phase I (Ohmic Heating Studies) was completed in September 1984, and Phase II (Additional Heating Studies) in October 1988. Phase III (Full Power Optimisation Studies) ended in February 1992. The scientific aims of Phase III were to obtain maximum performance in the limiter configuration (currents up to 7MA) and to optimise X-point Operation (currents up to 6MA) including a comparison of H-modes in the X-point configuration using beryllium (lower X-point) with carbon (upper X-point) dump plates.

The JET programme was then dominated by the insertion of a new phase, Phase IV: the Pumped Divertor Characterisation Phase, which began in February 1994 and ended in June 1995.

In mid-1996, the lifetime of the Project was further extended to the end of 1999, to enable the Project to carry out an ITER Support Programme.

Objectives in Support of ITER

The purpose of the extension of JET to the end of 1999 was to provide further data of direct relevance to ITER, especially for the ITER-EDA, before entering into a final phase of D-T operation. In particular, the extension:

i) was to make essential contributions to the development and demonstration of a viable divertor concept for ITER, and
ii) carry out experiments using D-T plasmas in an ITER-like configuration, which will provide a firm basis for the D-T operation of ITER;

while allowing key ITER-relevant technology activities, such as the demonstration of remote handling and tritium handling, to be carried out.

Divertor Studies

The divertor must fulfil three main functions:

(i) exhaust plasma power at acceptable erosion rates;
(ii) control plasma purity; and
(iii) exhaust helium "ash" and provide density control.

For ITER, successful divertor operation must also be compatible with H-mode operation with Edge Localised Modes (ELMs), which could lead to high local heat deposition.

Erosion can be reduced by decreasing the plasma temperature at the target plates which can be achieved with high density and high recycling near the targets. However, the exhausted plasma power conducted to the target plates in this high recycling regime is not reduced and has to be distributed over a large surface area. To some extent, this can be achieved by inclining the target plates so as to project a larger surface area to the conducted heat flux which flows along the magnetic field.

An alternative approach is to reduce the conducted power to the target plates by atomic physics processes (charge exchange, hydrogen and impurity radiation) in the divertor channel. These power losses can be enhanced by seeding the divertor plasma with impurities which must then be retained in the divertor by plasma flows. This requires sufficient pumping and recirculation of the plasma in the divertor. In addition, of course, the divertor conditions must not affect adversely the main plasma performance and this requires the divertor plasma to be decoupled as much as possible from the main plasma. In particular, the leakage of neutrals from the divertor to the main plasma must be reduced as far as possible. Such "closure" of the divertor can be achieved by introducing baffle structures at the entrance to the divertor or maintaining a sufficiently dense plasma to attenuate neutrals within the divertor (plasma "plugging"). The geometry of the divertor is thus important in providing the necessary degree of closure, and several different divertor configurations must be tested.

The JET divertor programme is based on three generically different divertor configurations with increasing closure (Mark I, Mark IIA and an ITER-specific Mark IIGB), which are being tested sequentially. In this way, the various options for an ITER divertor are being studied in a co-ordinated way designed to lead to a solution giving compatibility between power exhaust, purity control and high performance (H-mode). A major part of the strategy is the development and validation of numerical codes for the edge and divertor plasma so that they may be used for extrapolation to the geometry, dimensions and operating conditions of ITER.

The relatively "open" Mark I divertor which was used for the 1994/95 experimental campaign was replaced during the 1995/96 shutdown by the Mark II divertor. This divertor comprises a common base structure capable of accepting various target assemblies which can be exchanged by remote handling. The divertor geometry (degree of closure and target configuration) is being varied and its effect on divertor and main plasma performance is being studied.

The first target assembly (Mark IIA), which was used for the 1996/97 experimental campaign, was a moderate "slot" divertor which is significantly more closed than the Mark I divertor. Mark IIA allowed operation under a wide range of plasma configurations and conditions and made high power, high current operation possible on both the horizontal and vertical target plates.

The second target assembly (Mark IIGB), which was used for the 1998 experimental campaign, is a deep divertor of the gas box type with a well baffled entrance. The aim is to distribute the exhaust power over the length of the divertor. This is assisted by the free recirculation of neutrals below the baffle on one or both sides of the divertor plasma legs. Recirculation also allows greater flows, better pumping and better impurity retention in the divertor.

The experimental results from the three JET divertor configurations, together with those from smaller tokamaks and model calculations, will allow the ITER divertor design to be validated.

D-T Plasma Studies

JET performed the first magnetic confinement experiments using D-T in 1991. These experiments which used a dilute fuel mixture of just 10% tritium in deuterium, produced significant fusion power (peaking at 1.7MW and averaging 1MW over 2 seconds). The US tokamak TFTR has since produced ≈10MW of fusion power, using the optimum D-T mixture of 50% tritium in deuterium. TFTR also showed that, under certain conditions the thermal insulation of D-T plasmas could be better than that of pure deuterium plasmas. TFTR was shutdown in April 1997.

JET experiments in DTE1 showed that, in comparison with previous experiments in pure deuterium, the heating power needed to access the H-mode was lower for D-T and lower still for pure tritium. On the other hand, the better thermal insulation observed with D-T under some TFTR operating conditions was not found in standard ITER conditions. The first clear evidence of alpha particle heating was obtained, confirming experimentally the process by which ignition and thermonuclear burn will occur in ITER. DTE1 also provided the first test of a large scale technology for processing tritium through an operating tokamak and was followed by the first major modification of a tokamak interior using fully remote handling techniques.

DTE1 was a major technical and scientific success. A wide range of major new results was obtained, confirming the need for a further, longer phase of D-T operation to increase fusion performance and for a thorough study of the physics and technology of D-T plasmas at the end of JET operations. This will be provided for by DTE2, which will capitalise on the performance improvements achieved in the preceding experimental campaigns with deuterium to access regimes with substantial levels of alpha particle heating. This will allow a comprehensive study of the physics of thermonuclear generated alpha particles, following further plasma optimisation, particularly in the optimised shear regime. This further period of D-T operation will also provide a full evaluation of the technology of processing tritium in support of an operating tokamak, and will provide information valuable for the ITER licensing process.

Programme Plan

The programme to the end of 1999 is illustrated in Fig.38. It covers all the agreed objectives for the JET extension.

During early 1999, further ITER Urgent physics studies will be undertaken, the Mark IIGB divertor will be tested experimentally with deuterium plasmas at high power, and plasma performance will be optimised in deuterium in preparation for DTE2. The design of the Mark IIGB provides flexibility to modify the target geometry with relative ease. Two target geometries for Mark IIGB are possible and a septum, to limit the communication between the inner and outer divertor legs and to absorb energy from energetic neutrals and photons, could be removed at a later stage.

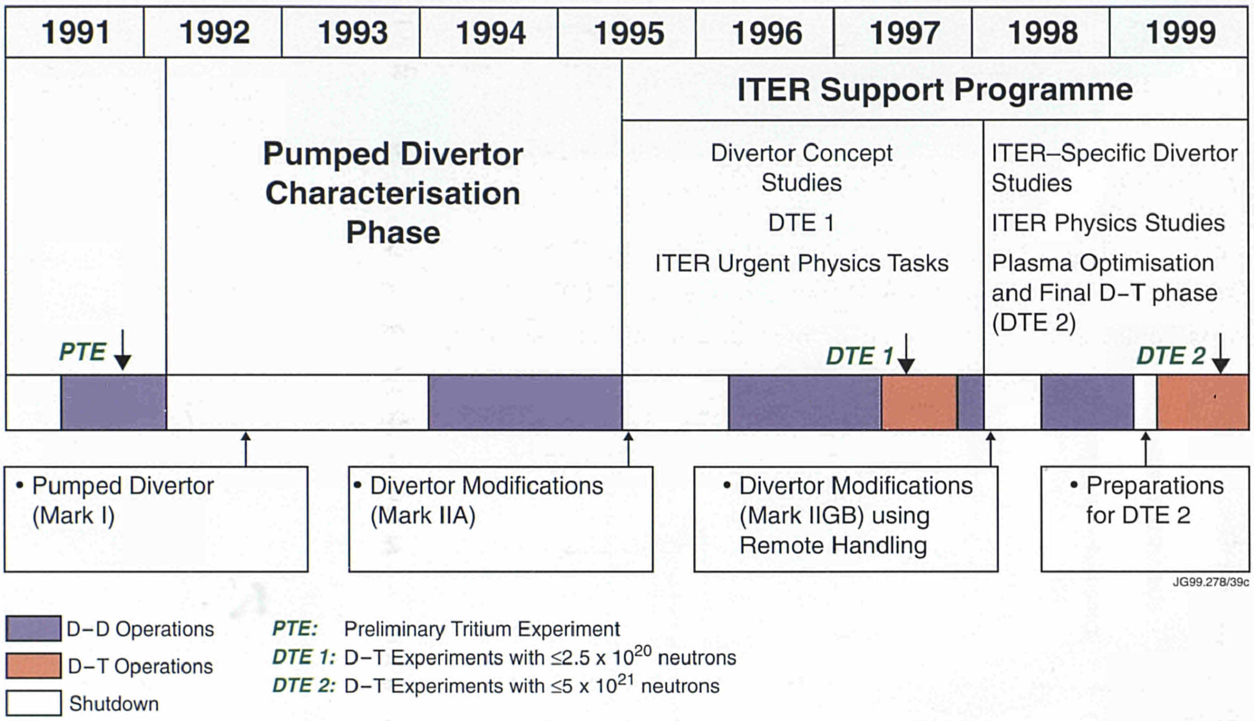


Fig.38: The JET Programme Schedule to end-1999

Further D-T experiments are planned to take place at the end of JET operations. The present Programme Plan foresees such experiments (DTE2) lasting up to eight months and producing up to 5×10^{21} neutrons. Every effort will be made to reduce the actual neutron production, within this upper limit, while still satisfying JET's role in supporting the Next Step in the world fusion programme. In this way, the activation of the JET structure would be kept as low as possible compatible with fulfilling the required objectives. The possible use of the JET facilities beyond the end of 1999 would, however, have a major impact on the planning of DTE2.


THE JET PROJECT
JET 1983-1996

Members and Organisation

Members

The JET Joint Undertaking had the following Members at the end of 1998:

The European Atomic Energy Community (EURATOM);

The Belgian State, acting for its own part ('Laboratoire de Physique des Plasmas de l'École Royale Militaire - Laboratorium voor plasma-physica van de Koninklijke Militaire School') and on behalf of the Université Libre de Bruxelles' ('Service de physique statistique, plasmas et optique non-linéaire de l'ULB'); and of the 'Centre d'Études de l'Energie Nucléaire (CEN)/ 'Studiecentrum voor Kernenergie' (SCK);

The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain;

The Commissariat à l'Énergie Atomique (CEA), France;

The 'Ente per le Nuova Tecnologie, l'Energia e l'Ambiente' ('ENEA') representing all Italian activities falling within the Euratom Fusion Programme including that of the 'Consiglio Nazionale delle Ricerche', (CNR);

The Hellenic Republic, Greece;

The Forskningscenter Risø (Risø), Denmark;

The Grand Duchy of Luxembourg, Luxembourg;

The Austrian Academy of Sciences;

The Instituto de Cooperaçao Cientifica e Tecnológica Internacional (ICCTI), Portugal;

Dublin City University (DCU), Ireland;

The Forschungszentrum Karlsruhe (FZK), Germany;

The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Germany;

The Swedish Natural Science Research Council (NFR), Sweden;

The Swiss Confederation, Switzerland;

The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands;

The Technology Development Centre Finland (TEKES);

The United Kingdom Atomic Energy Authority (UKAEA), Host Organisation.

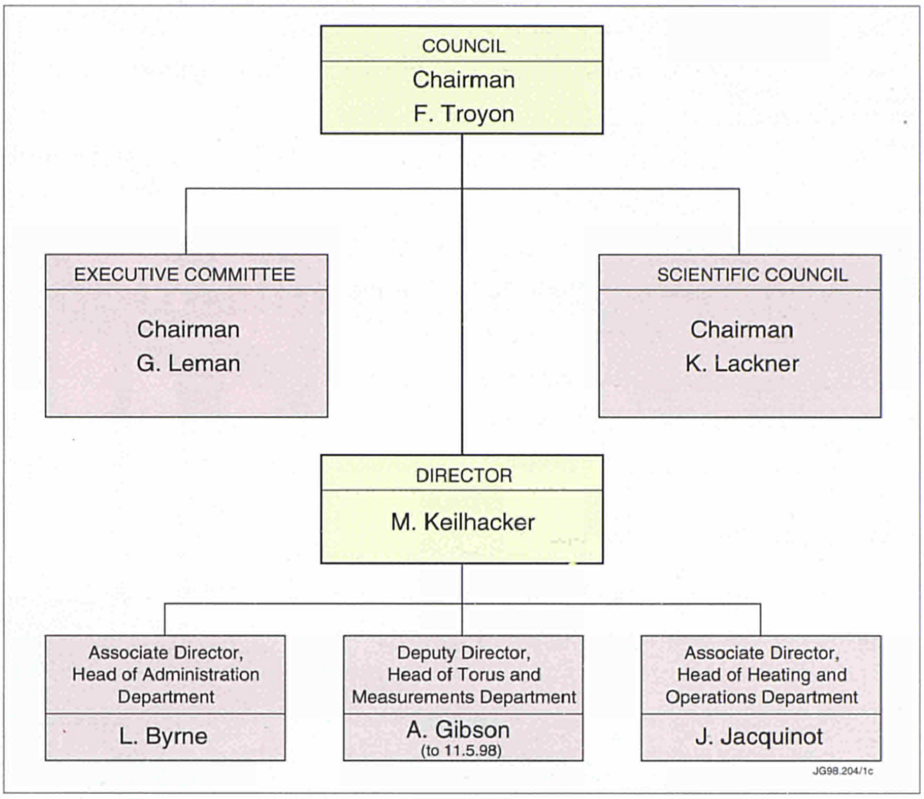


Fig.39: Overall Project Structure

Management

The JET Joint Undertaking is governed by Statutes which were adopted by the Council of the European Communities on 30 May 1978. The organs of the Joint Undertaking are the JET Council and the Director of the Project. The JET Council is assisted by the JET Executive Committee and is advised by the JET Scientific Council (Fig.39).

JET Council

Each member of the Joint Undertaking is represented on the JET Council, which is required to meet at least twice yearly. The Council is responsible for the management of the Joint Undertaking and for:

- Nomination of the Director and Senior Staff of the Project with a view to their appointment by the Commission or the Host Organisation as appropriate;
- Approval of the annual budget, including staffing, the Project Development Plan and the Project Cost Estimates;
- Ensuring collaboration between the Associated Laboratories and the Joint Undertaking in the execution of the Project, including the establishment of rules on the operation and exploitation of JET.

Three meetings of the JET Council were held during the year: on 18th-19th March, 18th-19th June and 14th-15th October 1998. The membership of the JET Council is shown in Appendix I.

JET Executive Committee

The JET Executive Committee is required to meet at least six times a year. Its functions include:

- Advising the JET Council and the Director of the Project on the status of the Project on the basis of regular reports;
- Commenting and making recommendations to the JET Council on the Project Cost Estimates and the Draft Budget, including the establishment of staff, drawn up by the Director of the Project;
- Approving, in accordance with the rules on the award of contracts established by the JET Council, the tendering procedure and the award of contracts;
- Promoting and developing collaboration between the Associated Laboratories and the Joint Undertaking in the execution of the Project.

The membership of the JET Executive Committee is shown in Appendix II. The Committee met six times during 1998: on 5th-6th February, 14th-15th May, 9th July, 16th-17th September, 5th November and 3rd December 1998.

JET Scientific Council

The Statutes confer the following functions on the JET Scientific Council:

- Upon the request of the JET Council, to advise on scientific and technical matters, including proposals involving a significant change in the design of JET, its exploitation, and its long-term scientific implications;
- To perform such other tasks as the JET Council may request it to undertake.

The JET Scientific Council met twice during the year: on 3rd-4th June and 29th-30th September 1998.

The JET-SC Chairman reported to the JET Council, on two occasions, on:

- Results from the DTE1, ITER Urgent Physics and Mark IIGB Divertor Campaigns;
- JET operation at 4T;
- JET Programme to end-1998;
- JET Programme Options to end-1999; and
- Access to JET data for those participating in approved collaboration agreements.

During 1998, the Joint JET and JET Scientific Council Reliability Assessment Group continued to assess the technical risks of JET operation at toroidal fields above 3.45 Tesla.

The membership of the JET Scientific Council is shown in Appendix III.

Host Organisation

The United Kingdom Atomic Energy Authority, as the Host Organisation for the JET Joint Undertaking, has made available to the Joint Undertaking, the land, buildings, goods and services required for the implementation of the Project. The details of such support, as well as the procedures for co-operation between the Joint Undertaking and the Host Organisation, are covered by a "Support Agreement"

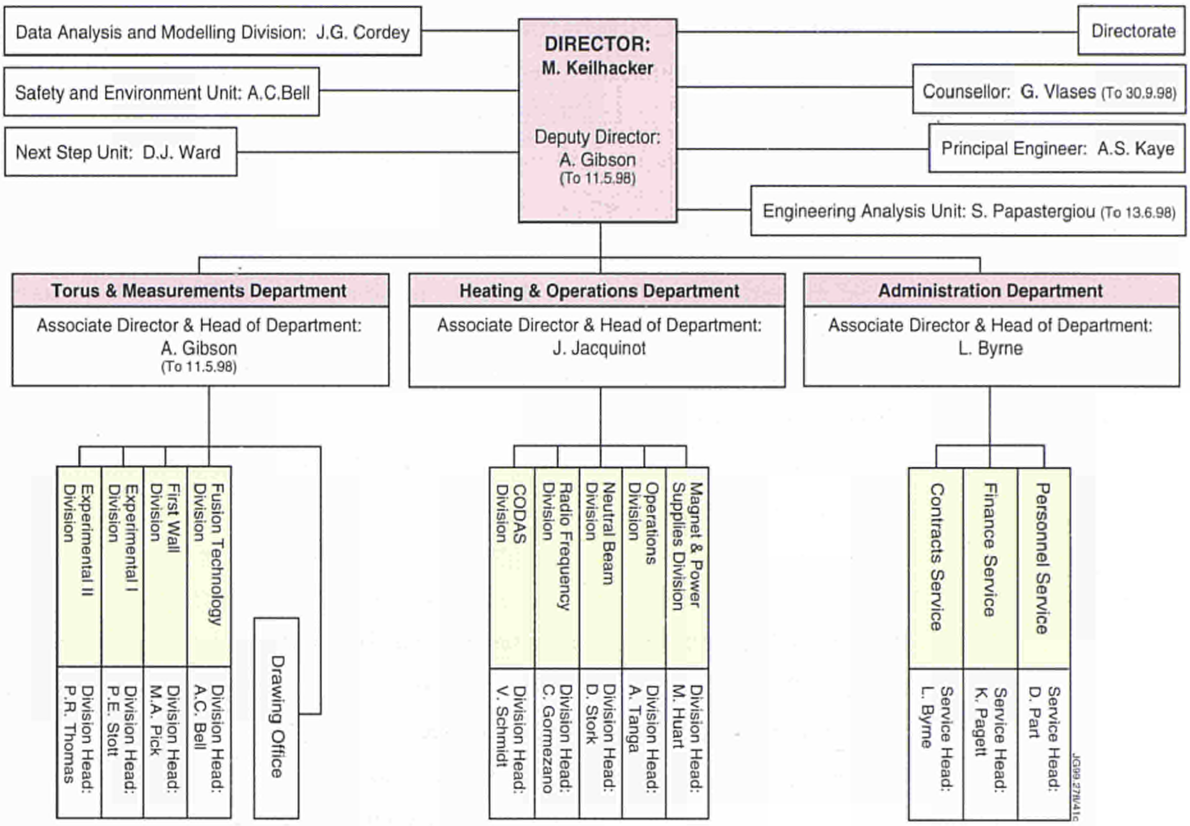


Fig.40: JET Departmental and Divisional Structure

between both parties. In addition to providing staff to the JET Team, the Host Organisation provides support staff and services, at proven cost, to meet the requirements of the JET Project.

Project Team Structure

The Director of the Project

The Director of the Project, Dr. M. Keilhacker, is the chief executive of the Joint Undertaking and its legal representative. He is responsible to the JET Council for the execution of the Project Development Plan, which specifies the programme, and for the execution of all elements of the Project. The Project Development Plan covers the whole term of the Joint Undertaking and is regularly updated. The Director is also required to provide the JET Council and other subsidiary bodies with all information necessary for the performance of their functions.

Internal Organisation

The internal organisation of the Project consists of three Departments and the Directorate. The three Departments are: Torus and Measurements Department; Heating and Operations Department; and Administration Department. The Project Departmental and Divisional structure is shown in Fig.40. Further details of the Technical Departments are given in the 1998 JET Progress Report.

Directorate

The Heads of the Departments report to the Director of the Project and together with the Director form the JET Directorate. Various special functions are carried out by the Director's Office. The Internal Audit Office monitors the financial activities and provides advice on accounting and control procedures as well as maintaining links with the Court of Auditors. The Project Control Office is responsible for financial planning and for the preparation of the Project Development Plan and Project Cost Estimates. The JET Council Secretariat provides Secretarial Services to the JET Council and to the Executive Committee and also to the JET Project Board.

Within the Directorate are three technical units (The Next Step Unit, Safety and Environment Unit, and Engineering and Analysis Unit) and one Division (The Data Analysis and Modelling Division).

Torus and Measurements Department

The Torus and Measurements Department has overall responsibility for the performance capacity of the machine: this includes enhancements directly related to this (excluding heating) and the long term planning associated with integration of these elements to achieve ultimate performance. The Department is also responsible: for fusion technology requirements for the active phase, including tritium handling and processing; for construction and operation of necessary measurement diagnostic systems and the interpretation of experiment data; for maintaining high vacuum conditions; for enhancements to the JET device; and for providing remote handling. The main functions of the Department are:

- to design, procure and implement enhancements to the JET device;
- to provide and maintain clean conditions inside the vessel which lead to high quality plasma discharges;
- to conceive and define a set of coherent measurements;
- to be responsible for construction of necessary diagnostics;
- to be responsible for diagnostics operation, quality of measurements and definition of plasma parameters;
- to design and develop remote handling methods and tools to cope with JET requirements;
- to design and construct facilities for handling tritium and for waste management.

The Department consists of four Divisions (First Wall Division, Fusion Technology Division, Experimental Division 1 (ED1) and Experimental Division 2 (ED2)) and one Group (Drawing Office).

Heating and Operations Department

The overall responsibility of the Heating and Operations Department is for the efficient and effective day-to-day operation of the machine. In addition, the Department has responsibility for plasma heating and auxiliary equipment and related physics; the design and operation of power supplies; the data systems comprising data control, acquisition and management, as well as contributing to the execution and evaluation of JET's experimental programme. The main functions of the Department are:

- preparing and co-ordinating operation of the machine across Departments and Divisions;
- heating and current drive and analysis of its effects in the plasma;
- plasma fuelling, including pellet injection;
- designing and employing power supplies for ensuring efficient operation and control of the machine; and
- to organise and implement data acquisition and computing.

The Department consist of five Divisions (Operations Division, Neutral Beam Heating Division, Radio Frequency Heating Division, Magnet and Power Supplies Division and Control and Data Acquisition System Division (CODAS)).

Project Management

The internal organisation of the Project (Fig.40) is enhanced by a matrix managerial structure which functions through Committees and Task Forces led by the Director and other senior staff.

The JET Project Board is responsible to the Director for the overall management of the Project while the Technical Project Board addresses issues of a technical and scientific nature. Both are chaired by the Director and attended by Division and Service Heads. The Experiments Committee, also chaired by the Director, establishes and monitors the Experimental Programme within the broad outline set by the Project Development Plan. Detailed technical appraisals of the Programme are made by the Co-ordination Meetings (Commissioning/Operations, Design/Assembly and Data Evaluation). The formulation, execution and review of the Programme is carried out by Task Forces (there were four during 1998), the leaders of which report at the Experiments Committee. Science Meetings are held on a weekly basis to subject experimental proposals and results to discussion and peer review.

Administration Department

The Administration Department is responsible for providing Contracts, Finance and Personnel services to the Project. In addition, the Department is responsible for the administration of the Publications and Public Relations Groups.

Administration

Introduction

The three main aspects of JET's administration - Finance, Contracts and Personnel - are reported in this section. There are also contributions on the Public Relations and Publications Groups.

Finance

The initial budgets for 1998 were approved at 75.05MioECU for Commitments and 79.56MioECU for both Income and Payments. The Commitments and Payments Budgets included an Operations Reserve of 5.80MioECU. The JET Council agreed the release from the Commitments Budget of 4.50MioECU for use in 1998 and the balance of 1.30MioECU to be carried forward to 1999. The Payments Operations Reserve was also released in full but 4.50MioECU has been reserved against the 9.00MioECU commitment provision made in 1997 in line with the ex-gratia payment envisaged as part of the out-of-court settlement of the JET UKAEA staff case proposed by the European Parliament.

The Commitments and Payments Budgets each are divided into two phases of the Project - Extension to Full Performance and the Operational Phase; subdivisions distinguish between investment, operating, and personnel costs, each with further detailed cost codes. The Extension to Full Performance Phase was closed during 1998.

Commitments

Of the total final appropriations in 1998 of 78.14MioECU (including 3.09MioECU brought forward from previous years), 65.85MioECU was committed and the balance of 12.29MioECU was available for carrying forward to 1999. The details of the commitment appropriations available and of the amounts committed in the Operational Phase during the year are shown in Tables 3 and 4.

COMMITMENT APPROPRIATIONS	MioECU
FINAL COMMITMENTS BUDGET FOR 1998	75.05
AMOUNTS BROUGHT FORWARD FROM PREVIOUS YEARS.	3.09
	78.14
COMMITMENTS MADE DURING THE YEAR	65.85
BALANCE OF APPROPRIATIONS AT 31 DECEMBER 1998 AVAILABLE FOR USE IN 1999	**12.29**

Table 3: Commitment Appropriations for 1998

Income and Payments

The actual income for 1998 was 77.10MioECU to which was added 2.05MioECU available appropriations brought forward from previous years giving a total of 79.15MioECU. Compared to the budget there was an excess of income in respect of bank interest and other income of 0.02MioECU, which is carried forward to offset Members' future contributions and a shortfall in income for Specific Fusion Research of 0.43MioECU. This shortfall is offset by a corresponding reduction in the payments appropriations. After adjustment for the shortfall in income, total payment appropriations for 1998 were 85.65MioECU; payments in the year amounted to 65.79MioECU; 0.17MioECU was transferred from the Special Account and will be offset against Members' future contributions. The balance of unspent payment appropriations was 19.69MioECU, of which 13.80MioECU was transferred to the Special Account to meet commitments outstanding at 31 December 1998 and 5.89MioECU has been carried forward and will be used to offset Members' future contributions. (Payments are summarised in Tables 4 and 5).

		COMMITMENTS		PAYMENTS	
BUDGET HEADING		BUDGET APPRO-PRIATIONS MioECU	OUTTURN MioECU	BUDGET APPRO-PRIATIONS MioECU	OUTTURN MioECU
PHASE 2	**EXTENSION TO FULL PERFORMANCE**				
TITLE 1	PROJECT INVESTMENTS	0.00	0.00	0.03	0.03
PHASE 3	**OPERATIONAL**				
TITLE 1	PROJECT INVESTMENTS	0.16	0.10	0.55	0.52
TITLE 2	OPERATING COSTS	31.01	22.45	32.14	22.26
TITLE 3	PERSONNEL COSTS	46.97	43.30	52.93	42.98
TOTAL PHASE 3		78.14	65.85	85.62	65.76
PROJECT TOTAL - ALL PHASES		**78.14**	**65.85**	**85.65**	**65.79**

Table 4: Commitments and Payments for 1998

Table 5: Income and Payments for 1998

INCOME AND PAYMENTS	MioECU	
INCOME		
BUDGET FOR 1998		79.56
INCOME RECEIVED DURING 1998		
(I) MEMBERS' CONTRIBUTIONS	75.76	
(II) BANK INTEREST	1.26	
(III) MISCELLANEOUS	0.01	
(IV) UNUSED APPROPRIATIONS BROUGHT FORWARD FROM PREVIOUS YEARS	2.05	
(V) INCOME FOR SPECIFIC FUSION RESEARCH	0.07	
TOTAL INCOME		79.15
VARIATION FROM BUDGET		(0.41)
REPRESENTING:		
INCOME IN EXCESS OF BUDGET CARRIED FORWARD TO OFFSET AGAINST MEMBERS' CONTRIBUTIONS		0.02
SHORTFALL OF INCOME AGAINST BUDGET REDUCING AVAILABLE PAYMENT APPROPRIATIONS		(0.43)
PAYMENTS		
BUDGET FOR 1998	79.56	
AMOUNTS AVAILABLE IN THE SPECIAL ACCOUNT TO MEET OUTSTANDING COMMITMENTS AT 31 DECEMBER 1997.	6.52	
REDUCTION IN APPROPRIATIONS CORRESPONDING TO SHORTFALL OF INCOME	(0.43)	
TOTAL AVAILABLE APPROPRIATIONS FOR 1998		85.65
ACTUAL PAYMENTS DURING 1998	65.79	
FROM SPECIAL ACCOUNT TRANSFERRED TO INCOME.	0.17	
		65.96
UNUTILISED APPROPRIATIONS AT 31 DECEMBER 1998		
CARRIED FORWARD IN THE SPECIAL ACCOUNT TO MEET OUTSTANDING COMMITMENTS AT THAT DATE.	13.80	
CARRIED FORWARD TO OFFSET MEMBERS' FUTURE CONTRIBUTIONS	5.89	
		19.69

Table 6: Percentage Contributions to JET for 1998, based on the Euratom participation in Associations' Contracts for 1998

MEMBER	%	MioECU
EURATOM	80.0000	60.61
BELGIUM	0.1817	0.14
CIEMAT, SPAIN	0.4186	0.32
CEA, FRANCE	1.8581	1.41
ENEA, ITALY	1.8395	1.39
RISO, DENMARK	0.0827	0.06
LUXEMBOURG	0.0037	0.00
ICCTI, PORTUGAL	0.0970	0.07
DCU, IRELAND	0.0378	0.03
KFA, GERMANY	0.5388	0.41
IPP, GERMANY	2.4385	1.85
FZK, GERMANY	0.7578	0.57
NFR, SWEDEN	0.2299	0.17
SWITZERLAND	0.4978	0.38
FOM, NETHERLANDS	0.3158	0.24
TEKES, FINLAND	0.0895	0.07
UKAEA	10.5921	8.02
ÖAW, AUSTRIA	0.0207	0.02
	100.0000	**75.76**

FINANCIAL TRANSACTIONS	MioECU
CUMULATIVE COMMITMENTS	1,787.5
CUMULATIVE PAYMENTS	1,764.9
UNPAID COMMITMENTS	22.6
AMOUNT CARRIED FORWARD IN THE SPECIAL ACCOUNT	13.8
AMOUNT AVAILABLE FROM 1997 AND 1998 TO SET OFF AGAINST FUTURE CONTRIBUTIONS FROM MEMBERS	6.1

Table 7: Summary of Financial Transactions at 31 December 1998

Contributions from Members

The budget for Members' contributions was 77.76MioECU (Table 6) funded as follows:

- 80% from the general budget of the European Atomic Energy Community (Euratom);
- 10% from the UK Atomic Energy Authority as Host Organisation;
- 10% from members who have Contracts of Association with Euratom in proportion to the previous year's contribution from Euratom towards the cost of their Association Contracts.

Bank Interest

During the year, funds are normally received on a quarterly basis in respect of Members' contributions and intermittently for other items. Therefore, the Project has funds not immediately required for the discharge of its commitments; these funds are placed on deposit accounts at market interest rates. During 1998, earned interest amounted to 1.26MioECU.

Appropriations from Earlier Years

Unused payment appropriations and excess income over budget of 2.05MioECU arising in 1996 were transferred to income in 1998.

Summary

Table 7 summarises the financial transactions of the JET Joint Undertaking as at 31 December 1998. These have yet to be audited. The final audited accounts will be published in due course.

Contracts Service

Contracts Activity

The contract activity for 1998 is summarised in Table 8. Many of the larger contracts involved advance and retention payments for which bank guarantees were required by JET. The total value of guarantees held as at 31 December 1998 was 187,100ECU.

Table 8: Formal Tender Actions and Contracts placed during 1998

FORMAL TENDER ACTIONS	SUPPLY	SERVICE	PERSONNEL	TOTAL
NUMBER	153	29	71	253

CONTRACTS PLACED	MAJOR (>75KECU)	MINOR (<75KECU)	DIRECT ORDERS	AMENDMENTS	TOTAL
QUANTITY	52	2,103	6,636	564	9,355
VALUE					
MIOECU	5.789	7.849	1.519	24.058	39.215

Imports and Exports Services

Contracts Service is responsible for the import and export of JET goods. 377 imports were handled in 1998 while the total exports amounted to 186. There were also 647 issues of goods to UK firms. The total value of issues to all countries for the year was 2.672MioECU.

Stores Organisation

The bulk of JET material is procured on a "just in time" basis and the Stores Organisation provides a receipts and delivery service for this material to the Project. The total number of such receipts in 1998 amounted to 10,023.

Administration of Contracts

The distribution of contracts between countries is shown in Tables 9 and 10. Table 9 includes all contracts with a value of 10,000 ECU and above placed prior to 1984, together with all contracts placed during the period 1984-98. Table 10 is an allocation of "high-tech" contracts, which is based on the figures shown in Table

Table 9: Allocation of JET Contracts

COUNTRY	TOTAL OF KECU	% OF TOTAL
UK	746,594	61.58
GERMANY	169,792	14.00
FRANCE	93,315	7.69
ITALY	61,085	5.04
SWITZERLAND	43,526	3.59
DENMARK	13,812	1.14
NETHERLANDS	18,746	1.55
BELGIUM	13,580	1.12
SWEDEN	7,623	0.63
IRELAND	1,334	0.11
FINLAND	958	0.08
SPAIN	224	0.02
PORTUGAL	122	0.01
OTHERS	41,781	3.44
TOTALS	**1,212,492**	**100.00**

COUNTRY	TOTAL OF KECU	% OF TOTAL
UK	153,421	28.58
GERMANY	147,372	27.42
FRANCE	81,427	15.14
ITALY	53,128	9.89
SWITZERLAND	35,417	6.60
DENMARK	7,448	1.39
NETHERLANDS	17,303	3.22
BELGIUM	5,080	0.95
SWEDEN	5,024	0.94
IRELAND	426	0.08
FINLAND	303	0.06
SPAIN	224	0.04
PORTUGAL	67	0.01
OTHERS	30,473	5.68
TOTAL	**537,113**	**100.00**

Table 10: Allocation of JET "High-Tech" Contracts

9 but excludes all contracts below 5,000 ECU and contracts covering civil works, installation, pipework, consumables (including gases), maintenance operations and office equipment (including PCs).

Personnel Service

Staffing Position

The number of JET Team staff fell by 24% this year (Table 11) primarily reflecting the gradual redeployment of Euratom staff in the period up to the end of 1999 when the JET Joint Undertaking shall terminate as a Project on expiry of its term. Seventy six and a half team posts were vacated in 1998 by staff departures and a further two and a half by five UKAEA staff converting to part time working. Of the sixty Euratom and DGXII staff who left, fifty seven transferred to new posts in the Commission and one retired. Seventeen UKAEA staff left, including six retirements and three who were recruited to posts with the Commission. There were no new Team staff assignments in 1998. Figure 41 shows the composition of the JET Team by nationality. Contract personnel on individual contracts, charged to Title 3 of the JET budget, numbered 164.5 at 31 December 1998, a decrease of fifteen on the previous year.

	DEC 1996	DEC 1997	DEC 1998
UKAEA	229.5	209.0	192.5
EURATOM	115.0	106.0	47.0
DGXII	5.0	4.0	3.0
TOTAL	**349.5**	**319.0**	**242.5**

Table 11: JET Staffing Position over the period 1996-98

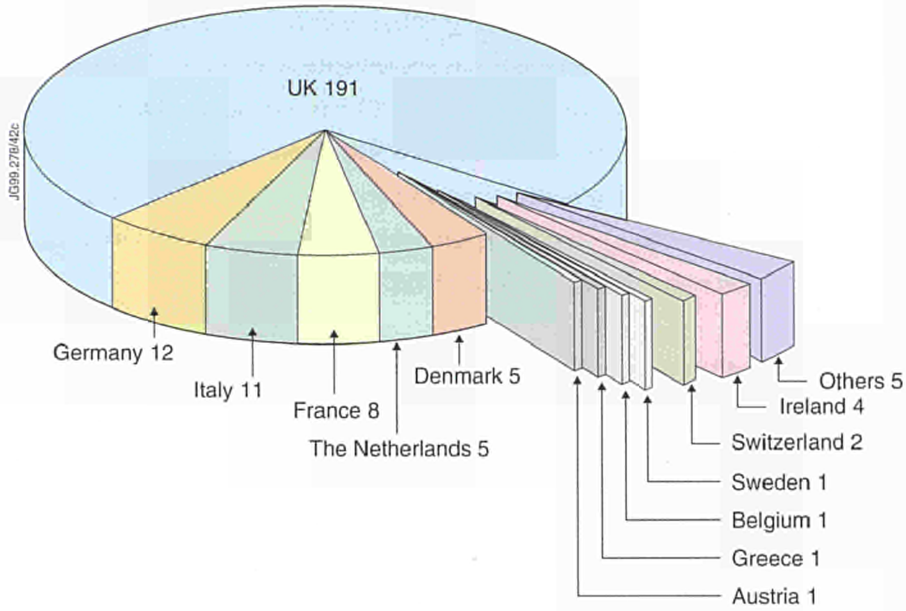


Fig.41: Composition of JET Team by nationality at 31 December 1998

JET Statutes: the Project Team

During the year the JET Council completed its task of revising the JET Statutes and Supplementary Rules concerning the secondment, assignment and management of the staff of the JET Joint Undertaking, following the judgement of the European Court of First Instance in December 1996 concerning the status of UKAEA employees assigned to JET. The Council of Ministers approved the modified JET Statutes which inter alia enable future recruits to the JET Team to be seconded by their Parent Organization under a new Secondment Scheme. The revised Supplementary Rules and the Secondment Scheme Rules which were developed by a JET Council Working Group, were approved in October 1998 by the JET Council.

Promotions

In 1998, four existing Team staff were appointed to posts at Group Leader level comprising two UKAEA staff members and two Euratom. Ten UKAEA and eleven Euratom staff were promoted to a higher grade by their respective employers, following the annual promotion exercises.

Conditions of Service

Euratom staff received the usual pay increments and bonuses, following the reviews of staff performance. For the first time the performance of UKAEA staff at JET was reviewed jointly with UKAEA Culham employees and performance pay increases and bonuses awarded accordingly.

At the end of 1998, the UKAEA renewed the contracts of the fixed term appointees at JET whose contracts were due to expire at the end of the year, including three who were given permanent appointments.

During 1998, the Group Incentive Bonus Scheme which was formerly paid to UKAEA staff at Level 6 and 7 was extended to all UKAEA staff and bonuses of 1.8% of salary were paid.

JET has reviewed its working arrangements and documentation in the light of the UK Working Time Regulations and has implemented a number of measures to ensure that JET's arrangements are compliant. JET has also updated and renewed its registration under the UK Data Protection Act to ensure that personal data continuing to be held during the winding up period is properly registered.

The UKAEA Retention of Experience Allowance was paid to all 197 UKAEA staff in post on 31 December 1998, at a cost of 1.27MioECU.

Staff Relations

At the beginning of the year there were several meetings between members of the JET Management and the Staff Representatives Committee. Subjects discussed included the JET budget and programme to the end of 1999, the Project's future thereafter, the working pattern for JET operations in 1998 and Sunday working. Following difficulties in securing nominations for the Staff Representatives Committee, in May 1998 the staff decided not to elect an SRC.

The JET UKAEA Team Staff dispute concerning the status of the UKAEA staff assigned to JET continued during the year, with cases proceeding through the European Court of First Instance.

In 1994, the European Parliament formally voted to make available from the Community budget 2MioECU for disbursement to UKAEA staff assigned to JET. In October 1997 the Secretary of State for Social Security turned down the UKAEA's appeal against the UK Department of Social Security's ruling that there was a liability for National Insurance contributions associated with this payment. In October 1998 the statement of grounds for this decision was formally notified to the UKAEA and JET and was not contested further, but the issue of whether the employer's NI contributions owing to the Contributions Agency could be taken from the original 2MioECU remained unclear. Payment was made from JET funds as an interim measure, with JET Council agreement, while further legal advice was sought on the status of the 2MioECU, 10.2% of which had been witheld from the initial disbursements in 1994.

JET supports social activities among the staff by subsidising events and activities. The Social Sports and Cultural Committee was awarded £18,300 in 1998 to allocate to staff activities and clubs.

Assigned Associate Staff

The Associations provided a total of 27.7 man-years of effort to JET during 1998. Tables 12 and 13 show contributions made by the Associations in 1997 - 8 and the distribution of Assigned Associate Staff within the Project.

Consultants

Two consultants contributed 66 man-days of scientific/technical support work to the Project.

Table 12: Staff assignments from Associated Laboratories during 1997-98

LABORATORY	MAN-YEARS 1997	MAN-YEARS 1998
UKAEA (UK)	14.8	12.9
NFR (SWEDEN)	6.0	4.7
IPP/KFK (GERMANY)	2.3	1.2
CEA (FRANCE)	1.5	2.0
ENEA (ITALY)	2.3	3.0
ICCTI (PORTUGAL)	2.0	2.2
CRPP (SWITZERLAND)	1.8	0.1
CIEMAT (SPAIN)	0.1	0.1
TEKES (FINLAND)	1.0	1.5
TOTAL	**31.8**	**27.7**

Post Graduate Researchers

At the end of 1998, there were two post-graduate researchers at JET. One under the Cooperative Awards in Science and Engineering (CASE) and the other under the Commission's Mobility Scheme.

Students

JET supported 21 students in 1998, 18 of whom undertook long term placements of 13 weeks or more. JET also continued to be an Approved Work Experience Provider. As a result 17 secondary pupils from local schools spent on average, two weeks gaining work experience relevant to their examination studies. In addition JET maintained its support of placements under the CSN agreement with the French government, whereby military service can be carried out in a non-military role at a research establishment.

Training

During 1998:

- 44 Team staff and 28 contractors attended short external training courses in order to acquire specific required skills;
- 6 Team staff received support for long-term courses for professional development;
- 156 personnel from all categories of staff attended major conferences and workshops.

Table 13: Assigned Staff within the Project during 1997-98

DEPARTMENT	MAN-YEARS 1997	MAN-YEARS 1998
TORUS AND MEASUREMENT	18.1	14.0
HEATING AND OPERATIONS	7.8	6.8
DIRECTORATE AND DATA ANALYSIS AND MODELLING	5.9	6.9
TOTAL	**31.8**	**27.7**

Approximately 75 Team staff received language tuition in French, German and Italian. 15 candidates sat the London Chamber of Commerce and Industry examinations in the relevant language.

Press and Public Relations

In 1998 it was important to maintain the good level of public visibility that JET had achieved during the DTE1 experiments in 1997. The Remote Tile Exchange (RTE) provided an opportunity for maintaining a reasonable level of input to science journalists. The RTE was covered in a new video that has proven extremely popular called "Reaching Ahead, A Man-Machine System at JET". There was also a successful press visit to see the work as it proceeded. Subsequently, there was considerable TV coverage, including an episode of BBC TV's "Tomorrow's World" centred around several reports from JET, and including an interview with the Director enabling him to state his confidence in the future of fusion as a power source.

A new public relations venture started at the SOFT Conference in Marseille, France in September and was followed up at the IAEA Conference in Yokohama, Japan in October. This was an exhibit entitled "25 Years of JET" giving a detailed account of the scientific and technical history of JET. In addition the travelling local exhibition continued its tour of the Oxfordshire County Museums receiving a further 13,000 visitors by the end of the year.

Exhibitions and videos are useful and powerful public relations tools but nothing is better than a visit to see JET and to feel the enthusiasm and commitment of the staff. In 1998, despite resource limitations, over 1,200 people visited the site. These included three UK MPs (Norman Baker, Michael Heseltine and Andrew Stunnell), one UK MEP (Gordon Adam), delegations from the Finnish and Dutch Nuclear Societies and M. René Pellat, Haut Commissionaire of the CEA.

Publications Group

The Publications Group provides a Graphics, Phototypesetting, Photographic and Reprographics service for the Project. The Group is led by the Publications Officer, who is also responsible for the clearance, production and distribution of all JET documents. In addition, the Group arranges attendance at major international Conferences, and prepares posters for these Conferences and Meetings.

Conferences

JET provided contributions to a number of major meetings, as follows:

- 13th International Conference on Plasma Surface Interactions, San Diego, USA (May 1998) (5 Invited Papers and 11 Posters);
- 25th European Physical Society Conference on Plasma Physics and Controlled Fusion, Prague, Czechoslovakia (June 1998) (2 Invited Papers and 33 Posters);

- 20th Symposium on Fusion Technology, Marseilles, France (September 1998) (2 Invited Papers and 26 Posters);
- 17th IAEA Fusion Energy Conference, Yokohama, Japan (October 1998) (11 Invited Papers and 14 Posters); and
- 40th Annual Meeting of the American Physical Society – Division of Plasma Physics, New Orleans, USA (November 1998) (1 Invited Paper and 4 Posters).

In total, the Group prepared 129 Papers and 98 Posters for presentations to about twenty different Conferences throughout the world. Arrangements were also made by the Group for 100 participants to attend these major meetings during the year.

Publications

The Publications Office is responsible for the clearance and production of all JET presentations (including Journal Papers, Reports, Conference Papers, Poster Contributions, Lectures, etc). Throughout 1998, over 216 publications were cleared for external presentation.

During the year, 253 documents were published from the Project and the full list is included as an Appendix to the 1998 JET Progress Report. This total included 11 JET Reports, 89 JET Preprints, 6 JET Internal Reports and 6 JET Divisional Notes. All these documents are produced and disseminated by the Group on a wide international distribution. In addition, 101 papers were published in scientific Journals.

In total, the Group produced 4934 new illustrations and figures and took 2400 new photographs for publications and other disseminated material during 1998.

APPENDIX I

The JET Council (Chairman: F. Troyon; Vice-Chairman: J. Routti)

Member	Representative
The European Atomic Energy Community (EURATOM)	J. Routti (Vice-Chairman) U. Finzi
The Belgian State, acting for its own part ('Laboratoire de Physique des Plasmas de l'École Royale Militaire - Laboratorium voor plasma-physica van de Koninklijke Militaire School') and on behalf of the Université Libre de Bruxelles' ('Service de physique statistique, plasmas et optique non-linéaire de l'ULB'); and of the 'Centre d'Études de l'Energie Nucléaire (CEN)/'Studiecentrum voor Kernenergie' (SCK)	P.E.M. Vandenplas G. Michaux
The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain	A. Grau Malonda C. Alejaldre
The Commissariat à L'Énergie Atomique (CEA), France	Mrs. C. Cesarsky M. Chatelier
The 'Ente per le Nuova Tecnologie, l'Energia e l'Ambiente' ('ENEA') representing all Italian activities falling within the Euratom Fusion Programme including that of the 'Consiglio Nazionale delle Ricerche', (CNR); dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	R. Andreani C. Mancini
The Hellenic Republic (Greece)	A. Katsanos A. Grecos
The Forskningscenter Risø (Risø), Denmark	J. Kjems Ms. A Lisberg (to June) J.P. Lynov (from June)
The Grand Duchy of Luxembourg (Luxembourg)	J. Olinger C. Bartocci
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal (to October) The Instituto de Cooperaçao Científica e Tecnológica Internacional (ICCTI), Portugal (from October)	C. Varandas Mrs. M.E. Manso
Ireland (to October) Dublin City University (DCU) (from October)	F. Turvey M. Hopkins (to November)
The Forschungszentrum Jülich GmbH (KFJ), Federal Republic of Germany (to October) The Forschungszentrum Karlsruhe (FZK), Germany (from October)	J.E. Vetter
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Germany	K. Pinkau
The Österreichische Akademie der Wissenschaften (ÖAW), Austria	H. Winter (from October) E. Kny (from October)
The Swedish Natural Science Research Council (NFR), Sweden	G. Leman T. Hellsten
The Swiss Confederation	F. Troyon (Chairman) P. Zinsli
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	K.H. Chang F.C. Schüller
The Technology Development Centre Finland (TEKES)	S. Karttunen R. Munther
The United Kingdom Atomic Energy Authority (UKAEA)	J.R. Bretherton D.C. Robinson

Secretary: J. McMahon, JET Joint Undertaking

APPENDIX II

The JET Executive Committee (Chairman: G. Leman; Vice-Chairman: J-P. Rager)

Member	Representative
The European Atomic Energy Community (EURATOM)	J-P. Rager (Vice-Chairman) U. Finzi
The Belgian State, acting for its own part ('Laboratoire de Physique des Plasmas de l'École Royale Militaire - Laboratorium voor plasma-physica van de Koninklijke Militaire School') and on behalf of the Université Libre de Bruxelles' ('Service de physique statistique, plasmas et optique non-linéaire de l'ULB'); and of the 'Centre d'Études de l'Energie Nucléaire (CEN)/'Studiecentrum voor Kernenergie' (SCK)	R. Vanhaelewyn P.E.M. Vandenplas
The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain	F. Manero (to January) A. Grau Malonda E. Ascasibar (from January)
The Commissariat à L'Énergie Atomique (CEA), France	Mrs. P. Livanos B. Goudal (to July) B. Franel (from July)
The 'Ente per le Nuova Tecnologie, l'Energia e l'Ambiente' ('ENEA') representing all Italian activities falling within the Euratom Fusion Programme including that of the 'Consiglio Nazionale delle Ricerche', (CNR); dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	A. Coletti F. Pecorella
The Hellenic Republic (Greece)	N. Chrysochoides
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The Grand Duchy of Luxembourg (Luxembourg)	C. Bartocci M. Hoffman
The Junta Nacional de Investigação Cientîfica e Tecnológica (JNICT), Portugal (to October) The Instituto de Cooperaçao Cientîfica e Tecnológica Internacional (ICCTI), Portugal (from October)	J. da Costa Cabral F. Serra
Ireland (to October) Dublin City University (DCU) (from October)	F. Turvey Ms. S. Fahy
The Forschungszentrum Jülich GmbH (KFJ), Federal Republic of Germany (to October) The Forschungszentrum Karlsruhe (FZK), Germany (from October)	U. Nobbe (to May) A. Kurz (from May)
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Germany	Mrs. I. Zilker-Kramer (to October) Mrs. S. Agnoli (from October)
The Österreichische Akademie der Wissenschaften (ÖAW), Austria	—
The Swedish Natural Science Research Council (NFR),	G. Leman (Chairman) L. Gidefeldt
The Swiss Confederation	M. Tran S. Berthet
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The Technology Development Centre Finland (TEKES)	R. Salomaa R. Munther
The United Kingdom Atomic Energy Authority (UKAEA)	F. Briscoe M. Cox

Secretary: J. McMahon, JET Joint Undertaking

APPENDIX III
The JET Scientific Council (Chairman: K. Lackner)

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