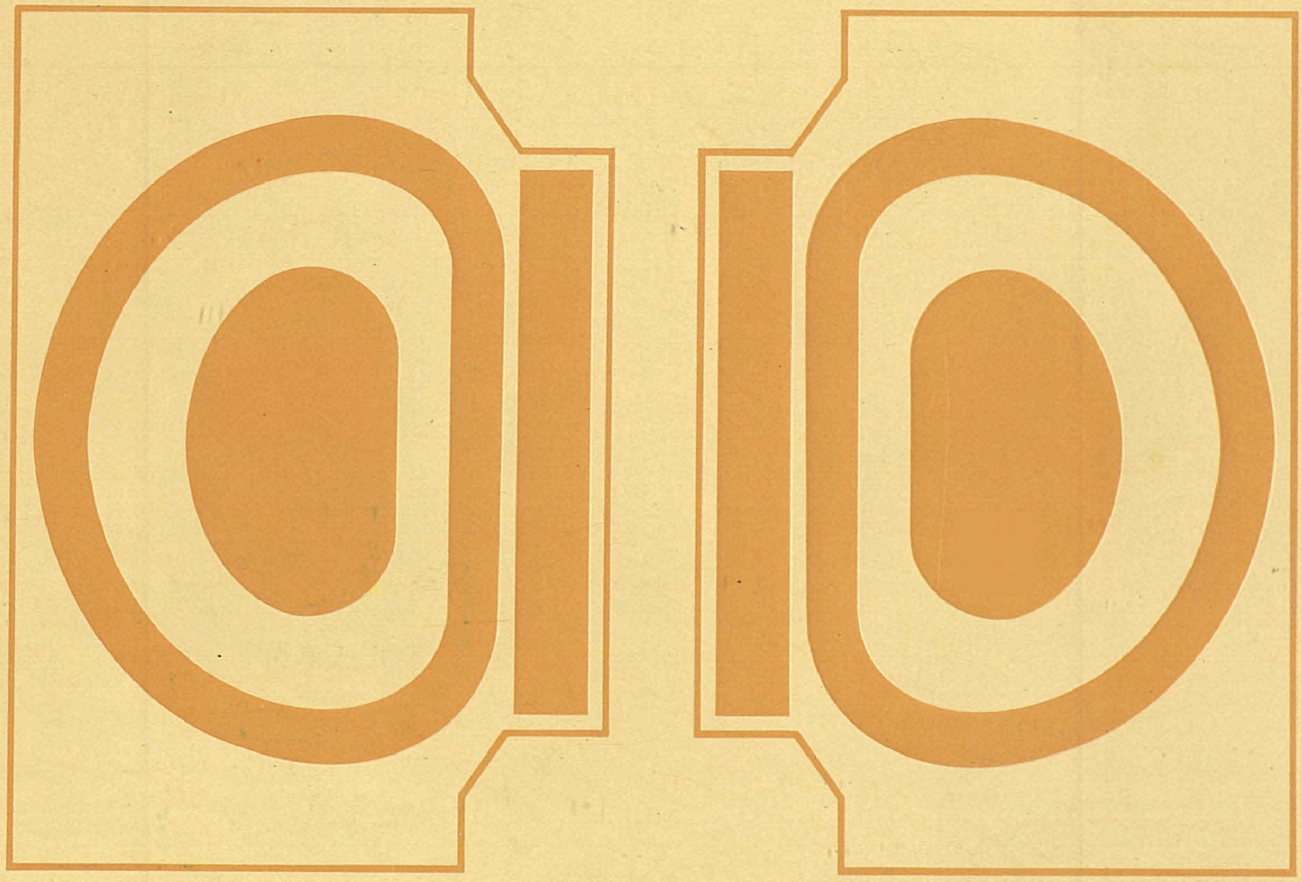
JOINT EUROPEAN TORUS JET

JET JOINT UNDERTAKING

ANNUAL REPORT 1990



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Preface

Preface

The Joint European Torus (JET) has now operated successfully for the past eight years. In each year, JET has made major contributions to the development of nuclear fusion research. It is gratifying to report that JET has maintained its momentum during 1990 and has retained its position as the world's leading fusion experiment.

The first half of the year was spent on planned modifications to the machine, which included the replacement of one of the toroidal field coils. This extremely complex task, which required removal of a complete machine octant, was an important achievement which was carried out successfully within the scheduled timescale. The main aim of the experimental programme in the second half of the year was to improve plasma performance in operations with good reliability and with a high proportion of experiments with large plasma currents, up to 7MA.

Both additional heating systems have had significant successes. One of the neutral beam injectors has been converted from 80kV to 140kV operation, with the objective of achieving greater beam penetration into the plasma. Although the beam power is reduced at this voltage, the increased penetration has enabled more efficient heating of the all-important central plasma region. This loss of heating power has been compensated for by an increase in power from the second injector, which has been upgraded above the design specification of 80kV to 85kV operation. The flexibility and usefulness of the neutral beam injection system was further enhanced by the successful operation of one unit with Helium beams at 120kV. The purpose was to reduce the neutron production which activates the structure and which would limit the in-vessel working at the start of the subsequent shutdown.

The radio-frequency heating generators have also been upgraded, with which 21MW of power was coupled to the plasma, which is close to the anticipated limit with this present system. A notable technical achievement has been the use of a feedback system to automatically control the plasma position to maintain a constant loading resistance during transitions from the low to the high confinement mode of plasma operation.

A new facility, a prototype lower hybrid current drive system was introduced on the machine during the year. This prototype, one third the size of the full system, has launched about 1.5MW of microwave power into the plasma to drive a 1MA plasma current. Such current drive systems could allow a tokamak fusion reactor to operate in steady state.

During the year, a prototype high-speed pellet injector has been developed, which has been designed to fire 6 millimetre diameter pellets of solid deuterium into the plasma at speeds up to 4 kilometres per second. This should allow pellets to penetrate to the centre of a hot plasma where the maximum density is required and provide important information on refuelling a plasma reactor.

During the operational period in the second half of the year, JET was operating at full power and made substantial progress towards achieving reactor conditions. The best value achieved of the fusion triple product [$n_i \tau_E T_i$] was $9 \times 10^{20} m^{-3}$keVs, less than an order of magnitude from that required in a reactor. This is closer to reactor conditions than any other fusion experiment, which demonstrates JET's important role in determining the parameters required for the Next Step of the development programme. JET is in fact the only machine in the world to have reached, in individual experiments, the plasma temperatures, densities and confinement times required in a reactor. However, these values have not been achieved simultaneously. The lining of parts of the inner wall of the torus with beryllium has played a major role in the reduction of impurities in the plasma and in the resultant improvement of JET plasma parameters.

One major problem requiring a solution before a reactor can be built is that of removing impurities from the plasma, as impurities rapidly deteriorate plasma parameters to the extent that the reactions would no longer be self-sustaining in a reactor. The JET Council has already agreed a proposal to extend the Project to 1996 in order to enable the Project to address this problem. Whilst awaiting the approval of the Council of Ministers for the proposed extension, JET is required to operate two parallel programmes, which is causing considerable strain on both staff and resources. I hope very much that the situation will be resolved in the near future and I thank all the staff for their patience.

The fusion community as a whole is actively engaged in planning the Next Step beyond JET. This is likely to be a world-wide collaboration involving the United States of America, the USSR, Japan and Europe, with the aim of designing an experimental reactor, called ITER [International Thermonuclear Experimental Reactor]. The Fusion Programme Evaluation Board, set up by the Commission to conduct an independent evaluation of the Community's programme in the field of Controlled Thermonuclear Research, has recommended Europe's participation in ITER whilst retaining the capability to proceed with NET if the ITER initiative proves too difficult to continue. JET's recent results have been crucial in defining the parameters for a next step device, to the extent that these may now be defined with a high degree of confidence. I believe this in itself is a measure both of JET's pre-eminent position in fusion and the expertise and experience of the JET Team.

This lead position which JET has achieved in world fusion research owes much to the continuing and excellent support which it receives from all parties involved in the European Fusion Programme, particularly from the Associations. I again record my gratitude to my colleagues on the JET Council and to the members of the JET Executive Committee and the JET Scientific Council for their assistance and guidance to the Project during the year and especially to those who retired from these Committees during the year.

Finally, I pay tribute to the Director of the Project, Paul-Henri Rebut and to all JET staff who, with their dedication and hard work, have maintained JET's position in the forefront of fusion research. I am confident that by their perseverance they will continue to maintain this position in the remaining years of the Project.

P. Fasella
Chairman of the JET Council

May 1991

Introduction, Summary and Background

Introduction

The Joint European Torus is the largest project in the coordinated 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 and scientific aspects of the JET Project for the same periods can be found in the JET Progress Reports.

Report Summary

The Report is essentially divided into two main parts:

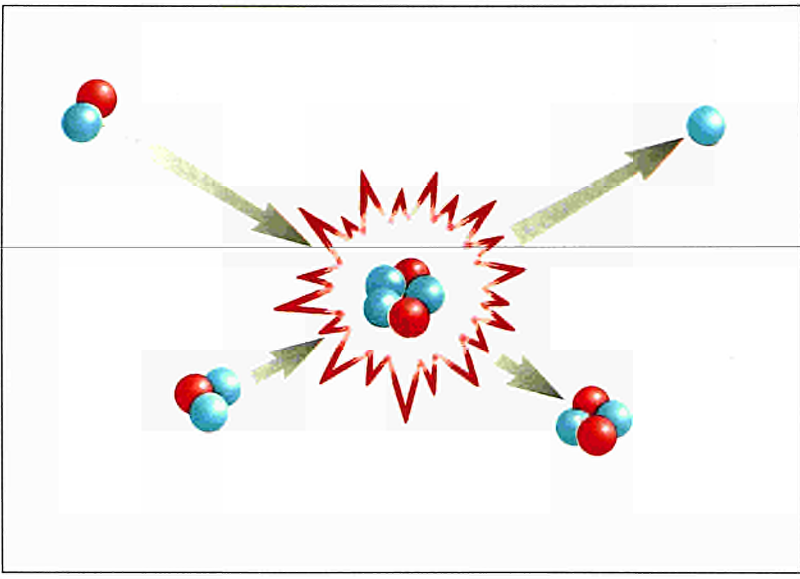
- the scientific and technical programme of the Project;
- the administration and organization of the Project.

The first part of the Report includes a brief general 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 the Euratom and International Fusion Programmes, which summarise the main features of the JET apparatus and its experimental programme and explains the position of the Project in the overall

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 that 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.



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.

Euratom programme. In addition, this relates and compares JET to other large fusion devices throughout the world and confirms its pre-eminent position in fusion research.

The following section reports on the technical status of the machine including: technical changes and achievements during 1989; details of the operational organisation of experiments and pulse statistics; and progress on enhancements in machine systems for future operation. This is followed by the results of JET operations in 1990 under various operating conditions, including ohmic heating, radio-frequency (RF) heating, neutral beam (NB) heating and various combined scenarios in different magnetic field configurations; the overall global and local behaviour observed; and the progress towards reactor conditions. In particular, the comparative performance between JET and other tokamaks, in terms of the triple fusion product, shows the substantial achievements made by JET since the start of operations in 1983. This section concludes with a discussion of future scientific prospects. The scientific part of this Report concludes with 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 and describes the administration of JET. In particular, it sets out the budget situation; contractual arrangements during 1990; and details of the 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, agreement was reached to set up an international design team which started work in the UK later that year, and by the middle of 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 JET Joint Undertaking was originally established for a duration of 12 years, beginning on 1st June 1978.

It was decided that the device would be built on a site adjacent to the 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. Fig.1 shows the site of the JET Joint Undertaking at Culham, near Oxford in the U.K.

The Members of the JET Joint Undertaking are Euratom, its Associated Partners in the framework of the Fusion Programme, including Sweden (NFR) and Switzerland, together with Greece, Ireland 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, the UKAEA pays ten per cent, with the remaining ten per cent 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 drawn 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 adopted a new multi-annual European fusion programme for the period January 1988 to March 1992 and agreed the prolongation of the JET Joint Undertaking to 31st December 1992. A proposal to prolong JET to 31st December 1996 was submitted to the Council of Ministers in October 1990.

Objectives of JET

The decision of the Council of Ministers 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

Conditions for Fusion

Fusion reactions can only take place if the nuclei are brought close to one another. But all nuclei carry a positive charge and therefore repel each other. By heating the gaseous fuels to very high temperatures, enough energy can be given to the nuclei for the repulsive force to be overcome sufficiently for them to fuse together. In the case of 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 it puts 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 $5x10^{21}m^{-3}skeV$. 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	*$2.5x10^{20}m^{-3}$*
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).

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.

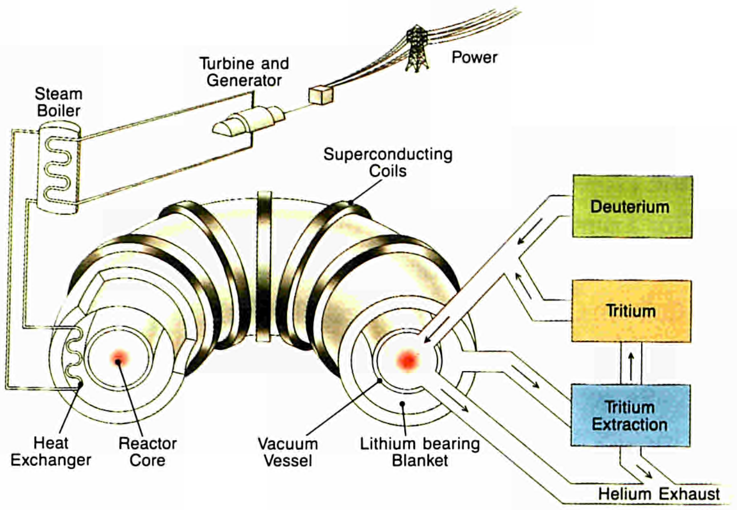
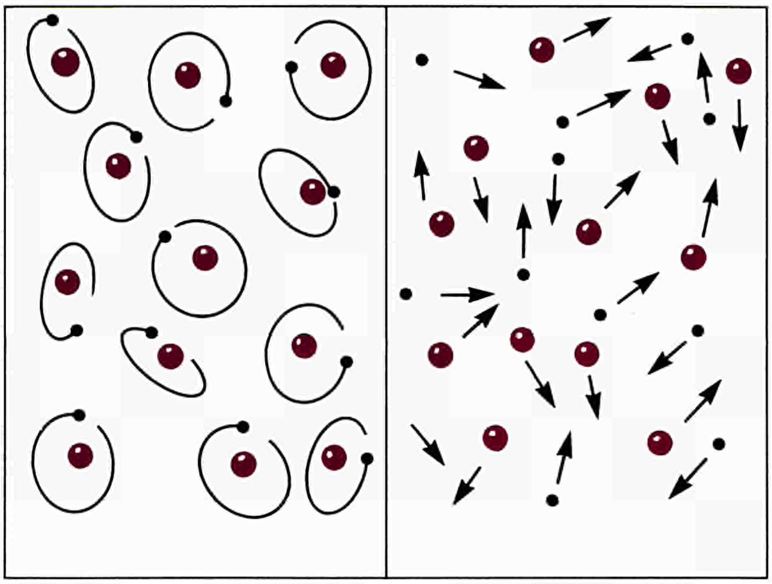


Fig.1: The site of the JET Joint Undertaking, near Oxford in the United Kingdom.



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 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 U.S.S.R.

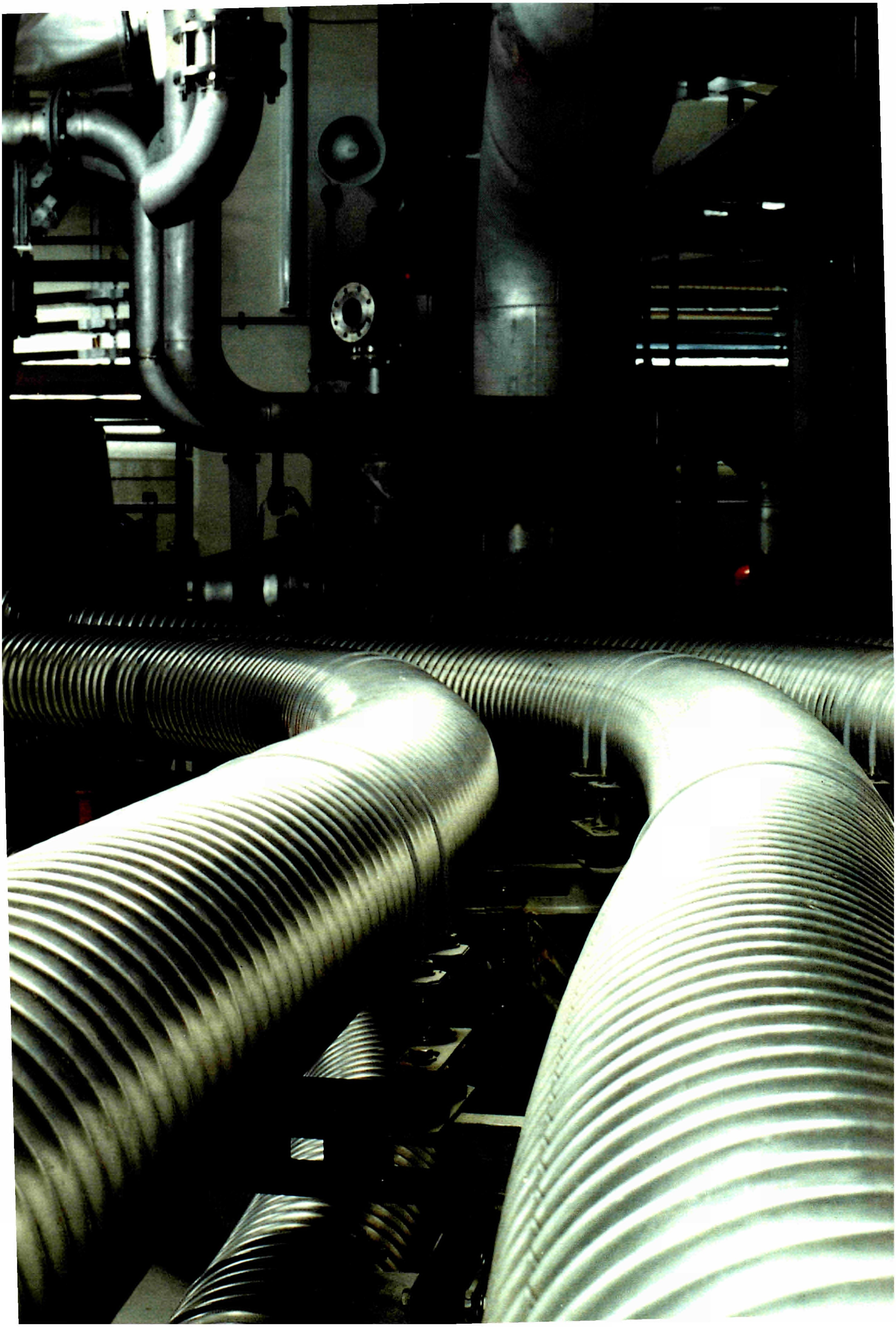
experiments up to conditions close to those needed in a thermonuclear reactor.'

The principal objective of JET is to enable the essential requirements of a tokamak reactor to be defined. To do this, a plasma approaching reactor conditions must be created and studied.

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 of the key technologies that will be required in subsequent fusion reactors. These are the use of tritium and the application of remote maintenance and repair 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 principal design parameters are presented in Table I.

The toroidal component of the magnetic field on JET is generated by 32 large D-shaped coils with copper windings, which are equally

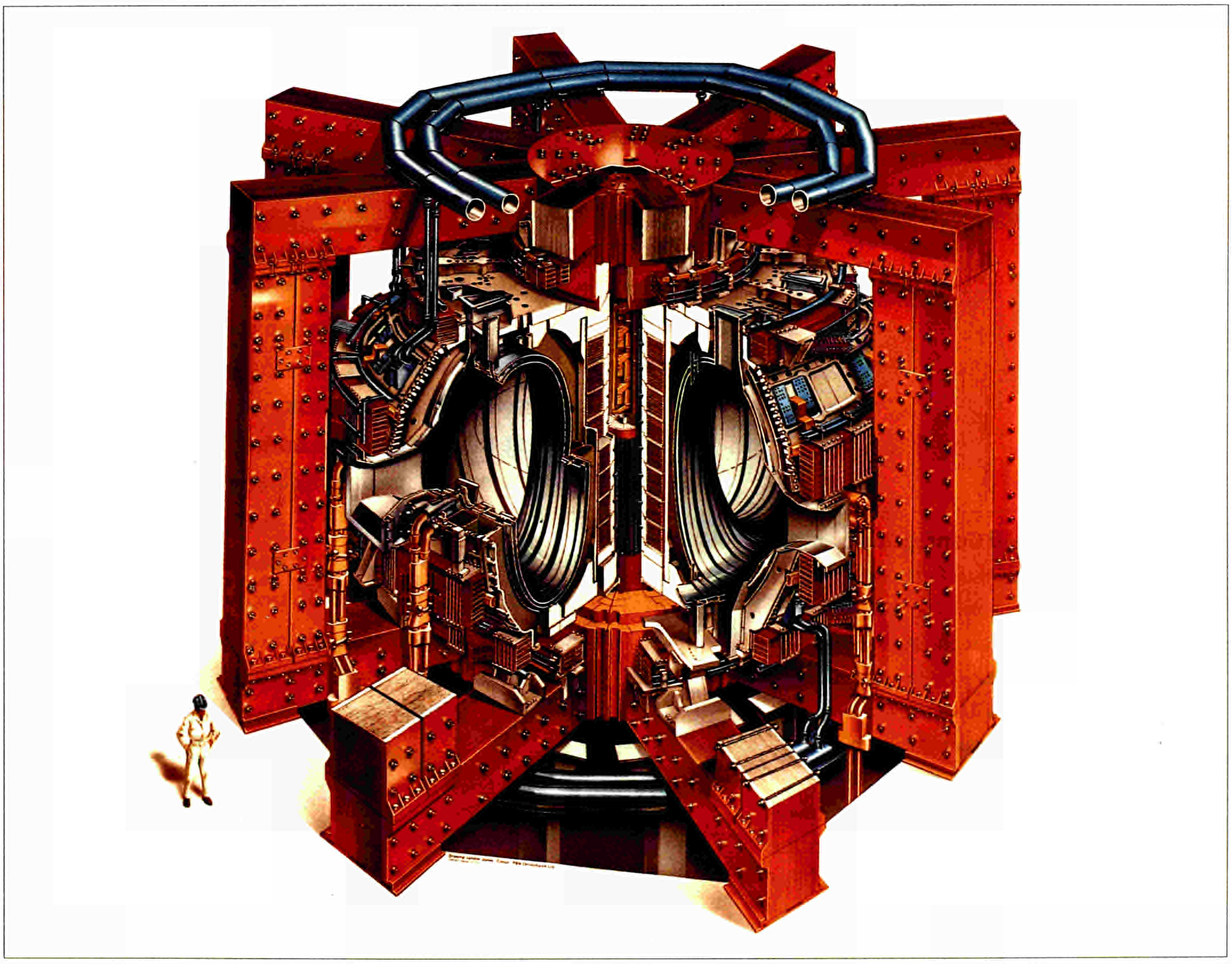


Fig.2: Diagram of the JET apparatus.

Table I: Original Design Parameters of JET

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 available to drive plasma current	34Vs
Additional heating power	25MW

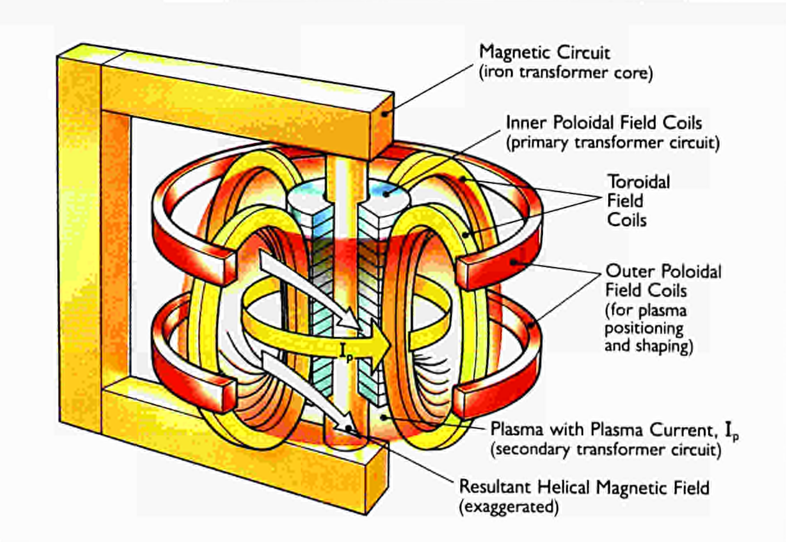
spaced around the machine. The primary winding (inner poloidal field coils) of the transformer, used to induce the plasma current which generates the poloidal component of the field, is situated at the centre of the machine. Coupling between the primary winding and the toroidal plasma, acting as the 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 shaping and stabilising the position of the plasma.

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 ten

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.



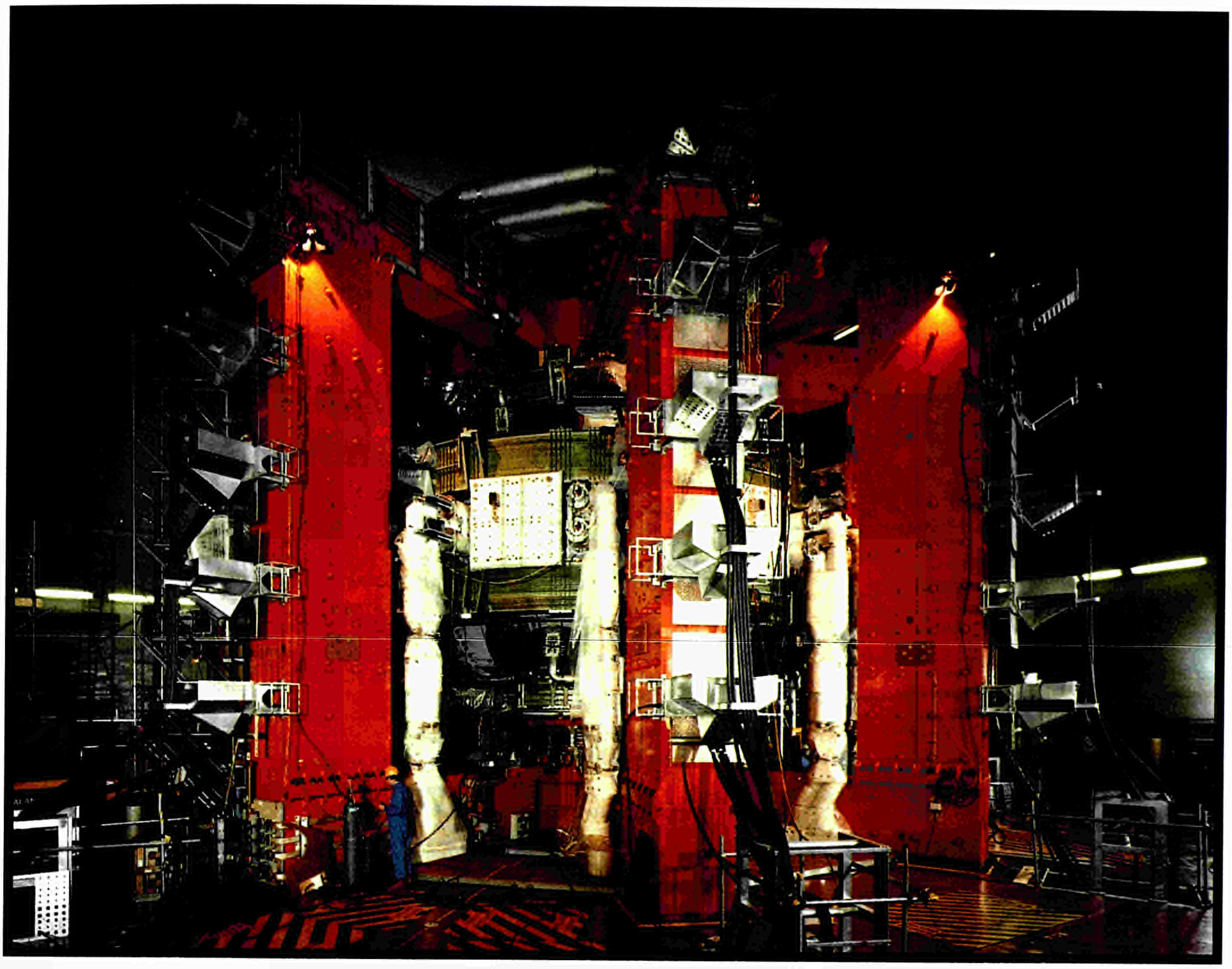


Fig.3: The JET experimental apparatus photographed in May 1983

minutes, with each one lasting up to 60s. 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 gram.

The construction phase of the Project, from 1978 to 1983, was completed successfully within the scheduled five year period and within 8% of 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. The JET Tokamak is shown in Fig.3 just prior to the start of operation in June 1983. 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 1990 reached 21MW 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.

So far, experiments have been carried out using hydrogen or deuterium plasmas. In the final stage of the programme, it is planned to operate with deuterium-tritium plasmas so that abundant fusion reactions occur. The alpha-particles liberated from the reactions should then produce significant heating of the plasma. During this phase of operation, the machine structure will become radioactive to the extent that any repairs and maintenance would have to be carried out using remote handling systems.

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 its 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 radiofrequency 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.

The Community Fusion Research Programme

All fusion research in Europe is integrated into one single Community Programme. Successive programme decisions by the Council of Ministers have described the Community Fusion Programme as "a long-term co-operative project embracing all the work carried out in the Member States in the field of controlled thermonuclear fusion". It is designed to lead in due course to the joint construction of prototype reactors.

The Commission of the European Communities is responsible for the implementation of the Community programme. It is assisted in this task by the Consultative Committee for the Fusion Programme (CCFP), composed of national representatives. The programme is executed through Contracts of Association between the Community and organisations within the Member States that are active in the field, through the JET Joint Undertaking, the NET Agreement (Next European Torus), and through the Community's Joint Research Centre (JRC).

This Community approach has led to an extensive collaboration between the fusion laboratories. For example, most of the Associations undertake work for other Associations. The Associations are partners in JET and NET and work for them through various types of contracts and agreements. The Community Fusion Programme has built across Europe genuine scientific and technical community of large and small laboratories, readily able to welcome newcomers, and directed towards a common goal. Indeed, two non-Member States, Sweden and Switzerland, are now fully associated with the Programme and enjoy the same rights and responsibilities as Member States.

A stepwise strategy towards the Prototype Commercial Reactor is foreseen, including after JET, an Experimental Reactor (Next Step) and a Demonstration Reactor (DEMO). The results from JET and from the medium-sized devices in the Associated Laboratories should allow the definition, with confidence, of the plasma size and the plasma current of a Next Step Tokamak, the major goal of which is to achieve thermonuclear ignition during long pulse operation. The Next Step is conceived as a device to demonstrate the safe operation of a tokamak which integrates important technologies of a fusion reactor, and should test components and subsystems essential for a fusion reactor. The Next Step must provide the basic data for building a demonstration fusion reactor (DEMO) capable of producing electricity with a capacity comparable to that of future commercial plants, taking due account of environmental constraints. The main objective of the current fusion programme, decided by the Council of Ministers for the period up to March 1992, is to establish the physics and technology basis necessary for the detailed engineering design of the Next Step. In the field of physics and plasma engineering, this implies the full exploitation of JET and of the medium-sized tokamaks in the Associated Laboratories, and, in the field of technology, the strengthening of the current fusion technology programme.

In the frame of the Third Framework Programme of Community Activities in the field of Research and Technological Development (1990 to 1994), a specific programme in the field of Controlled Thermonuclear Fusion has been presented by the Commission to the Council of Ministers for decision. The first priority objective of the specific programme (1990 - 1994) is to provide the scientific and technological base, and to prepare industry for the construction of a Next Step device. The engineering design of the Next Step will be undertaken preferentially in the frame of the quadripartite international collaboration International Thermonuclear Experimental Reactor (ITER). To fulfil the first priority objective of the specific programme, a large fraction of the 1990-1994 activities, including those performed on JET and within the Associations, will be in

TABLE 2: Large Tokamaks operating around the World

Machine	Country	Minor radius a(m)	Elongation κ	Major radius R(m)	Plasma current I(MA)	Toroidal field B(T)	Input power P(MW	Start Date
JET	EC	1.20	1.8	2.96	7.0	3.5	36	June 1983
JT-60	Japan	0.90	1.0	3.0	3.2	4.8	25	April 1985
TFTR	USA	0.85	1.0	2.50	3	5.2	32	Dec. 1982
Tore-Supra	France	0.70	1.0	2.4	1.7	4.5	23	April 1988
T-15	USSR	0.70	1.0	2.4	2.0	4.0	-	Jan. 1989
DIII-D	USA	0.67	2.0	1.67	3.5	2.2	20	Feb. 1986
FT-U	Italy	0.31	1.0	0.92	1.6	8.0	-	Dec. 1988

TABLE 3: Plasma Parameters of Large Tokamaks

Parameter		JET (H-mode)	TFTR (Hot-ion Mode)	DIII-D (H-mode)
Electron Temperature	T_e(keV)	9	12	3.8
Ion Temperature	T_i (keV)	22	30	17
Central ion density	$n_e(\times 10^{19} m^{-3})$	4	6.7	3.8
Effective charge	Z_{eff}	1.4	2.5	3.5
Confinement time	τ_E (s)	1.1	0.16	0.1
Neutral beam power	P_{NB}(MW)	16	25	15
Fusion product ($\times 10^{20} m^{-3}$keVs)	$n_i T_i \tau_E$	9	3.2	0.05

support of the Next Step. In particular, a prolongation of the JET Joint Undertaking to 1996 is proposed in order to establish reliable methods of plasma purity control in conditions relevant to the Next Step.

The scientific and technical achievements of the Community Fusion Programme place Europe in the forefront of world fusion research. JET, which is the leading fusion experiment in the world, has made substantial progress towards the demonstration of the scientific feasibility of fusion. A substantial contribution towards this success has been due to research carried out in the Associated Laboratories such as the discovery of the H-mode on ASDEX (IPP Garching, FRG) and developments in plasma heating systems (AEA, Culham Laboratory and CEA, France).

Currently, expenditure on fusion research through the Community budget is running at the rate of about 200MioECU a year. When funding by national administrations an other national bodies is taken into account, the expenditure on fusion from all sources in Europe totals about 450MioECU a year. About 1750 professional scientists and engineers are currently engaged in fusion research in Europe.

This leading position of the Community Fusion Programme has made Europe an attractive partner for international collaboration. For example, bilateral framework agreements have now been concluded with Japan, USA and Canada. A similar one is under discussion with the USSR. There are also eight specific agreements in the frame of the International Energy Agency, including the co-operation among the three large tokamak facilities (JET in Europe, JT-60 in Japan and TFTR in the USA). However, the most far-reaching development in international collaboration has been in connection with the International Thermonuclear Experimental Reactor (ITER) Project. Following initiatives taken at the highest political level, the four parties (the European Community, Japan, USSR and USA) agreed in early 1988 to participate on an equal quadripartite basis in the joint development of a conceptual design for an experimental reactor of the tokamak type. The ITER conceptual design activities were concluded at the end of 1990. The single conceptual design thus developed is now available to each of the Parties. Presently, negotiations are under way to continue the ITER collaboration into a six-year period of Engineering Design Activities.

Large International Tokamaks

Plasma current is an important factor in determining the confinement of the plasma and, in particular, of the energetic fusion products, the alpha-particles. On a worldwide basis JET is the machine with the largest plasma current by far; followed by DIII-D, General Atomics, San Diego, USA; JT-60 at JAERI in Japan; and TFTR at Princeton Plasma Physical Laboratory (PPPL), USA. Table 2 sets out an overview of these tokamaks with their main parameters and starting dates. Other operating devices with plasma currents in excess of 1MA are also included.

Other smaller tokamaks exist throughout the world or are under construction, each dedicated to specific tasks of studying different aspects of physics, engineering and heating of plasmas. In addition, these large tokamaks have also been designed with specific tasks. For instance, in Tore Supra, France, the main magnetic field is created by superconducting coils. The various machines are also designed to test various heating systems. Ion Cyclotron Resonance Frequency (ICRF) and Neutral Beam (NB) heating are now commonly applied in excess of 10MW each. Electron Cyclotron Resonance Heating (ECRH) of several MW has been applied in some devices. Non-inductive current drive by means of various heating methods include Lower-Hybrid Current Drive (LHCD). LHCD has also undergone preliminary tests in JET to complement the ICRF and NB heating systems.

JET, JT-60 and DIII-D are capable of producing magnetic field configurations, that have open magnetic surfaces within the vacuum vessel near the edge of the plasma. The plasma is then defined by a magnetic limiter and not by a mechanical limiter in contact with the confined plasma. The magnetic limiter configuration, with its high shear, not only leads to higher plasma edge temperatures and a better global confinement, but also permits better particle and impurity control.

1990 has been another year of continuing progress worldwide towards reaching the conditions for fusion energy ignition. In addition, further progress has been made in improving understanding of some of the basic processes occurring inside a tokamak plasma

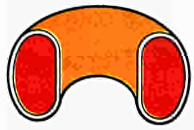
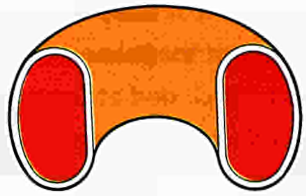
		TFTR	JET	ITER
				
Minor radius	a	0.85	1.25m	2.15
Major radius	R	2.48m	2.96m	6.0
Elongation	κ	1.0	1.8	2
Toroidal Field	B	5.0T	3.45T	4.85
Input Power	P	30MW	36MW	30-180MW
Fusion factor	Q_{DT}	0.25	0.9	40
Plasma current	I	3	7	22

Fig.4: Operating parameters of three large tokamak designs

(such as, the so-called high confinement mode of operation or H-mode). Further advances are expected in the near future with the installation of the new pumped divertor configuration in JET and the start-up of JT-60 Upgrade in Japan. The latter machine will have similar dimensions to those of JET. It will have a plasma volume of 100m^3, an open divertor configuration with 6MA plasma current and an initial Neutral Beam (NB) heating power of 28MW (to be upgraded in 1992 to 40MW) and 9MW of Ion Cyclotron Resonance Frequency (ICRF) Heating. Therefore, it can be expected that three machines: JET, JT-60-U, and TFTR will operate with plasma parameters close to break-even conditions.

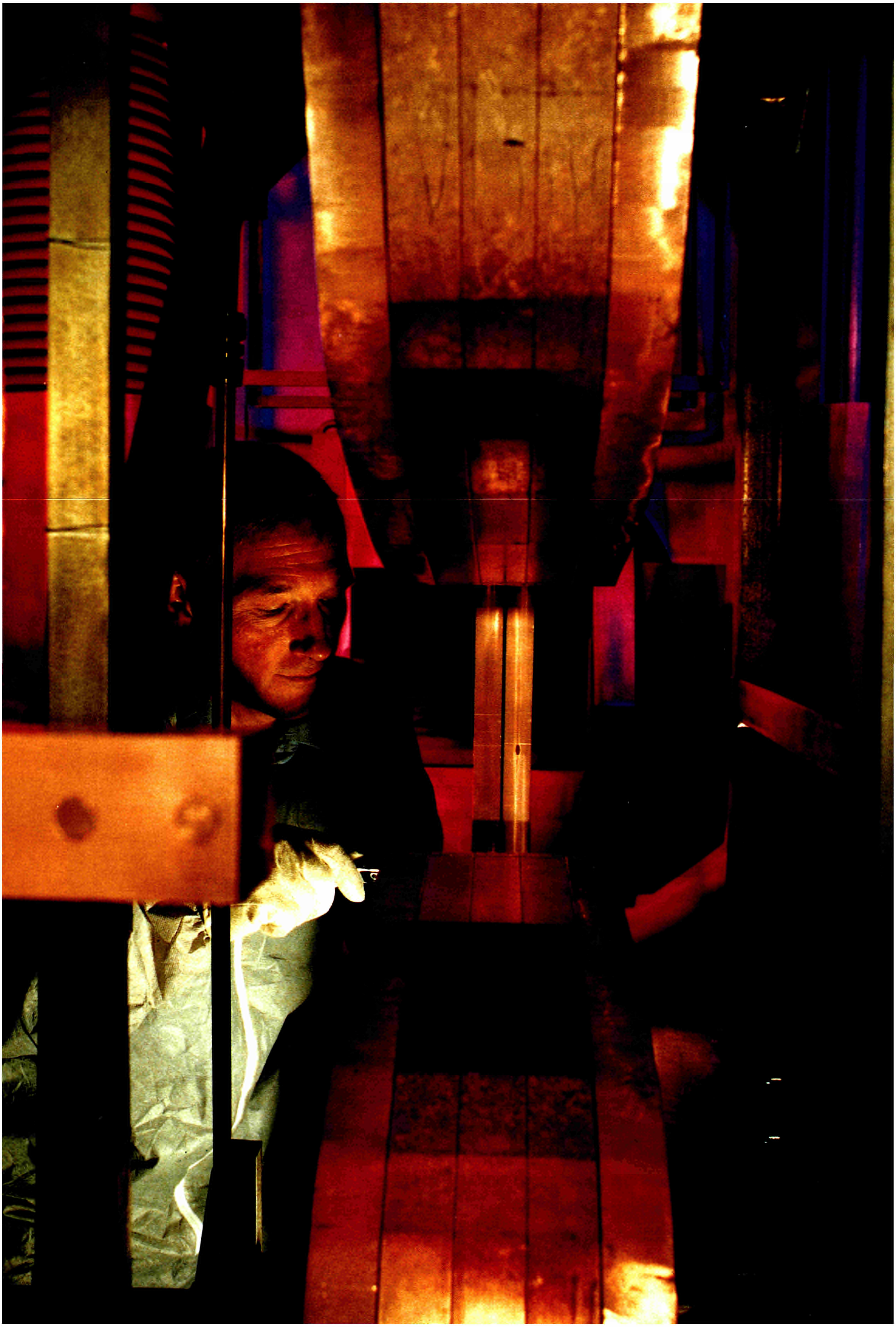
The performance of fusion devices is generally characterized by a parameter termed the triple product $n_i \tau_E T_i$. Here n_i is the density of the hydrogen isotope in the centre of the device, τ_E the energy confinement time and T_i the central ion temperature. Break-even in energy production is defined by $Q_{DT} = 1$, which corresponds to a triple fusion product of ~10x10^{20}m^{-3}skeV for typical radial profiles of temperature and density in steady state conditions. Ignition occurs at values of the triple product of 5-8 times higher, when the alpha-particle energy production balances the power losses of the plasma.

JET has achieved fusion product values of ~9x10^{20}m^{-3}s keV in both medium (≈10keV) and high (≈30keV) central ion temperatures at high and medium central ion densities, in conditions which are equivalent to a Q_{DT} = 0.9. This is within a factor of ~5-8 of that required in a fusion reactor (see Table 3). TFTR has reached ion temperatures of ~35keV, and a triple product value ≈3x10^{20}m^{-3}s keV (when corrected for dilution). Projections for the designed nonthermal ion distribution in this device with high power density, suggest Q_{DT} values of 0.4-0.7. However, in both machines the obtained results are still of a transient nature and have not yet been sustained in steady state.

Another important parameter for fusion is the so-called plasma beta which is the ratio of the pressure exerted by the plasma to the pressure of the magnetic fields. The highest toroidal beta of 11% has been obtained in the DIII-D tokamak in San Diego, U.S.A. The toroidal beta is important for the economic aspects of a reactor. Typical values for the next generation devices like ITER, the International Thermonuclear Experimental Reactor, are expected to be around 5%. TFTR, PBX-M also in Princeton, U.S.A. and JT-60 at JAERI, Naka-machi in Japan also reported high beta poloidal values at low plasma currents. DIII-D showed that quasi steady-state operation of a tokamak in a high confinement regime (H-mode) is in principle possible, by demonstrating H-modes of duration up to 10s. H-modes are often characterised by a strong evolution in time, particularly of the density, leading in the end to a termination of the H-mode.

Both JET and TFTR have reached high fusion factors. Fig.4 shows the main parameters and schematic diagrams of the cross-section of TFTR and JET, the two machines closest to break-even (Q=1), together with a next step device (ITER). However, JET has approached breakeven conditions transiently, with a calculated Q_{DT} value close to unity during one energy confinement time. The transient nature of the good fusion conditions is at present limited in JET by local overheating of sections of the wall surfaces. This leads to a high influx of impurities, which terminate the good plasma conditions. A new phase is planned for JET to demonstrate a reactor relevant solution to this problem, that should lead to a sustained production of a few MW of alpha-particle heating by 1996.

An extensive exchange of information, equipment and scientists exists within the worldwide fusion community. In particular, a collaboration agreement between the large tokamak groups in EEC, USA and Japan was signed in 1986. Subsequently, this culminated in the setting up of a collaboration between the EEC, USA, USSR and Japan, under the auspices of the International Atomic Energy Agency (IAEA), to perform a conceptual design of an International Thermonuclear Experimental Reactor (ITER). The main objective of the ITER project is to define a single concept that should suffice to demonstrate the scientific and technological feasibility of fusion. JET is providing input to the ITER studies. JET's immediate directions are to improve impurity and density control and to investigate improvements in confinement and fusion products in various material and magnetic limiter configurations at high additional powers and increased plasma currents.



Technical Status of JET

Introduction

The present technical status of JET is described in the following three sections:

- The first section outlines details of technical achievements made during the main operating periods of 1990 and the developments and improvements implemented during the shutdowns at the beginning and end of 1990;
- Machine operations during the operating periods are summarized in the second section;
- The final section sets out the main details of continuing technical developments on equipment for future installation.

Technical Achievements

Introduction

During early 1990, the machine was already well into a scheduled shutdown. The main tasks of the shutdown, which started in October 1989, were to replace a faulty toroidal field coil, to install beryllium screens for the ICRF heating antennae and to assemble the prototype Lower Hybrid launcher and waveguides.

Following the successful replacement of the faulty toroidal field coil with a spare one, the re-assembly of the machine proceeded smoothly. One particularly critical operation was the rewelding of the internal strengthening rings of the vacuum vessel. Due to excellent preparation work, no particular difficulty was experienced and mechanical surveys confirmed that the vessel octant had been reassembled within 1-2mm of its original location. Advantage was also taken of the shutdown to repair a number of small leaks between the main vessel volume and its interspace. Such small leaks do not pose any problem as long as the machine operates with deuterium, but would not be acceptable during tritium operation.

Early in 1990, a decision was taken to replace the graphite X-point protection tiles at the bottom of the vessel with beryllium tiles. The tiles used for this purpose were the ICRF antennae side protection tiles and therefore there were not optimised for X-point operation. Due to the curvature of the tile profile and shadowing effects between adjacent tiles, the useful length in the toroidal direction (ie, the length intersected by magnetic field lines) is only one-tenth of the total toroidal circumference. Nevertheless, the use of such tiles was considered desirable to gain experience with beryllium target plates prior to installation of the larger and better designed dump plates. The design of the supports and the installation of these X-point beryllium tiles extended somewhat the duration of the shut-down. The vacuum vessel was closed and evacuated by early June 1990.

The other main in-vessel activities of the shutdown were the installation of beryllium screens for the ICRF antennae and the assembly of the lower hybrid launcher. No particular difficulties were encountered during this work.

The shutdown from October 1989 to early 1990 involved work in two shifts, six days per week for about seven months. A total of 8000 man-hours was spent inside the beryllium-contaminated vessel. There were no safety incidents involving beryllium. This must be considered as a major success and a consequence of the considerable effort made at JET in organisation and provision of support teams and facilities for beryllium handling and in contamination control. Between January and March 1990, in-vessel work was able to proceed without full protective suits. Face masks were found to be adequate in view of the low residual beryllium contamination. The use of face masks allowed up to eight workers simultaneously inside the vessel, whereas this number was restricted to four when full-suits were used.

In February 1990, immediately after the reassembly of Octant No.3, which had contained the faulty toroidal field coil, electrical tests were carried out on the complete toroidal field magnet. These tests revealed that another coil, at Octant No.4, was also faulty. This was a major setback which lead to the concern that the fault in the toroidal field coils might be systematic and potentially could develop in other coils. The newly found fault was an order of magnitude smaller than the previous one and this explained why it had not been detected earlier. Detection methods rely on inductive measure-ments and due to the close proximity of the Octant No.3 coils, the strong magnetic coupling between the two faulty coils resulted in the smaller fault being masked by the adjacent large fault. More electrical tests were systematically carried out on all toroidal field coils, which clearly indicated that no other fault comparable to the first one existed on any other toroidal field coil.

By the end of 1989, and well before the discovery of the second electrical fault in a toroidal field coil, a decision had already been taken to use an organic dielectric fluid to cool the toroidal field coils, in the future. Since the electrical faults were caused by the presence of low conductivity water inside the coil insulation, the use of a fluid with intrinsically high dielectric properties would prevent the reoccurrence of such faults.

A survey of existing fluids restricted the choice of fluid to chlorinated or fluorinated products which combine the desirable properties of non-flammability, adequate radiation resistance, low viscosity and low toxicity. The final choice, following chemical compatibility tests with the epoxy resin used for the coil insulation, was for Trichlorotrifluoroethane-113 (CFC-113). The use of this fluid implied considerable modifications of the cooling loop to ensure absolute tightness. The flexible rubber hoses which connect each turn of each coil (1536 hoses in total) had also to be replaced with a CFC-113 compatible type of hose. The conversion work was carried out within a very tight time schedule but nevertheless was completed in time for re-commissioning of the cooling loop in April. The system operated fully satisfactorily throughout the 1990 experimental campaign.

Operation took place from May to November with an interruption of four weeks in August due to an outage of the high voltage power grid for planned maintenance. It is noteworthy that the toroidal field coil fault did not affect operation. No long term evolution of the fault was detected throughout the 1990 experimental campaign.

During the second phase of operation, the experimental programme had to be somewhat limited due to damage to wall protection tiles. Some graphite tiles were fractured and some tile supports were bent or ripped from the walls. Such effects had been observed before but to a much lesser extent. The damage was attributed in most cases to large forces produced by currents flowing in the poloidal direction along the vessel walls or tile supports. The mechanisms which cause these poloidal currents are now better understood and the current value can be predicted. These currents appear during vertical instabilities and it has been estimated that the total intensity is about 0.2-0.25 of the total plasma current. The forces resulting from the interaction with the toroidal field are therefore considerable.

Monitoring the status of the wall protection tiles was essential during this period and was carried out each week using the In-Vessel Inspection System (IVIS). This system, which has been improved and extensively automated, proved invaluable and became an indispensable tool for the operation teams.

As planned, operation was concluded by the end of November and the machine was again in a shutdown period to install the dump plates for X-point operation. The dump plates will carry beryllium

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 through a system of circuit breakers.

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 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 reach deliver 2.6GJ of energy with a peak power output of 400MW.

tiles in the vicinity of the bottom X-point and graphite (CFC) tiles at the top X-point. By the end of December 1990, the lower dump plates were installed and preparatory work started for fitting the upper dump plates. Remedial work was also carried out to strengthen the tile supports and tile attachments in such a way that they could resist the large forces due to poloidal and eddy currents. A large part of this work was already underway at the end of 1990.

Replacement of Faulty Toroidal Field Coil

The faulty toroidal field coil was discovered in Octant No.3 during 1989. At the end of 1989, the octant was removed from the machine

Fig.5: An octant being removed from the torus.

and transferred to the Assembly Hall (see Fig.5). The faulty coil was changed during January 1990. The operations for changing a coil had been defined previously but, as the interior of the vacuum vessel was now contaminated with beryllium, special precautions had to be taken to keep the vessel sealed, and at the same time, allow work to proceed inside the vessel. In February, the rebuilt octant was transferred to the Torus Hall and re-assembled into the machine. Again, this operation was similar to the original assembly with extra precautions to avoid beryllium contamination. Subsequent surveys confirmed that the octant had been replaced to within an accuracy of 1-2mms of its original position. Following octant replacement, it was possible to lower the upper poloidal coils and raise the lower poloidal coils to their normal locations and reassemble the rest of the machine.

Subsequent tests and inspections revealed the cause of the failure of the toroidal field coil. There had been a leak at a brazed joint on one of the copper pipes between the external water connector piece and the main body of the coil. Since these pipes were enclosed in a rubber block, the water could not leak away. Instead, the water followed a path inside the coil outer insulation and travelled several metres along the coil circumference until a spot was found where the inter-turn insulation was not fully impregnated with epoxy resin. The inter-turn electrical faults were due to the relatively low electrical resistivity of the stagnant water.

Change of Magnet Coil Coolant

It was realised that such a fault could occur in other magnet coils, if similar conditions existed. By the end of 1989, a decision was taken to replace water as a coolant with an organic dielectric fluid. The use of a fluid with intrinsically high dielectric properties would prevent the reoccurrence of this type of fault. A survey of industrially available fluids was carried out, with the main criteria for selection being non-flammability, compatibility with the epoxy used for the coil insulation and low toxicity. Only chlorinated and fluorinated products were found to satisfy the criterion of non-flammability. Three products were pre-selected: Perchloroethylene, Trichlorotrifluoroethane and fluorinated fluids such as those used for the cooling of supercomputers. The first option was incompatible with epoxy resin, and the third option was eliminated on financial grounds.

The selection of Trichlorotrifluoroethane implied considerable modification of the cooling loop. The loop capacity was reduced to cutdown on the total volume and the cost of the fluid. Pipework was simplified and shortened, and leak tightness was an essential feature for CFC. All non-essential flanged connections, valves and instrument flanges were systematically eliminated and welded connections were implemented whereever possible. Remaining flanges were tightly sealed by a special liquid-rubber compound. Pump seals were replaced with CFC compatible bellow seals. In the Torus Hall, all flexible rubber hoses (1536 in total) were replaced with new CFC compatible hoses and all hose connectors were fitted with locking devices. In view of its higher density of CFC, stress analysis of pipework was carried out and additional supports installed, where required. Safety aspects were also most important and fixed CFC-113 detectors were fitted at various locations in the Torus Hall, access cell, basement and ventilation ducts. In spite of the very short time available to carry out these major modifications, the new cooling system was ready by the end of March 1990 and filled with 65m^3 (100 tonnes) of Trichlorotrifluoroethane. The system has operated fully satisfactorily throughout the 1990 experimental campaign.

In-Vessel Components

New beryllium X-point target plates were introduced at the bottom of the vacuum vessel during the early shutdown period. Thirty two segments 200mm wide and 800mm long were installed (see Fig.6). The status of the vessel at the beginning of operations is shown in Fig.7. Due to the narrow width of only a few mm for the X-point strike points, the power handling capability of the plates was low (e.g. 5MW for 1s). Even so, it was anticipated that by tailoring the gas-feed during discharges, higher loads could be accommodated. However, due to problems with inner wall protection, during the experimental campaign, insufficient time remained to evaluate this scenario.

Problems experienced with the wall protection were related to vertical plasma movement during disruptions and loss of position control. A fraction (up to 25%) of the total current was transformed

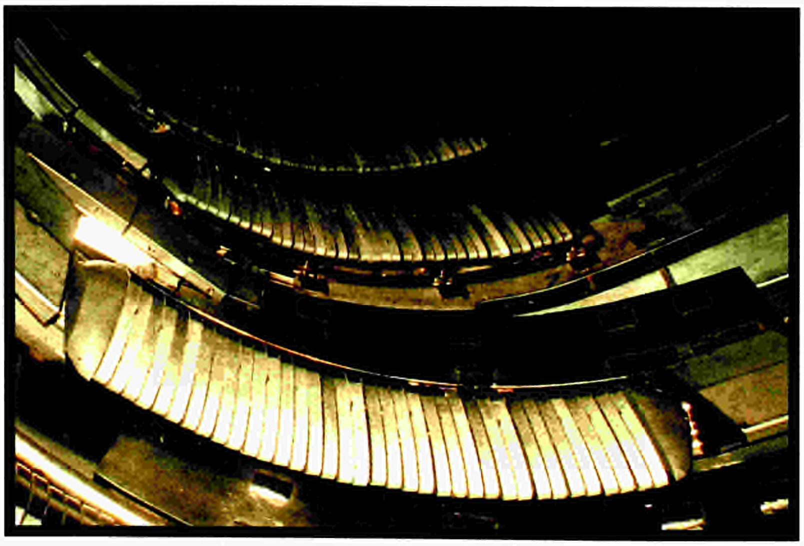


Fig.6: Discrete beryllium X-point target plates at the bottom of the vessel.

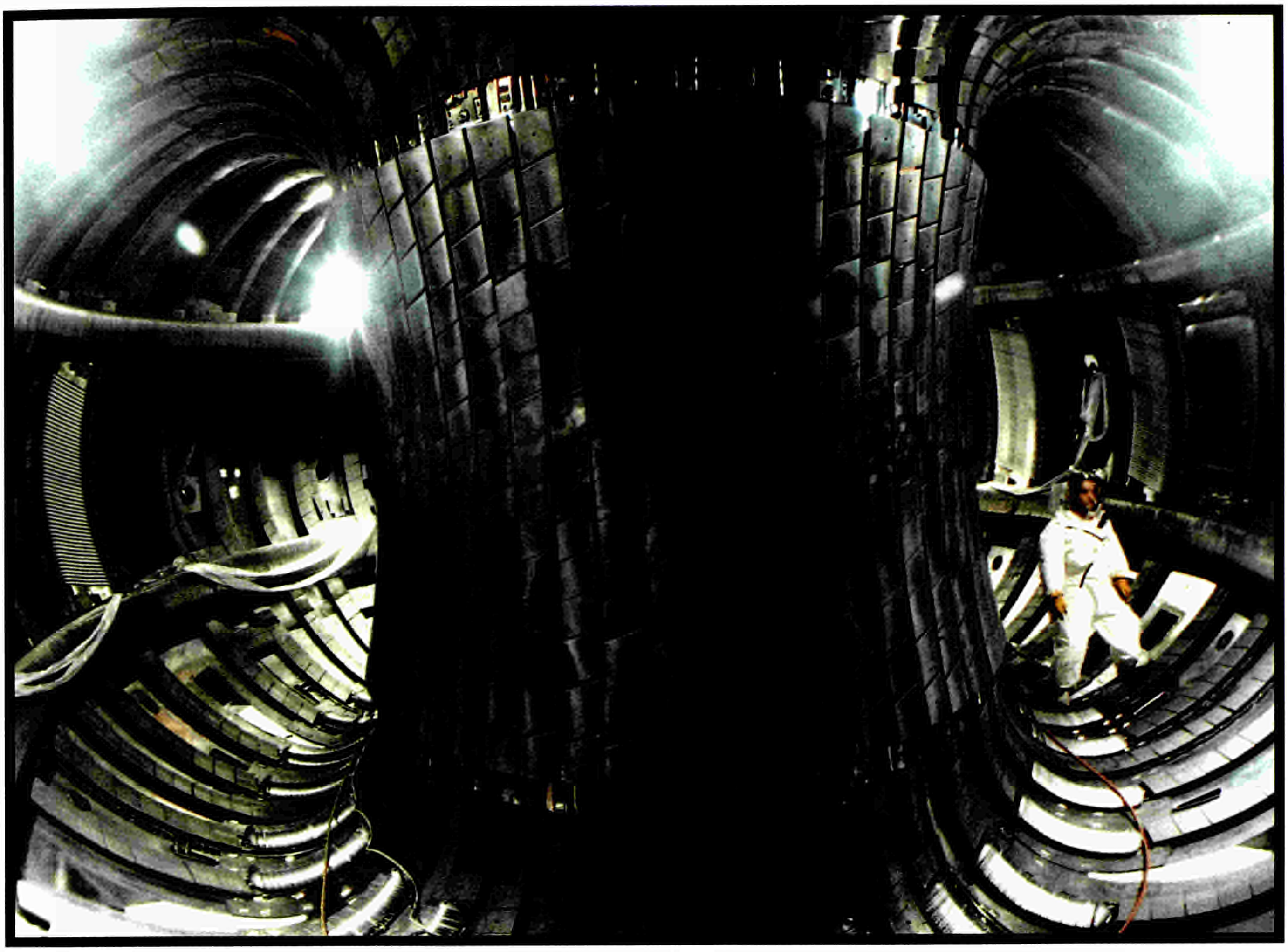


Fig.7: Status of the vessel at the beginning of 1990 operation.

into poloidal currents (halo currents), which upon contract with the wall, were then transferred to the vessel structure, including the wall protections. This is a new phenomenon, which had not been observed earlier and was related to the improved purity of the plasma. The wall components were originally designed to withstand eddy current forces due to the decay of the poloidal magnetic field, but were not strong enough to cope with the forces created by the interaction of these halo currents with the toroidal field. One example of the resulting damage is shown in Fig.8 for a section of the inner wall close to the midplane. Here, two tiles were lost by being pulled from their supports, and a third one is damaged and protrudes from the wall. The forces exerted on the tiles were calculated (and measured in a mechanical simulation) to be 500-700dN for each tile. This is more than one order of magnitude higher than forces due to eddy currents. A poloidal current of only 4-8kA transferred to these tiles is sufficient to explain this behaviour. At the end of the experimental period, a total of 49 tiles out of 2300 were dislocated or damaged. This still represents only a small fraction of the total number installed but made plasma operation difficult as the plasma-

Fig.8: Damage caused at the inner vacuum vessel wall.

wall distance had to be increased to values of up to 100mm. This made it impossible to systematically investigate high current operation (~7MA).

During the later shut-down, remedial action was taken to reinforce the wall protection in the affected areas: welds were strengthened, fasteners improved, weak mechanical supports were modified and cantilevered mountings were eliminated. The 1990 operational period will show how far these modifications have been successful. If wall damage is still experienced, different solutions will have to be tested, such as, for example, mechanical decoupling between wall protection and vessel with spring loaded supports. New wall elements being installed during the later shut-down are toroidally continuous X-point target plates at the top and bottom of the vacuum vessel. These replace the present target plates, which consisted of toroidally spaced energy dumps initially devised as wall protection. The power handling capability is anticipated to increase by a factor 2-3. It is expected that X-point discharges, compared with those before the change of target plates, can be run at higher powers or for longer times before incoming impurities degrade the plasma. Fig.6 shows the new X-point dump plates at the bottom of the machine during installation.

Gas Introduction System

The gas introduction system was updated to cope with requirements for increased gas feed. Due to the high pumping efficiency of in-vessel components and the ability to operate at higher densities following the introduction of beryllium, the amount of gas required for a discharge increased by nearly one order of magnitude, up to 1000mbar. Two more piezo-driven gas inlet systems were installed and worked satisfactorily. The related control system was modified to operate several valves in parallel. Experience with this approach was good and proved the reliability of the valves, which are foreseen for use during the tritium phase. Two additional systems of this new gas introduction module were designed and procured for installation during the 1990/91 shut-down. The purpose is to feed gas between the strike zones of X-point discharges at the bottom of the machine. This is a simulation of high recycling operation and will serve to gain experience with gas flow requirements for the pumped divertor configuration.

Neutral Beam Heating

The successful operation of both the Octant No.4 and Octant No.8 neutral beam injection systems, achieved during 1989 experimental campaign, was maintained throughout 1990, with high levels of both reliability and availability. Prior to the start of 1990 operations, conversion of the Octant No.4 system to 140kV injection voltage was completed to give one injection system at 140kV and the other at 80kV. Although the change to 140kV operation provided lower total power (7.8MW compared with ~10.5MW at 80kV), this was offset by enhanced beam penetration and, hence, more efficient heating of the central plasma region. Furthermore, the voltage of the Octant No.8 system was progressively increased beyond its 80kV design value to 85kV, resulting in ~11.5MW of power without decrease in reliability. These modifications resulted in further improvements 1990, with ion temperatures increasing up to 30keV.

The flexibility and usefulness of neutral beam injection in JET was further enhanced by the successful use of the Octant No.4 system to inject beams of both ^4He and ^3He at 120kV beam voltage into the plasma,during the final weeks of operation. The injection of beams of energetic helium offers the possibility of carrying out various interesting experiments on JET, in addition to avoiding the production of beam-plasma neutrons which both complicate the measurement of the thermonuclear neutron production and result in activation of the vacuum vessel. The Octant No.4 beamline was converted to ^4He operation with eight 120keV ^4He neutral beams. A limited experimental campaign was carried out using short pulses of injected ^4He to simulate a source of thermalised α-particles in the centre of the plasma and to measure their subsequent radial transport. During these experiments, a peak power of 6.8MW of ^4He was injected into the plasma for 1.5s.

For the final week of operation in 1990, the beamline was used to inject beams of ^3He at energies up to 125kV at a power level of 5.2MW for pulse lengths of up to 3s. This is the first time ^3He injection has ever been attempted. Although the first experiments were limited to 125kV by electrical breakdown in the accelerator, subsequent analysis indicates that minor adjustments of various timing

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 beamline system connected to the torus. The first beam sources have been designed to operate at accelerating voltages up to 80kV and for 1990 one system was substituted with units capable of operating up to 140kV. In addition, this box was alos converted to operate with helium (He^3 and He^4) beams during 1990. In the D-T phase, one unit will be converted for operation with tritium at 160kV.

Each system is connected to the torus by a long narrow duct through which up to 10MW of power can be directed.

circuits should enable the voltage to be increased to 155kV. Based upon the successful operation in 3He and 4He, both beamlines will be converted to be capable of this mode of operation, as required by the 1991 experimental programme. This should enable the availability of 13.5MW of 120kV ^{4}He or 15MW of 155kV ^{3}He beams.

Radio Frequency Heating

The ion cyclotron resonance frequency (ICRF) heating system is used for highly localized heating of the JET plasma. The wide frequency band (23 to 57MHz) allows variation in the heating position as well as the minority ion species which is resonant with the wave (H or 3He at present, D in the future D-T phase). The heating system is composed of eight units, each driving an antenna installed between the belt limiters in the toroidal vessel. Each unit is made of two

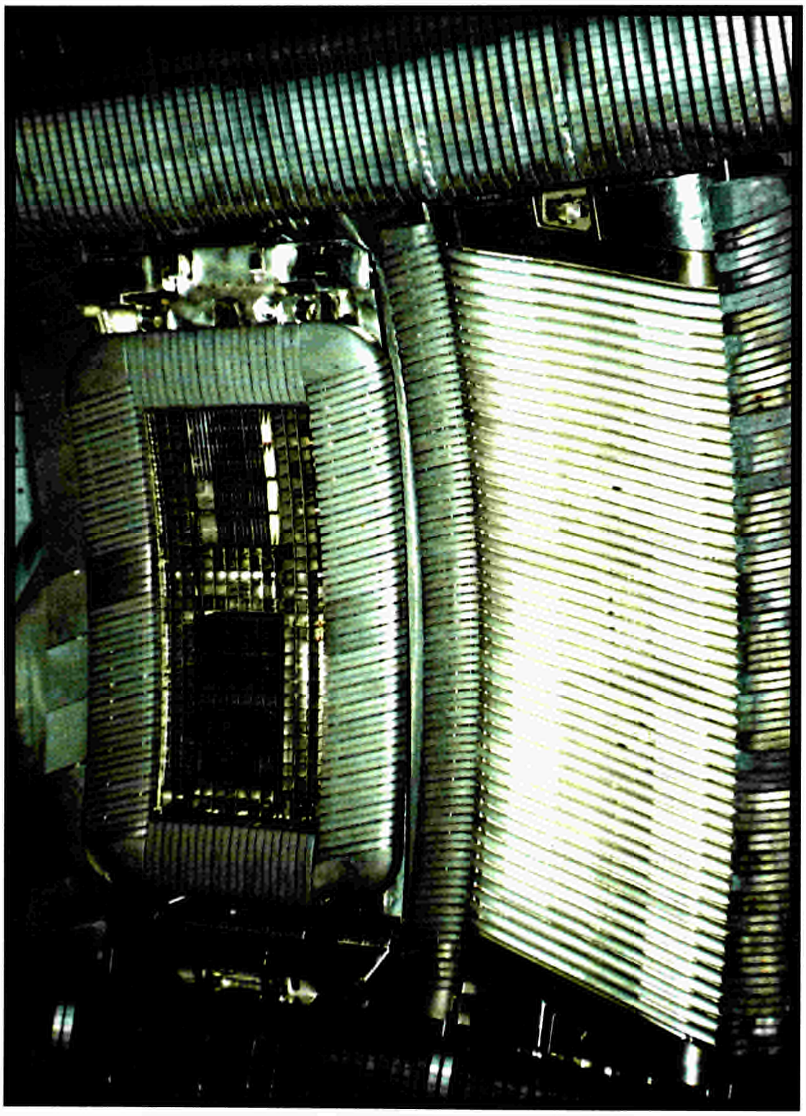


Fig.9: View of the LHCD launcher in the torus (on the right), adjacent to one of the existing eight ICRF antennae (on the left). The upper and lower prototype launchers together with the carbon side protection tiles (similar to ICRF) can clearly be seen. The ICRF antenna conductors are just visible through the beryllium bars of the new open screen.

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 mixes 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 on antenna located in the vacuum vessel on the outer wall. Ultimately, the eight RF generators will produce a maximum output power of 32MW.

identical sub-units, sharing a common high voltage power supply and a common low power RF drive. The original design power was rated at 15MW for 20s. However, the output stage of each sub-unit has been upgraded to 2MW each instead of the original 1.5MW to provide an amended design power of 24MW in the plasma. This modification was completed early in 1990, and a power of 22MW has

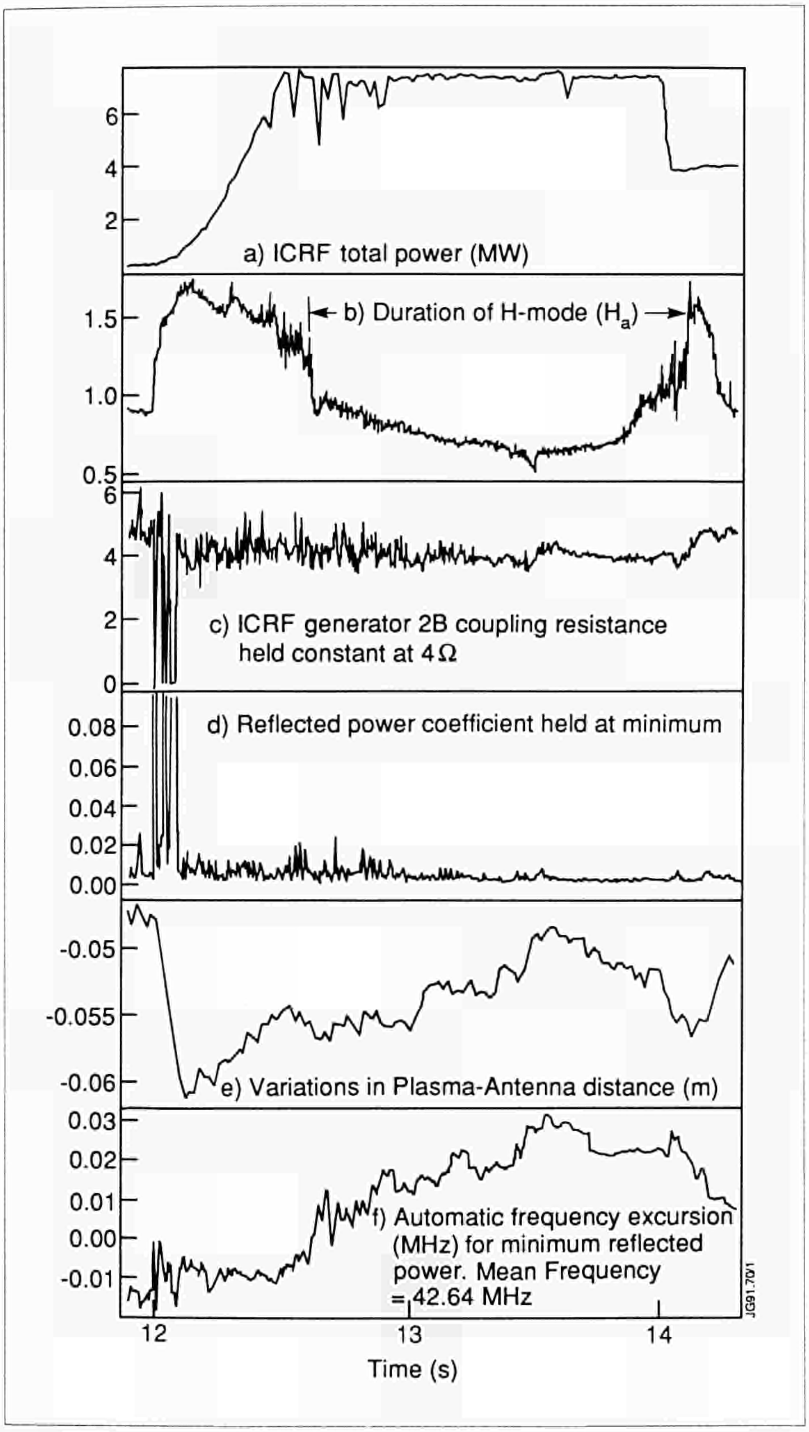


Fig.10: Antennae coupling resistive control of plasma position during H-mode transitions in Pulse No:21906. During the RF Power pulse (a), which contains an 'H' mode (b), the coupling resistance at the antenna (c) is held constant, and the reflected power kept at a minimum (d) by the automatic control of the plasma position (e) and incremental frequency (f).

been successfully coupled to the plasma for 1.75s. Pulse lengths were limited and longer durations were only possible at lower powers because of energy limitations on the vessel.

The original water-cooled nickel antennae screens released nickel impurity ions into the plasma under certain circumstances. Nickel radiation was normally negligible during material limiter operation but was the main source of difficulty in obtaining good H-modes with ICRF heating in the magnetic limiter configuration. In addition, the nickel screens had potential for creating the hazard of water leaks into the vessel. Consequently, a new set of screens made of solid beryllium elements were fitted for 1990 operation. The beryllium screens avoid circulating water in the screen elements and eliminated highly stressed welds between the elements and the water manifold. The screen losses are much reduced due to the good electrical properties of beryllium and heat can now be removed from the ends of the elements by water flowing in a manifold forming a picture-frame for the screen. The main components of the screen and antenna can be seen in Fig.9. The use of beryllium screens has significantly improved the quality of RF-only H-modes in JET.

A major difficulty for the RF plant is rapid variation of antennae loading with plasma. An example is the change of loading resistance, shown in Fig.10, during L- to H-mode transitions. Considerable progress was made in adjusting the plant settings rapidly to varying plasma conditions. During the pulse, a triple feedback loop adjusts the wave frequency, the length of tuning stubs and electrical length of the antennae circuits to minimise power reflected back to the generators. A new feedback circuit has been added which complements existing matching circuits. The plasma position is controlled by the desired RF coupling resistance which is held constant throughout the pulse. The existing frequency control makes fast orthogonal corrections for the plasma conductance and minor adjustments to the tuning stubs with the result that the RF generator tuning is held almost constant during the pulse, as shown in Fig.10.

Lower Hybrid Current Drive

The Lower Hybrid Current Drive (LHCD) system (12MW at 3.7GHz) is intended to drive a significant fraction of the current flowing in the plasma, by direct acceleration of the plasma electrons through interaction with LH waves. This should stabilize sawtooth oscillations, thereby increasing the central electron temperature and improving overall JET performance. This will be the main tool in JET for controlling the plasma current profile. A prototype system consisting of two launching units (one built by CEA Cadarche, France, and the other built by JET) fed by a total klystron power of 4MW was installed during 1990 (see Fig.9). In the limited experimental and

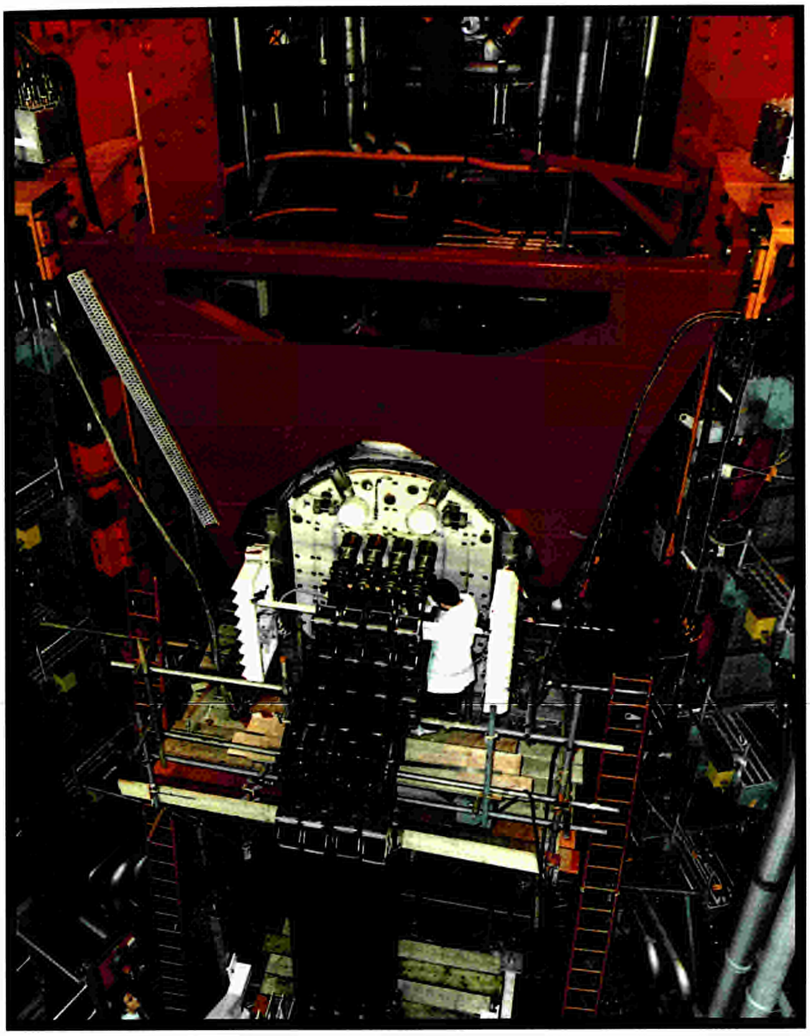


Fig.11: An external view of the Lower Hybrid Current Drive Launcher on JET. Its vessel is supported by the large red frame. The prototype has 24 waveguides connected to the RF vacuum windows at the point of entry to the vessel.

commissioning period that was available, the prototype system operated at 1.5MW for 20s and 1.6MW for 10s.

In installation of the launcher, precise positioning was required on the in-vessel hanger for supporting the grill mouth whilst enabling radial movement of the launcher (see Fig.11). In addition, the system for controlling the radial position of the launcher was installed, which is one of the main tools for achieving correct coupling between the RF waveguides and the plasma boundary. The feedback system is designed to allow the position to be controlled within ±1mm during the duration of the plasma pulse. This system has operated for the first time during the 1990 campaign, and the launcher was maintained within ±2mm for continuous periods up to ~100 hours during torus operation.

Pellet Injection

An important requirement for the successful operation of future fusion plasmas is a fuelling and density control system. One method of raising the density, and replenishing it during operation, is to inject pellets of solid hydrogen into the plasma at high speed so that these penetrate the outer plasma layers and reach the centre before completely evaporating. The resulting clean plasmas are comparatively resistant to disruption.

The mutli-pellet injector in JET was built and operated under a collaborative bilateral agreement between JET and the US Department of Energy (USDoE) (see Fig.12). It has operated reliably throughout 1990 and has delivered pellets (singly or bunched in sequences) with repetition rates up to $5s^{-1}$, in sizes of 2.7mm, 4mm or 6mm diameter. It was possible to extend the pellet injection scenarios up to 5MA plasma current and to inject 6mm pellets successfully into the plasma. The maximum central peak density immediately after injection achieved was raised to $4x10^{20}m^{-3}$ in the X-point configuration and up to $2.8x10^{20}m^{-3}$ for limiter plasmas.

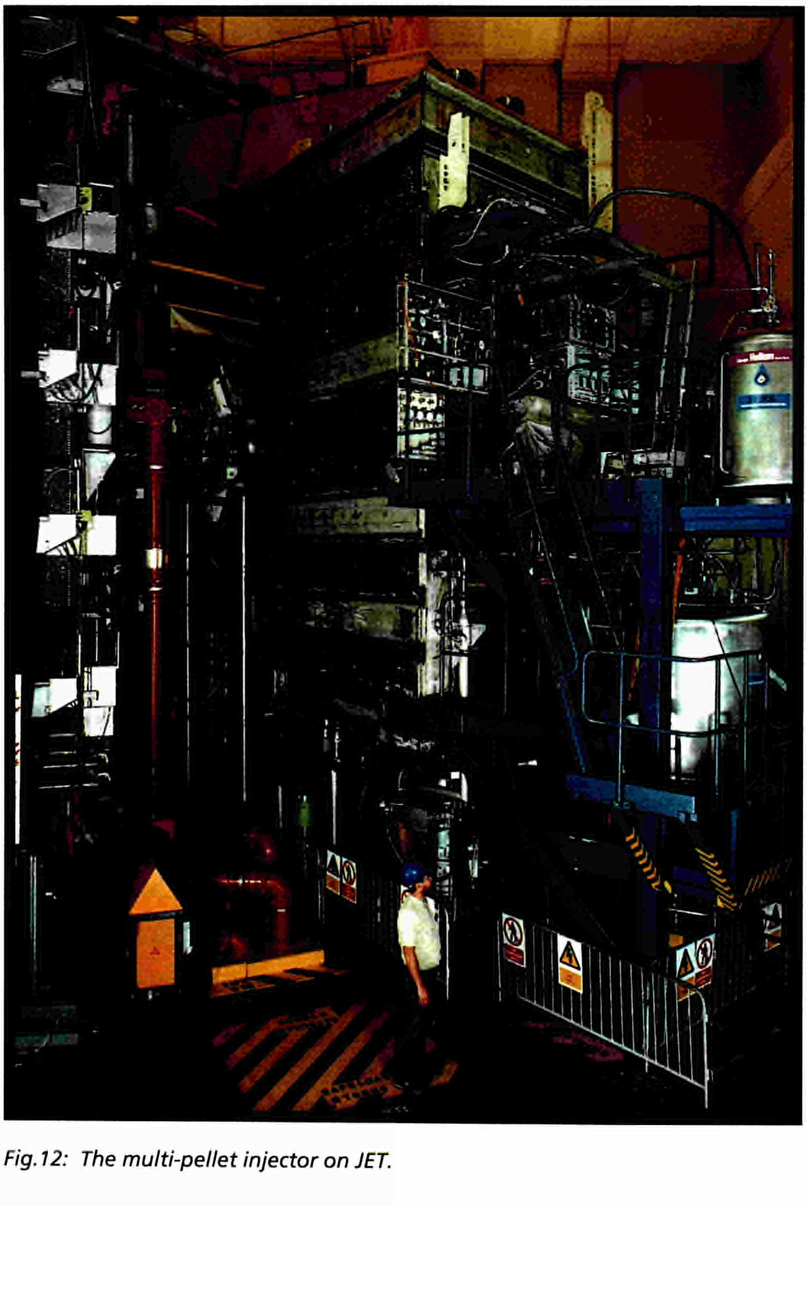


Fig.12: The multi-pellet injector on JET.

Diagnostics

The location of the JET measuring systems (or diagnostics) is shown in Fig.13 and their status at the end of 1990 is shown in Table.4. Operational experience has been good and many of these systems operate automatically with minimal supervision from scientific staff. The measurements obtained are accurate and reliable and provide important information on the behaviour of the plasma.

Temperature and Density Measurements

The electron cyclotron emission measurement system comprises four different types of spectrometer: rapid scan Michelson interferometers, Fabry-Perot interferometers, a twelve-channel grating polychromator and an eight-channel heterodyne radiometer. The system has continued to provide detailed information on the spatial and temporal variations of the electron temperature on all JET discharges. The Michelson interferometers provide measurement of the whole ECE spectrum with modest spectral and temporal resolution, thus providing temperature profiles under almost all plasma conditions. The twelve-channel grating polychromator, and the heterodyne radiometer give detailed information of the time de-

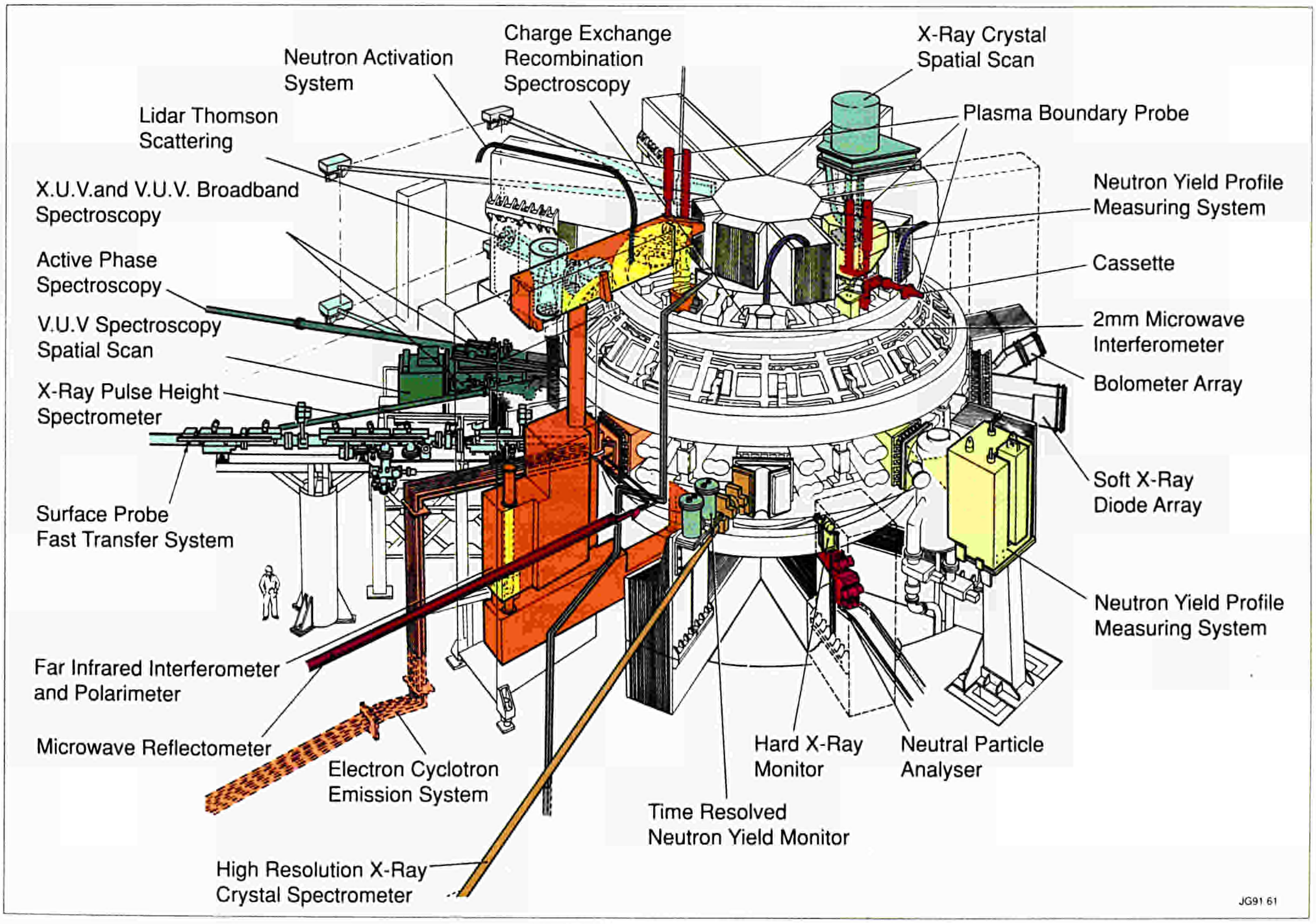


Fig.13: Location of JET diagnostic systems.

Table.4: Status of JET Diagnostics at the end of 1990

System	Diagnostic	Purpose	Association	Automation
KB1	Bolometer array	Time and space resolved total radiated power	IPP Garching	A
KC1	Magnetic diagnostics	Plasma current, loop volts, plasma position, shape of flux surfaces, diamagnetic loop, fast MHD	JET	A
KE1	Single point Thomson scattering	T_e and n_e at one point several times	Risø	A
KE3	Lidar Thomson scattering	T_e and n_e profiles	JET and Stuttgart University	A
KG1	Multichannel far infrared interferometer	$\int n_e ds$ on six vertical chords and two horizontal chords	CEA Fontenay-aux-Roses	SA
KG2	Single channel microwave interferometer	$\int n_e ds$ on one vertical chord	JET and FOM Rijnhuizen	A
KG3	Microwave reflectometer	n_e profiles and fluctuations	JET and FOM Rijnhuizen	A
KG4	Polarimeter	$\int n_e B_p ds$ on six vertical chords	JET and CEA Fontenay-aux-Roses	SA
KH1	Hard X-ray monitors	Runaway electrons and disruptions	JET	A
KH2	X-ray pulse height spectrometer	Monitor of T_e, impurities, LH fast electrons	JET	SA
KJ1*	Soft X-ray diode arrays	MHD instabilities and location of rational surfaces	IPP Garching	SA
KJ2*	Toroidal soft X-ray arrays	Toroidal mode numbers	JET	SA
KK1	Electron cyclotron emission spatial scan	$T_e(r,t)$ with scan time of a few milliseconds	NPL, UKAEA Culham and JET	A
KK2	Electron cyclotron emission fast system	$T_e(r,t)$ on microsecond time scale	FOM Rijnhuizen	A
KK3	Electron cyclotron emission heterodyne	$T_e(r,t)$ with high spatial resolution	JET	SA
KL1*	Limiter viewing	Monitor hot spots on limiter, walls, RF antennae, divertor target tiles	JET	A
KM1	2.4MeV neutron spectrometer	Neutron spectra in D-D discharges, ion temperatures and energy distributions	UKAEA Harwell	SA
KM3	2.4MeV time-of-flight neutron spectrometer		NEBESD Studsvik	A
KM7	Time-resolved neutron yield monitor	Triton burning studies	JET and UKAEA Harwell	A
KN1	Time-resolved neutron yield monitor	Time resolved neutron flux	UKAEA Harwell	A
KN2	Neutron activation	Absolute fluxes of neutrons	UKAEA Harwell	SA
KN3*	Neutron yield profile measuring system	Space and time resolved profile of neutron flux	UKAEA Harwell	A
KN4	Delayed neutron activation	Absolute fluxes of neutrons	Mol	A
KR2	Active phase NPA	Ion distribution function, $T_i(r)$	ENEA Frascati	A
KS1	Active phase spectroscopy	Impurity behaviour in active conditions	IPP Garching	SA
KS2*	Spatial scan X-ray crystal spectroscopy	Space and time resolved impurity profiles	IPP Garching	SA
KS3	H-alpha and visible light monitors	Ionisation rate, Z_{eff}, impurity fluxes from wall and limiter	JET	SA
KS4	Charge exchange recombination spectroscopy (using heating beam)	Fully ionized light impurity concentration, $T_i(r)$, rotation velocities	JET	SA
KS5	Active Balmer α spectroscopy	T_D, n_D and $Z_{eff}(r)$	JET	SA
KT1*	VUV spectroscopy spatial scan	Time and space resolved impurity densities	CEA Fontenay-aux-Roses	A
KT2*	VUV broadband spectroscopy	Impurity survey	UKAEA Culham	A
KT3	Active phase CX spectrioscopy	Fully ionized light impurity concentration, $T_i(r)$, rotation velocities	JET	SA
KT4*	Grazing incidence + visible spectroscopy	Impurity survey	UKAEA Culham	A
KX1	High resolution X-ray crystal spectroscopy	Central ion temperature, rotation and Ni concentration	ENEA Frascati	A
KY1	Surface analysis station	Plasma wall and limiter interactions including release of hydrogen isotope recycling	IPP Garching	Automated, but not usually operated unattended
KY2	Surface probe fast transfer system		UKAEA Culham	
KY3*	Plasma boundary probes	Vertical probe drives for reciprocating Langmuir and surface collecting probes	JET, UKAEA Culham and IPP Garching	
KY4	Fixed Langmuir probes (X-point belt limiter)	Edge parameters	JET	SA
KY5	Fast pressure gauges	Neutral particle fluxes on target	IPP Garching	M
KZ3*	Laser injected trace elements	Particle transport, T_i, impurity behaviour	JET	M
Kγ1	Gamma-rays	Fast ion distribution	JET	M

* Not compatible with tritium   A=Automatic; SA=Semi-automatic; M=Manual

pendence of the electron temperature at a number of fixed points in the plasma. The real-time processing system analyses all data from one of the Michelson interferometers, allowing real-time calculation of interlock signals required for the Pellet Launcher Protection System and real-time display of electron temperature profiles in the Control Room.

A cryogenic failure in the detector used for the Michelson interferometers occurred during 1989. The permanent replacement, installed for 1990 operations, showed better cryogenic and detector performance than the original system. The complete Michelson interferometer system was absolutely recalibrated using a large area, high temperature black-body source located inside the vacuum vessel. A new source, with slightly improved radiation temperature and full remote control, was brought into service for use in the beryllium contaminated vacuum vessel. Comparisons of ECE data with that from other diagnostics (in particular, the LIDAR Thomson scattering) indicated that the measured electron temperatures are within the normal level of accuracy ($\pm$10% in absolute level). The stability of the calibration appears to be as good as, if not better than, that of the system before the 1989 detector problems.

The upgrade of the heterodyne radiometer to 44 channels, in the frequency ranges 73-103GHz and 115-127GHz at $\approx$1GHz intervals, has been completed. This extended frequency coverage allows useful measurements over almost the full operating range of the toroidal field. Fig.14 shows data obtained from 25 radiometer channels each having a spatial resolution of $\approx$2cm, spread over a range of $\approx$1m. The signal-to-noise ratio of the measurements is typically >100, with a signal bandwidth of 10kHz. The microwave transmission interferometer has continued routine use for measurements of the line-of-sight electron density and for plasma control purposes. It has operated with high reliability and without modification.

The multichannel reflectometry instrument has 12 probing frequencies in the range 18-80GHz and probes electron densities in the range 0.4-8.0x10^{19}m^{-3}. It has two modes of operation: narrow band swept, for measuring the electron density profile; and fixed frequency, for measuring relatively fast movements of the different density layers. The instrument was brought into initial operation at the end of 1989 and was used extensively during 1990. The main operational difficulty experienced, arose from density fluctuations, which caused inaccuracies in the data from automatic fringe counting and period counting electrons. This was overcome by using filters and swept frequency techniques, which produced reliable operation.

A correlation reflectometry technique has been developed especially for studying density fluctuations. Correlation reflectometry has been carried out with a four channel reflectometer which

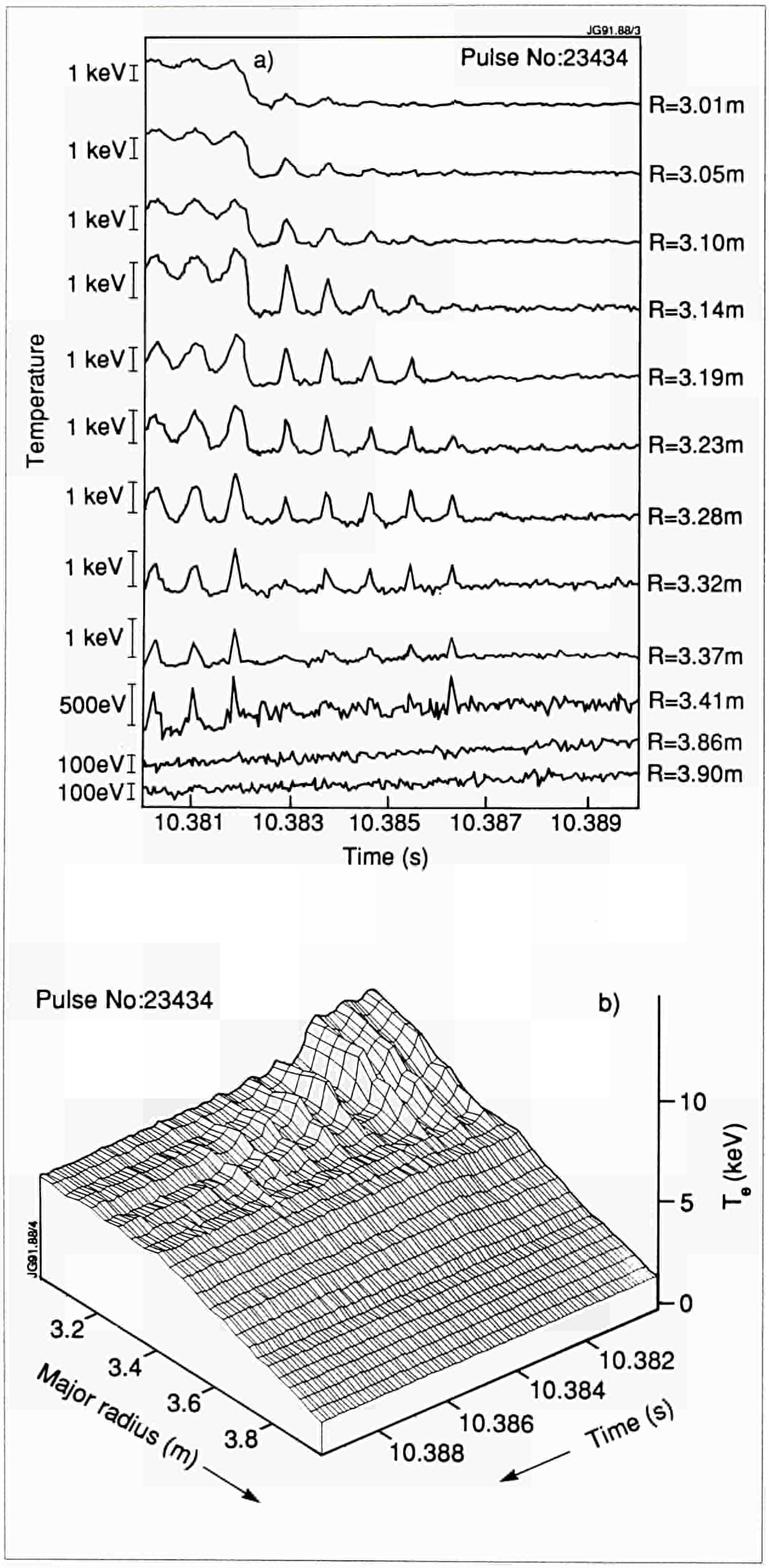


Fig.14: (a) the time evolution of the electron temperature around a sawtooth collapse, at a number of fixed radii. The signals shown are a subset of the 44 channels measured by the heterodyne radiometer. The existence of a localized MHD mode which persists through the sawtooth collapse is clearly visible; (b) data from 25 radiometer channels spanning the outer half of the plasma have been used to obtain the time evolution of the temperature profile in the same time range as part (a).

operates with radiation in the extraordinary mode. Four probing frequencies in the range 75.5 to 76.15GHz are used, which give separation between the reflecting layers, typically in the range 3-20mm. The fluctuating signal on each channel is recorded and the correlation level between the signals is calculated. The dependence of this level on the layer separation is determined by analysing results from the different channels. The data are interpreted in terms of fine-scale structures (i.e. 'density cells'), which rotate toroidally under the influence of the additional heating. From the analysis, an estimate of the radial extent of the structures and the effective toroidal wavenumber spectrum are obtained.

During 1990, work on the LIDAR Thomson Scattering system concentrated on maintaining routine operation and on the planned upgrade of the repetition rate. In addition, modifications were being prepared which should permit high spatial resolution measurements in the plasma edge region. The system operated routinely during the experimental campaigns in either the standard 0.5Hz/9 pulse mode or the ~1Hz/6 pulse mode for improved time resolution. During the year, an event occurred accidentally which enabled the robustness of the time-of-flight (LIDAR) technique to be demonstrated. The carbon tile used as a laser beam dump was dislodged from the inner wall exposing a bright metallic surface leading to a large increase (at least two orders of magnitude) in the stray laser light level. Despite this difficulty, it was possible to maintain operation, by adding only an extra polarizer in the collection optics path. Some data obtained under these conditions is shown in Fig.15.

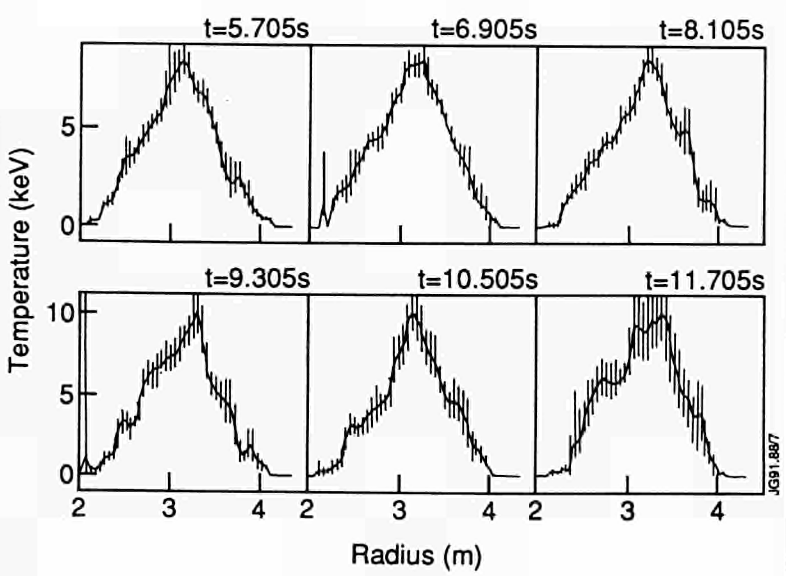


Fig.15: The electron temperature profile measured by LIDAR Thomson scattering in the presence of severe stray light.

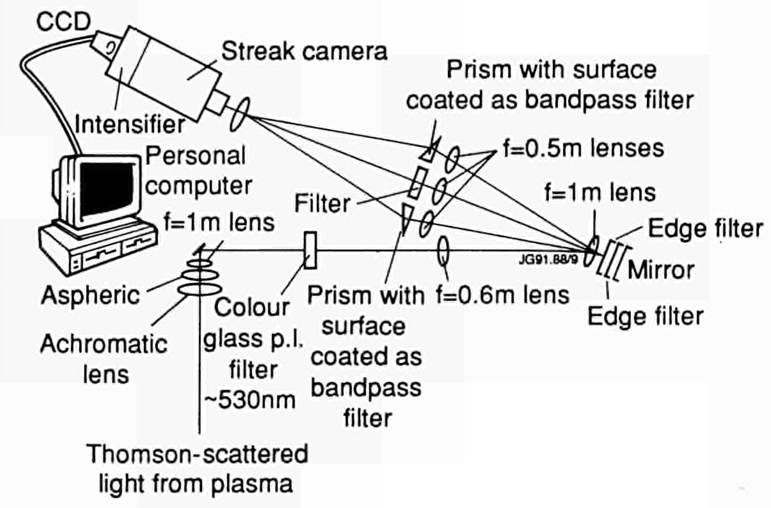


Fig.16: Schematic of the high resolution LIDAR Thomson scattering system under construction for edge measurements.

The upgrade for higher repetition rate has three main components: the installation of high reflectivity (99%) broad band dielectric collection mirrors; the use of PCs for fast data read-out and storage between laser pulses; and the procurement of a high repetition rate (10Hz) short pulse laser. The first two modifications were made during 1989 and were used successfully in 1990. Unfortunately, procurement of the 10Hz laser has met with difficulty and the contract has been terminated. As an alternative, a new system based on a 4Hz ruby laser is being considered, and tender action for such a laser has been initiated. Delivery is planned for early 1992.

An edge LIDAR diagnostic has been developed. One of the six parallel collection optical paths of the main LIDAR system has been redirected in the Roof Laboratory to provide an additional detection path. This path will include a new dispersion system suitable for lower temperature measurements and a new faster detection system based on a streak camera (Fig.16). This arrangement will provide LIDAR measurements with a considerably higher spatial resolution over a limited radial range in the outer region of the plasma. Preliminary stray and plasma light characterisation tests were successfully carried out towards the end of 1990 operations. A streak camera and intensifier unit were used together with an existing CCD camera, suitably modified, as a digitizer. Delivery of the final optical and detection systems is expected early in 1991 and after testing, will be commissioned during 1991 operations.

Spectroscopic ion temperature measurements at JET are based on the Doppler broadening of spectral lines emitted by either highly ionized impurity atoms (e.g. Ni^{26+}) for high resolution X-ray spectroscopy, or by fully stripped light impurity ions (e.g. Be^{4+} or C^{6+}) for Charge Exchange Recombination Spectroscopy (CXRS). The passive emission of the resonance line of Ni^{26+} emanates from the hot plasma core, whereas locations of the active charge exchange emission lines are defined by the intersection of neutral beam and a fan of viewing lines. CXRS is used routinely at JET to measure radial profiles of impurity ion temperatures.

The toroidal vertical and horizontal soft X-ray cameras, containing 120 detectors, have produced much new date in 1990, mainly due to the routine operation of the real-time trigger system. Data has been taken using the two filter technique with alternate filters of different thicknesses in front of adjacent detectors. By tomographic inversion, this allows the determination, of two separate profiles of soft X-ray emission from which, with knowledge of the impurity species, the plasma temperature and density may be determined on a rapid timescale (5ms). This method works reliably. The real-time tomography system has been installed and successfully operated and should be in routine operation in 1991. Adequate inversion speeds have been obtained and typical results are shown in Fig.17.

Boundary Measurements

Single element Langmuir probes in the upper carbon and lower beryllium divertor targets, as well as in the belt limiters, and RF and LH antenna protections have routinely provided measurements of

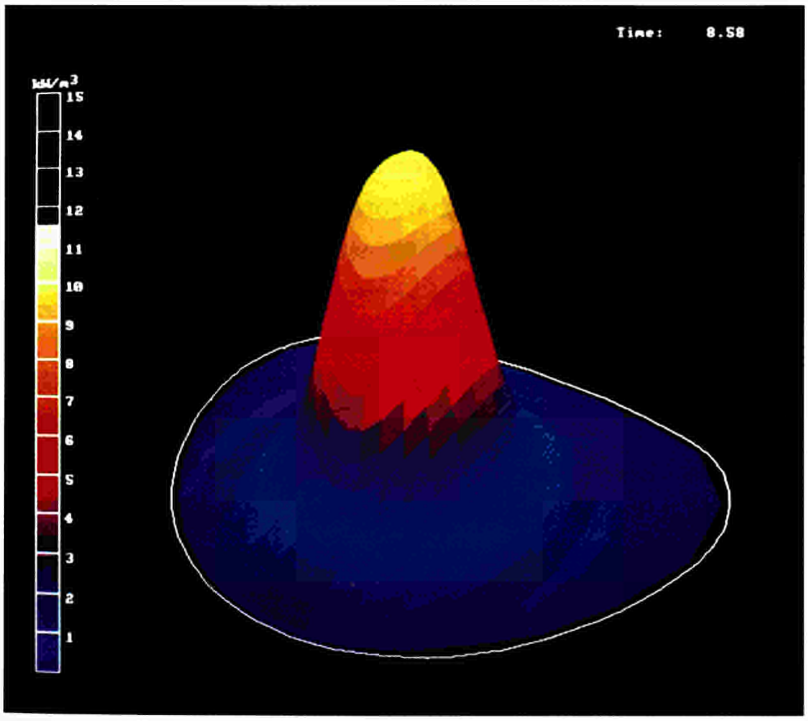


Fig.17: Typical output from the real-time tomography display taken during a plasma discharge.

the plasma parameters of the plasma edge scrape-off layer. Probes in the carbon divertor target plates have proven not to survive the extreme heat loads found near the strike point of the separatrix in pulses with full additional heating. A design study has started for a probe that would be retractable behind the limiter surface and would be extended for measurements only during a very short time (~50ms) (a so called "pop-up probe").

The fast moving reciprocating probe has been used regularly under remote control. The probe head had to be replaced several times due to unexpected plasma contact causing thermal shock damage. Therefore, new probe heads will be manufactured from carbon-fibre reinforced material offering improved protection against thermal shock. A retarding field analyser was used for the first time on the Fast Transfer System Facility to measure the ion temperature in the scrape-off layer. The entrance slit of this probe has proven to be too fragile for the power fluxes found in the scrape-off layer during heating a new more rugged version is under construction.

Observations of limiter surfaces have been made using cameras at various locations. Several wide-angle views have been used for general operational use and these are routinely recorded. With carbon surfaces, very high target temperatures are often observed during intense additional heating. Disruptions under these circumstances often release foreign bodies that can be clearly followed. For detailed studies of limiters and targets, narrow-angle views have been used, usually equipped with remotely controllable carousels with filters for H_α, BeI, II and CI, II, III. If the target temperature exceeds 1200°C, thermal radiation dominates line radiation and the surface temperature can be measured. All this information is recorded in standard professional video format and analysed afterwards on a PC-based system. This analysis system has further matured so that saturated areas on the picture can be restored with a software procedure and so that total deposited power deposited on a selected area can be also obtained.

Impurity Analysis

JET plasmas offer a variety of mixtures of light impurities in the hot plasma core for analysis by various spectroscopic means. Radial profiles of the effective ion charge, Z_{eff}, are determined from Abel inverted profiles of the multi-chord visible Bremsstrahlung signals and simultaneous measurements of main light impurities by charge exchange spectroscopy. The dilution factor (the ratio of deuterium density to electron density, n_d/n_e) is derived from the density of electrons and light impurities.

New methods of analysis of the soft X-ray data have been developed allowing the impurity density and Z_{eff} profile evolutions to be obtained automatically. Following introduction of beryllium in JET, the X-ray emission at energies above 1keV is dominated by Bremsstrahlung radiation from the background deuterium ions, and both Bremsstrahlung and recombination radiation from the impurity species. Under these circumstances, local values of impurity densities and concentrations, or alternatively of the effective charge Z_{eff}, are derived from tomographic measurements of the local X-ray emissivity at energies above 1-3keV, in conjunction with measurements of electron density and temperature profiles (see Fig.18). These calculations are performed using the intrinsic emissivities due to impurity ions. Typical uncertainties are ~25% and there is good agreement with measurements of impurity contamination using visible Bremsstrahlung. Detailed impurity transport measurements have been made by following the evolution of the impurity density profile after injection of high-Z impurities by laser blow-off.

Neutron Measurements

Several types of neutron spectrometers are operated at JET so that a wide range of operating conditions can be covered. For normal

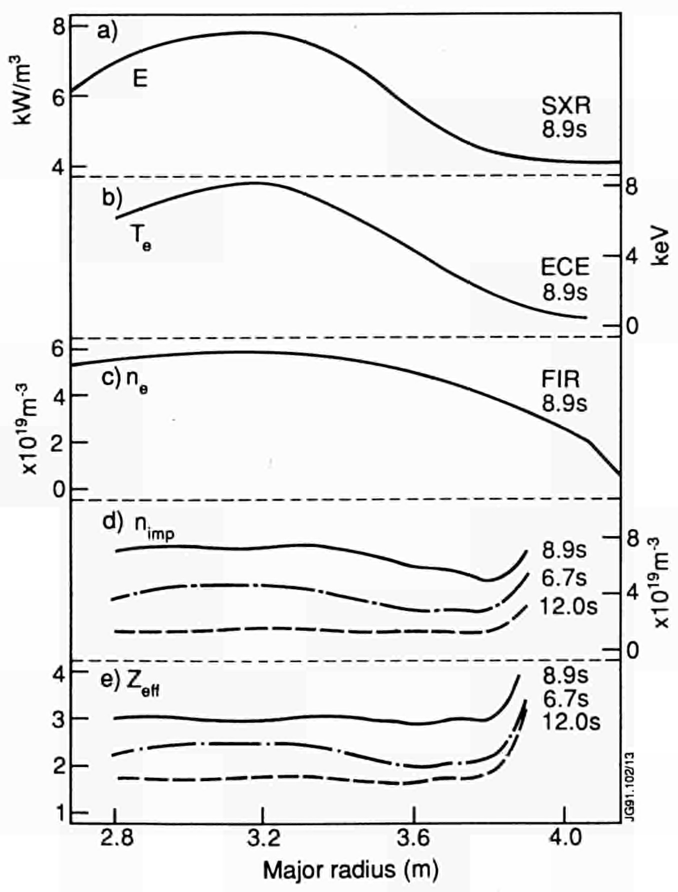


Fig.18: Radial profiles of (a) soft X-ray emissivity; (b) electron temperature from electron cyclotron emission; (c) electron density from far infrared interferometry; (d) impurity density profile; (e) corresponding Z_{eff} profile.

well-behaved discharges, it is possible to unfold the neutron energy spectra to obtain good estimates of the plasma central ion temperature and the beam-plasma to thermal neutron emission strengths. In addition, by combining the analysis with data from the other neutron diagnostics, the beam-beam component can also be identified.

Neutron Spectrometry has proven to be an indispensable diagnostic for the study of discharges in which high power ICRF heating is employed. This is due to the presence of beryllium as the major plasma impurity; ICRF heating generates a high energy tail of light ions (p, D or ^{3}He), which undergo exothermic reactions with beryllium and release energetic neutrons and gamma-rays. The neutron yields from these reactions can be sufficiently strong to compete with the D-D neutron yield. Under favourable conditions (low density and low impurity content), the application of RF power in addition to neutral beam leads to an enhanced D-D reaction rate due to second harmonic interaction with deuterium ions. In addition, experiments with ^{3}He neutral-beam injection provided an opportunity to exploit the Neutron Spectrometers for the measurement of ion temperatures up to 14keV, directly from the Doppler-broadening effect, without the added complication of neutron emission from beam-plasma interactions. This permitted direct comparison with temperatures obtained from the charge-exchange diagnostic, which had not previously been possible. Acceptable agreement was obtained.

The Neutron Profile Monitor provides a measure of the spatial variation of neutron emissivity throughout the plasma volume. A topic of particular interest is the change in emission profile during sawtooth crashes, which has been studied using tomographic inversion methods. Fig.19 gives an example of the dramatic change which takes place in the profile for a deuterium beam-heated discharge, whereas the change in total neutron emission strength recorded by the Fission Chambers is only 15%. If the sawtooth crash leads only to a displacement of the hot ions, conserving their energy and density, then no change in global emission would be expected. The change observed is attributed mainly to the contribution to total emission from beam-beam interactions which is important on-axis when the beam ion density is high, but varies inversely with density and so becomes small after the redistribution.

The strength of the neutron emission from JET plasmas is routinely recorded with sets of Fission Chambers mounted near three of the main horizontal ports of the machine. Their use for measuring the instantaneous neutron emission strength requires determination of absolute detection efficiencies to better than 10% accuracy. This is now achieved through the employment of foil activation

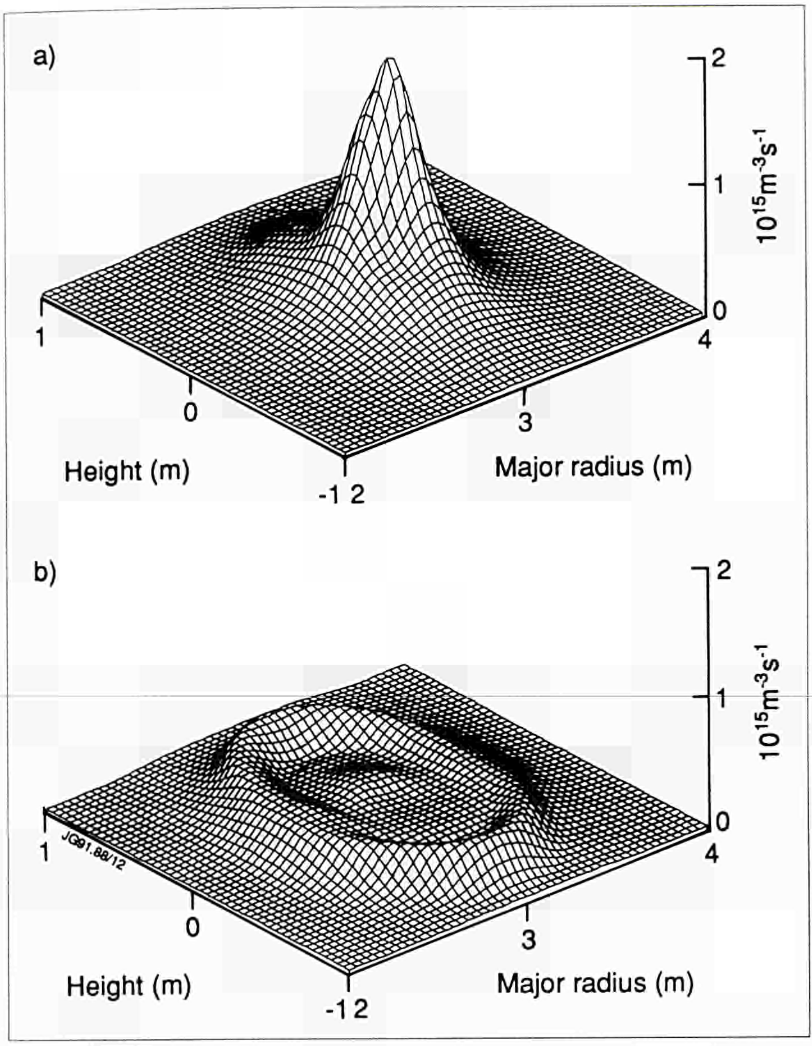


Fig.19: Tomographic presentation of the neutron emission profiles before and after a sawtooth crash for a discharge in which the central neutron emission before the crash is dominated by beam-beam reactions.

techniques, using two new irradiation positions that have been established inside the vacuum vessel to minimize the problems of modelling structures surrounding the plasma. Although the Fission Chamber detection efficiencies are now well established, they sometimes alter between operation periods in a manner that is not expected rom the nature of the changes made to nearby hardware. To assist in understanding these changes, a simplified computer model of the tokamak has been developed for use with neutron transport codes. This model has been validated by comparison with extensive in-vessel measurements and model calculations reproduce well the scan obtained by moving a source around the tokamak. These calculations indicate that the detection efficiency is relatively insensitive to the equipment arrayed around the ports. They also showed a 15% change in efficiency that took place over the 1989/1990 shutdown was attributable to the change from water to freon as a toroidal field coil coolant.

Fast Particle and Alpha Particle Studies

A new time-of-flight neutral particle analyzer was installed during 1990. The NPA is located at the bottom of Octant No.1, with a vertical line-of-sight crossing the torus mid-plane at major radius of 3.1m. The analyser is absolutely calibrated for the measurement of H^+, D^+, T^+, $^3He^{++}$ and $^4He^{++}$ ions in the energy range 0.5-200keV, although the analyzer is capable of measuring ≈300keV singly charged and ~600keV doubly charged ions.

The mass analysis is performed using time-of-flight/coincidence measurement. The latter feature gives discrimination against noise in the neutral flux measurements induced by the high neutron and γ-ray environment of JET. The full energy range is covered by 15 energy channels with $\Delta E/E = 0.05\text{-}1$, each equipped with three coincidence channels, enabling simultaneous measurement of a wide selection of particles. The two key features of the new system, discrimination against neutrons and high energy range, have been tested and successfully exploited in the last experimental campaign. High neutron and γ-ray discrimination factors of 100-400 have been measured, which makes it possible to measure neutral particle spectra during pulses of $3\times10^{18}\text{-}10^{19}$ neutrons/s.

A diagnostic system to measure the velocity and spatial distribu-

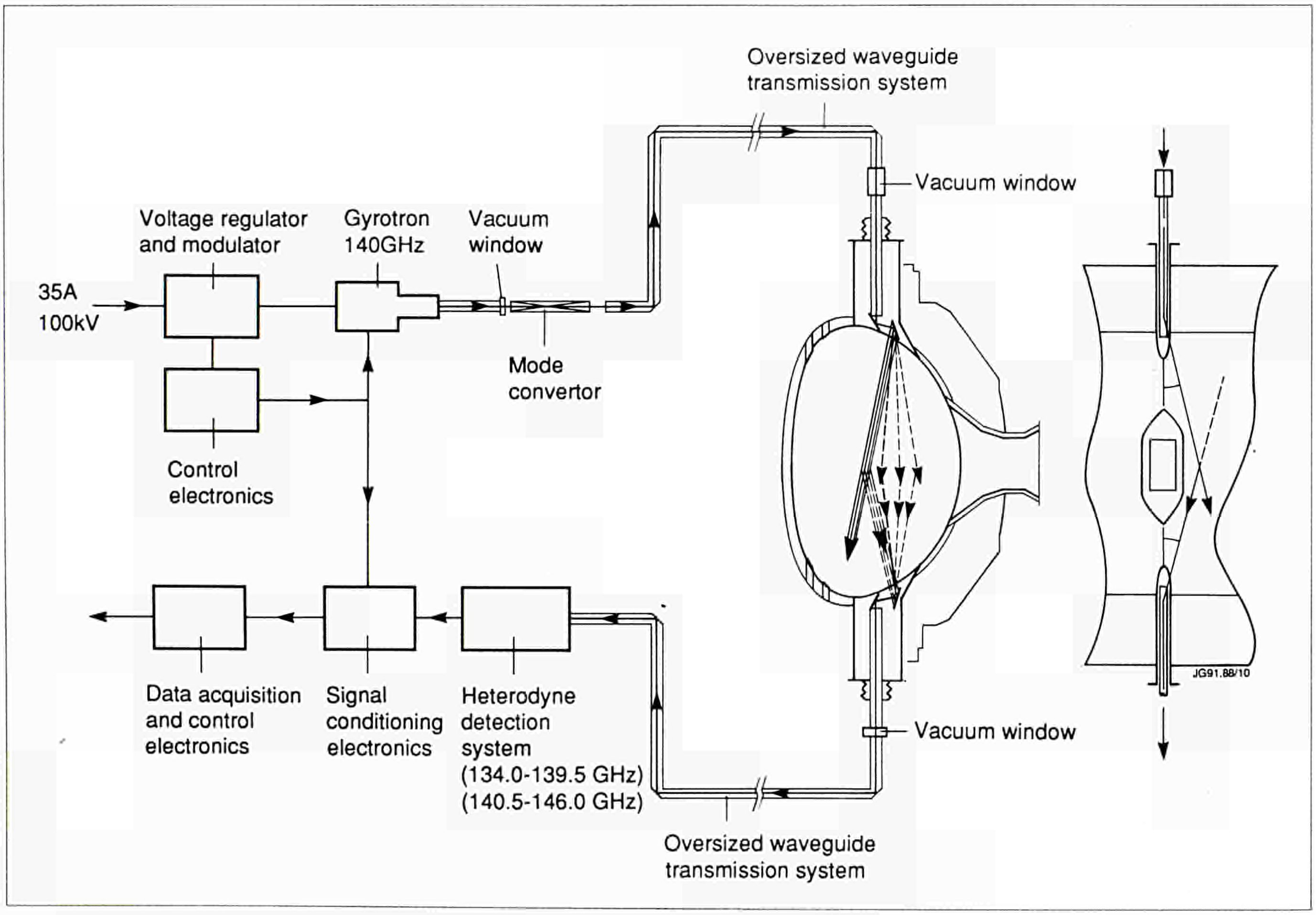


Fig.20: Schematic of collective scattering system for measuring spatial and velocity distributions of fast ions including alpha-particles.

tions of fast ions, including α-particles in the D-T phase, is in preparation. The system is based on collective scattering of radiation with a frequency of 140GHz generated by a powerful gyrotron source. During 1990, the development of high power 140GHz gyrotrons were sufficiently advanced to permit a start of construction of the collective scattering system. Design of the system was completed and contracts placed for all major components. The system will be implemented in two stages. There will be a preliminary stage aimed at validating the physics of the technique and making the first measurements of fast ions. This stage will also involve important tests of technical aspects of the system and will be undertaken in 1991. The system will then be upgraded for D-T operation and made compatible with the pumped divertor geometry of JET.

The principal system components are a gyrotron with power supplies and modulator, a mode convertor, oversized waveguide transmission systems for launch and detection, a multichannel heterodyne detector system, and signal conditioning and data acquisition electronics (see Fig.20). The gyrotron is a high power (>400kW), long pulse (>5s) tube, and for initial experiments, an existing prototype tube will be used. The waveguide will include special resistive sections to absorb power in unwanted modes. For initial operation, an inertially cooled sapphire disc will be used as the torus vacuum window. This will limit the gyrotron pulse length to a few seconds and so the design of a cryogenic sapphire window has been initiated. Radiation will be launched into the torus via two mirrors, the last mirror being rotatable in two independent directions. An identical arrangement at the bottom of the vessel will be used to detect the scattered radiation. The scattered radiation will be transmitted to a heterodyne detection system. Ultimately, there will be 40 channels between 123 and 156GHz. Both the fast ion and thermal ion features will be detected.

Remote Handling and Beryllium Handling

The main objective of the remote handling programme is to prepare for the introduction of tritium into JET, which will generate a large number of D-T fusion reactions, with a high flux of 14MeV neutrons. Some of these neutrons will be captured by the structure of the machine, making it too radioactive to approach. Therefore, all maintenance will need to be carried out by remote control from outside the Torus Hall. Special equipment and methods are also being developed for safe working with increased background radiation levels, slightly active dust and the use of beryllium in the torus. During 1990, remote handling development work was supported at a much lower level than planned due to the heavy involvement of manpower in the major shutdowns. This involvement meant that the articulated boom was unavailable for mock-up work whilst installed on the torus and then also unavailable whilst being maintained and prepared for the next shutdown.

The large remotely-controlled articulated boom has been designed for reaching into the JET vacuum vessel for maintenance and repair when the machine has become radioactive. It can carry loads of up to 1 tonne at the end of its 9m horizontal reach. Special tools have been developed for various remote handling tasks including welding and cutting parts of the vacuum vessel. During 1990 shutdowns, about 50 entries into the vessel were carried out under programmed teach-repeat control. Substantial use was made of the new editing facilities to reverse or mirror image existing teach files. This resulted in considerable time savings, particularly in the difficult manoeuvre through the narrow entry port, and is a significant step towards true remote operation of the boom. The boom was used for the installation of the new LHCD antennae (side protection and hanger), a complicated operation which fully exploited the articulations of the boom and their precise control. In November/ December, 32 dump plates were installed over a two week period.

A new boom extension structure was designed and verified with finite element analysis to check stress concentrations at the mechanical end stops during fault conditions. The new design allows an increase in the tilt angular range of motion so that vertical pick-up of components is safety achieved. This method has been used for both antennae and dump plate installation. A quick release mechanism has been designed to free the joints and retrieve the boom, should the actuators seize in the vessel. During 1990, a decision was made to build a new boom control system, to replace the existing PLC based design, which is ageing and difficult to enhance. The new hardware has already been selected and procured, and the analysis and design of software is well underway. It is expected that the new system will be ready for operation by the 1991 major shutdown.

The Telescopic Articulated Remote Mast (TARM), which will be attached and operated from the large 150 tonne crane, was delivered to JET and assembled on a stillage in the Assembly Hall, (see Fig.21). After careful mechanical testing and commissioning of the controls, a Mascot servomanipulator was installed on the terminal interface (docking) module and some turbomolecular pump maintenance scenarios were demonstrated. The TARM was subsequently hoisted onto the crane trolley to check its complex geometrical fit to the crane. Commissioning and refinement of the robotics control system, a uniquely complex system controlling 32 degrees of freedom, is in progress. The main controls are already proving most satisfactory in both teach-repeat and resolved motion.

Inspections of the inside of the vacuum vessel after disruptions

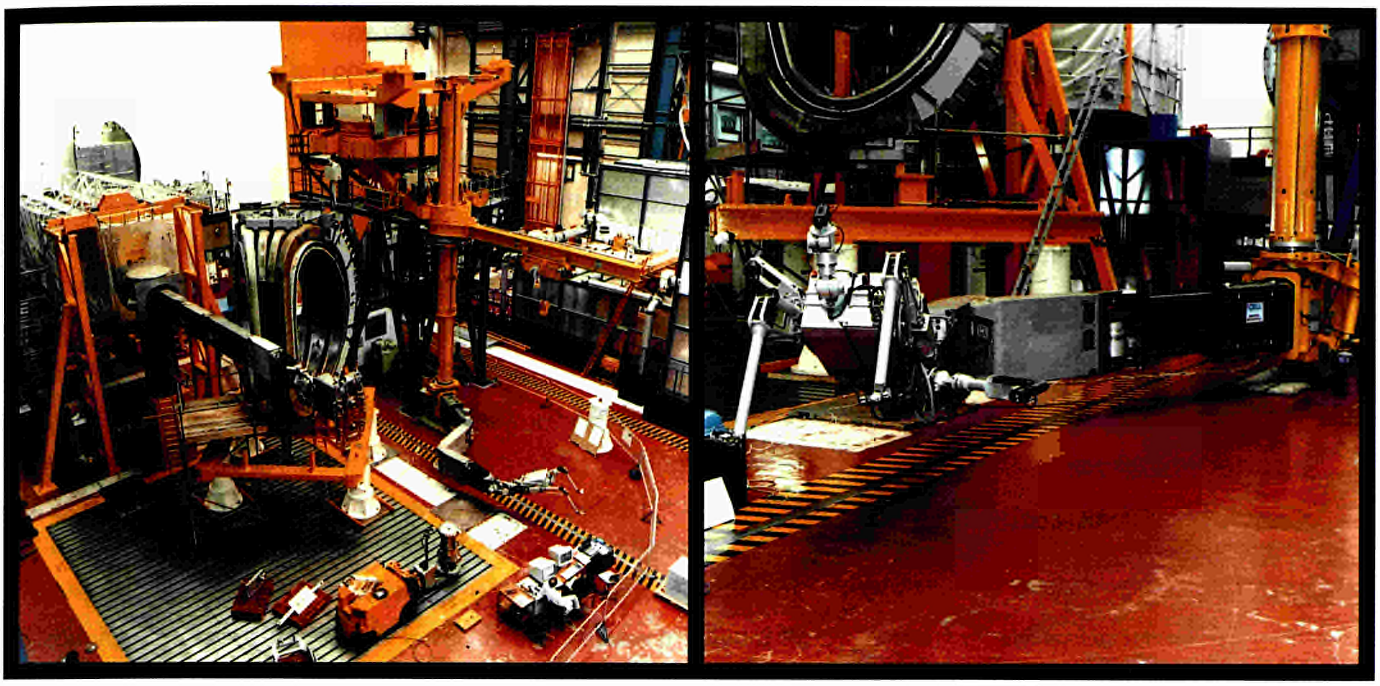


Fig.21: (a) the TARM installed on stillage in the Assembly Hall, shown with Mascot approaching a turbopump on a low level transporter for remote handling trials; (b) both TARM and Boom can reach the inside of the spare Octant for in-vessel tests.

have been carried out using the In-Vessel Inspection System (IVIS). This has permitted the location of damage, so enabling the operational programme to be tailored accordingly. In view of the increasing importance of these inspections, improvements of the quality of the image and its interpretation are being implemented. An alternative camera unit prototype has been developed, including a zoom facility for better resolution. A CCD camera is used because it is less affected by electrical noise, and sensitivity can be enhanced by integrating with the existing image processor. A new interface system has been developed, to compose on a workstation a wide angle mosaic of the recorded images, which are then easily retrieved and enlarged.

On beryllium related operations, there were about 27 weeks of in-vessel intervention work during 1990, in three shutdown periods. Respiratory protection and protective clothing were required through this period, with most of the work being carried out in pressurised suits. Further enhancements to the Torus Access Cabin (TAC) were carried out to improve the flow of personnel and materials. The most significant change was the attachment of the Cabin to the Site Active Drain Line which, in combination with a new filtration system, allows the aqueous waste from the Cabin to be disposed of without recourse to a mobile bowser.

The enclosed Beryllium Handling Facility in the Assembly Hall has been in operation throughout the year on support operations for the in-vessel programme. These have included component decontamiantion and modification. Planned improvements in this area include new decontamination equipment and aqueous waste filtration. These will be installed in 1991 when the facility will also be linked to the Site Active Drain Line. A dedicated facility for cleaning, inspection and repair of pressurised suits and respirators was commissioned in early 1990. Around 100 suits per week were handled during the shutdown periods. During the year, an 8m^3 drain tank was commissioned for the wash water. This has also been connected to the active drain line. The PVC workshop has been used to fabricate over 250 isolators during the year, in addition to carrying out site work on isolator systems using mobile RF welding equipment.

Waste generated during in-vessel operations is classified initially as potentially active waste. A sampling facility has been commissioned in the Beryllium Handling Facility and the waste samples are analysed at AEA Harwell Laboratory for activity. During 1990, 100m^3 of beryllium waste were disposed of in 200 litre drums. Analysis of the waste indicated levels of beryllium significantly less than 1%. Consequently, following an agreement with the Local Authority, a disposal method using a lockable covered skip for the double bagged housekeeping waste has been introduced. About 100m^3 of waste were disosed of by this method during the year.

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 Norsk Data minicomputers interfaced to the experiment through CAMAC 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 located at AEA Technology, Harwell Laboratory, for detailed analysis. A summary of information from the JET pulses is held in the JET Survey Data Bank.

Control and Data Management

The Computing Service is based on an IBM 3090/300J 3-way processor mainframe with a two vector facility. There are 70GBytes of disc storage and a further 240GBytes of IBM mass storage. The JET Mainframe Data Processing Centre is housed in a specially designed building at AEA Technology, Harwell Laboratory, U.K. and operated for JET under contract by a team from that Laboratory. The JET mainframe is also connected to the Harwell Laboratory CRAY2 computer.

The JET Computing Centre has been operating since June 1987 and the computing load has grown significantly since that date. The central computer was upgraded to the latest IBM technology 3090/300J model in February 1990, ensuring that good response time was maintained for interactive users and for the CAD systems in the JET Drawing Office, even at peak times. Also, prompt execution of the intershot analysis is ensured. A background load of batch work is also serviced but some of the increasing long batch job work-load, such as transport analysis and extensive structural analysis codes, is displaced outside the daytime period, when necessary.

The JET Data Management Group provides the contact between users, operators and system programmers, through the Help Desk Service, backed up by specialists in the Group. This ensures the smooth running of the system. The data communications between the JET site system and the Computer Centre are mainly the responsibility of CODAS Division and significant improvements have taken place in these areas.

JET Computations

Currently, 135GBytes of raw JET data (JPFs) are stored on the cached Mass Store in a compressed form, and a further 35GBytes of analysed data are stored on the Processed Pulse File (PPF) online data-base system. The Central Physics File (CPF), established during 1988, forms a complete higher level data selection and storage system. A subset of all data is extracted at time points of interest, determined by the Timeslice program and the interactive timeslice editor, TED, and stored in SAS databases. These data are the basis for extended statistical analysis, and the source for other extracts such as the TRANSPORT bank. This complete system is a fully automated process, and is used by many physicists in the Project.

Important advances have been made in the following areas of:

- One of the main difficulties in deriving experimental energy and particle fluxes lies in the consistency and accuracy of the measured input data such as temperature, density and radiation profiles. A set of check programmes has been developed and run as the initial step of the FALCON (**F**ast **A**nalysis of **L**ocal **Con**finement) code. For about 1600 time points in 600 JET discharges, individually checked heat and particle flux profiles are now available with estimated errors resulting from systematic error propagation studies. The FALCON system now plays a key role in ongoing experimental campaigns. Its data handling techniques and checkes on internal consistency of measured data have largely inspired the new design of routine data processing programs for JET;
- A new version of the quilibrium magnetic surface identification code (IDENTD) has been implemented. In addition to the magnetic signals and pressure profiles from laser scattering, this code also uses Faraday rotation measurements from a multichannel interferometer as input to determine magnetic flux surface configuration and current density profiles. The configuration bank now contains 10 to 20 configurations for each of about 650 JET discharges;
- For the planned pumped divertor, magnetic field calculations have been performed. Two codes INVERSX and PROTEUS, based on different methods and different finite-element discretisations, produced the same configurations within error bars of ~1% on integral quantities. These magnetic field configurations were subsequently used to model the scrape-off layer;
- To model impurity control, a versatile 11/2-D model has been developed which is based on a plasma model and an impurity

Prediction, Interpretation and Analysis

The prediction of performance by computer simulation, the interpretation of data, and the application of analytic plasma theory are of major importance in gaining an understanding of plasma behaviour in JET.

- *Prediction work continuously checks the measured behaviour against the different computational models, and provides a basis for long term programme planning;*
- *Interpretation plays a key role in the assessment of plasma performance, and hence in optimisation studies and programme planning;*
- *A major role of analytic theory is to compare the observed behaviour against that expected from existing analysis, and to modify the latter when there is divergence.*

A central task is to provide a quantitative model of tokamak plasmas with the ultimate objective of including all the important effects observed in JET and other tokamaks. It is preferable to understand each effect theoretically, but in some cases it may be necessary to rely on an empirical description.

For carrying out these tasks it is important that JET data is held in a readily accessible and understandable form.

model. This model has been used to simulate JET experimental results and to predict the retention of impurities by the planned pumped divertor. While much remains to be done for a satisfactory validation of the model, results obtained so far show an overall consistency of the model with experimental results.

Summary of Machine Operation

During 1990, JET operations were essentially made up of three periods:

a) *The first period (Weeks 12 to 24)*

This period included the following activities:

- CODAS and power supplies commissioning were carried out in parallel with shutdown activities;
- Lower X-point beryllium tiles were installed in the vessel;
- Power supply commissioning culminated in plasma recommissioning (Week 23), and led to the start of the experimental programme in Week 24;

b) *The second period (Weeks 24 to 30)*

- Experimental operation stopped in Week 25 to undertake remedial in-vessel work in Weeks 26 and 27. This work was required due to damage to in-vessel protection tiles (some fallen and some out of position). The damage resulted from high performance operation involving some disruptions;
- After some power supplies recommissioning (Week 27), the experimental programme was continued in Week 28, but was halted in Week 29 for vacuum-leak testing and repairs. During a plasma disruption, a diagnostic vacuum connection had been ruptured, which resulted in the abrupt loss of torus vacuum. Remedial work was rapidly performed;
- Plasma operation was achieved late in Week 29 and continued in Week 30 until a planned power outage (Weeks 31 to 34) to allow CEGB maintenance on the 400kV supply network. During this break, some in-vessel remedial work was carried out. In particular, protections were fitted between the lower X-point beryllium tiles and neighbouring graphite tiles to cover small gaps.

c) *The third period (Weeks 35 to 45)*

- Week 34 was devoted to commissioning as many systems as possible in the absence of the pulsed HV supply so that little power commissioning was required before plasma operation and the experimental operation were successfully restarted in Week 35;

- The experimental programme proceeded to the end of Week 44, when the planned 1990/91 shutdown began. Remedial and maintenance work was kept to a minimum to allow as much time as possible for the experimental programme. However, this phase of high-power operation was difficult, due to:
  i) increasing in-vessel damage as a result of high performance operation (protection tiles and their supporting structures dislodged). This damage was regularly monitored with the in-vessel inspection system (IVIS);
  ii) the constraint to restrict the neutron activation of the vessel (to limit the radiation dose for the in-vessel workers in the subsequent shutdown). During this period, one of the neutral beam injectors was converted from deuterium to helium operation. This permitted new and important experiments, while restricting neutron production.
- In Week 45, commissioning of the HV pulsed-power-supply reactive power compensation system was completed. This system will be operated in a fully integrated fashion in 1991.

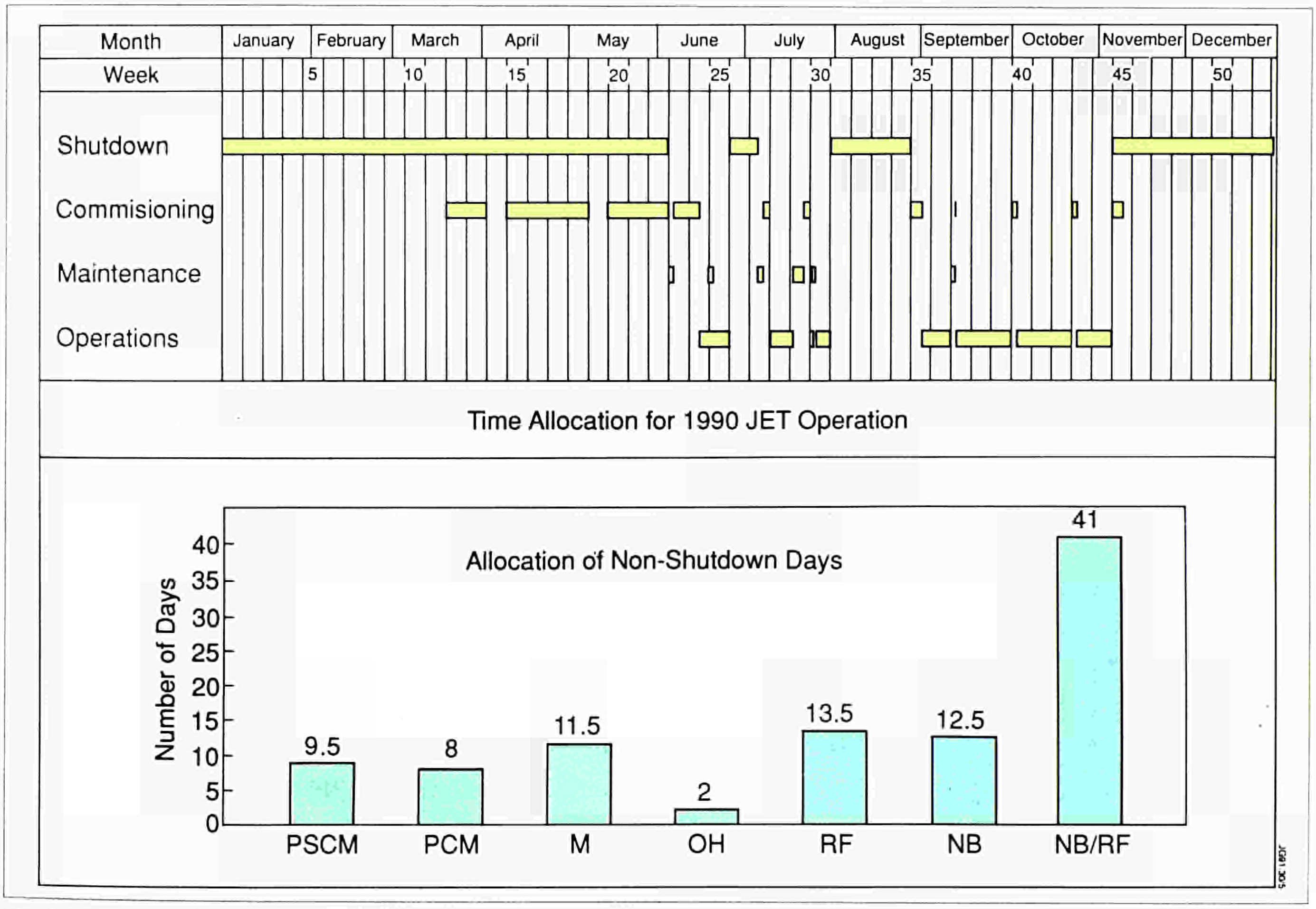


Fig.22: Allocation of days in which machine pulses were performed during 1990. PSC = power supplies commissioning, PCM = plasma recommissioning, M = maintenance and remedial work, OH = ohmic heating, RF = radio-frequency heating, NB = neutral beam heating, NB/RF = combined (NB and RF) heating.

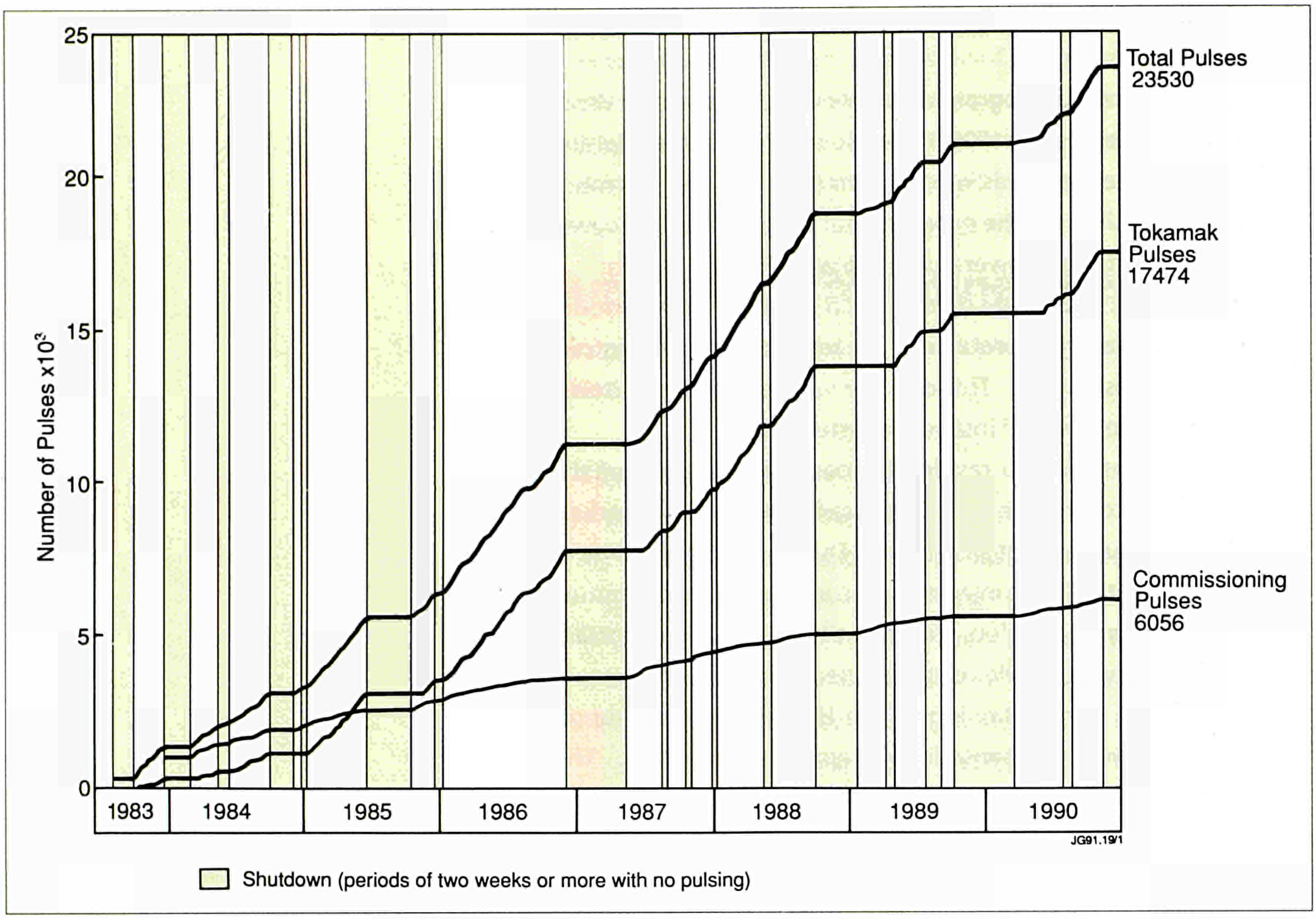


Fig.23: Cumulative totals of JET pulses.

During 1990, the machine was operated for 86.5 days, which was about the same period as in 1989. However, the relative amount of time for the experimental programme in 1990 was increased to 69 double-shift days compared with 56.5 double-shift days in 1989. This was due to:

i) much of the recommissioning activities were carried out in parallel with shutdown work;
ii) there were fewer maintenance and remedial days;
iii) regular six day-a-week double shift working (Monday to Saturday) was used both for operation and commissioning;
iv) commissioning was carried out in double-shift-day operation.

These operation days were divided among the different heating programmes as follows:

3%	Ohmic (OH) heating only;
21%	Radio Frequency (RF) heating only;
18%	Neutral-Beam (NB) heating only;
58%	Combined (NB and RF) heating.

Lower Hybrid Current Drive (LHCD), which involves the prospect of profile control was brought into initial operation.

The allocation of time to different activities is shown in Fig.22. The experimental programme was carried out by three Task Forces, and the double-shift operation days in which these were involved were distributed as follows:

Task Force L	(Limiter Plasmas)	36%
Task Force P	(Profile Effects)	29%
Task Force X	(X-Point Plasmas)	35%

The number of pulses in 1990 was 2500, bringing the total number of cumulative JET pulses to 23530. The relative number of commissioning pulses continued to decrease (see Fig.23), and operation clearly moved to higher plasma currents (>3MA) (see Fig.24).

In spite of the limited time available for operation and the relatively small number of pulses, 1990 was a year in which high performance operation was repeatedly achieved and in which most systems performed satisfactorily. Of most concern are the in-vessel components which became damaged as a result of the large forces associated with disruptions during high performance plasma operation. Improvements in the fixing of such components will be carried out in 1991 and methods for improving the control of disruptions are being considered.

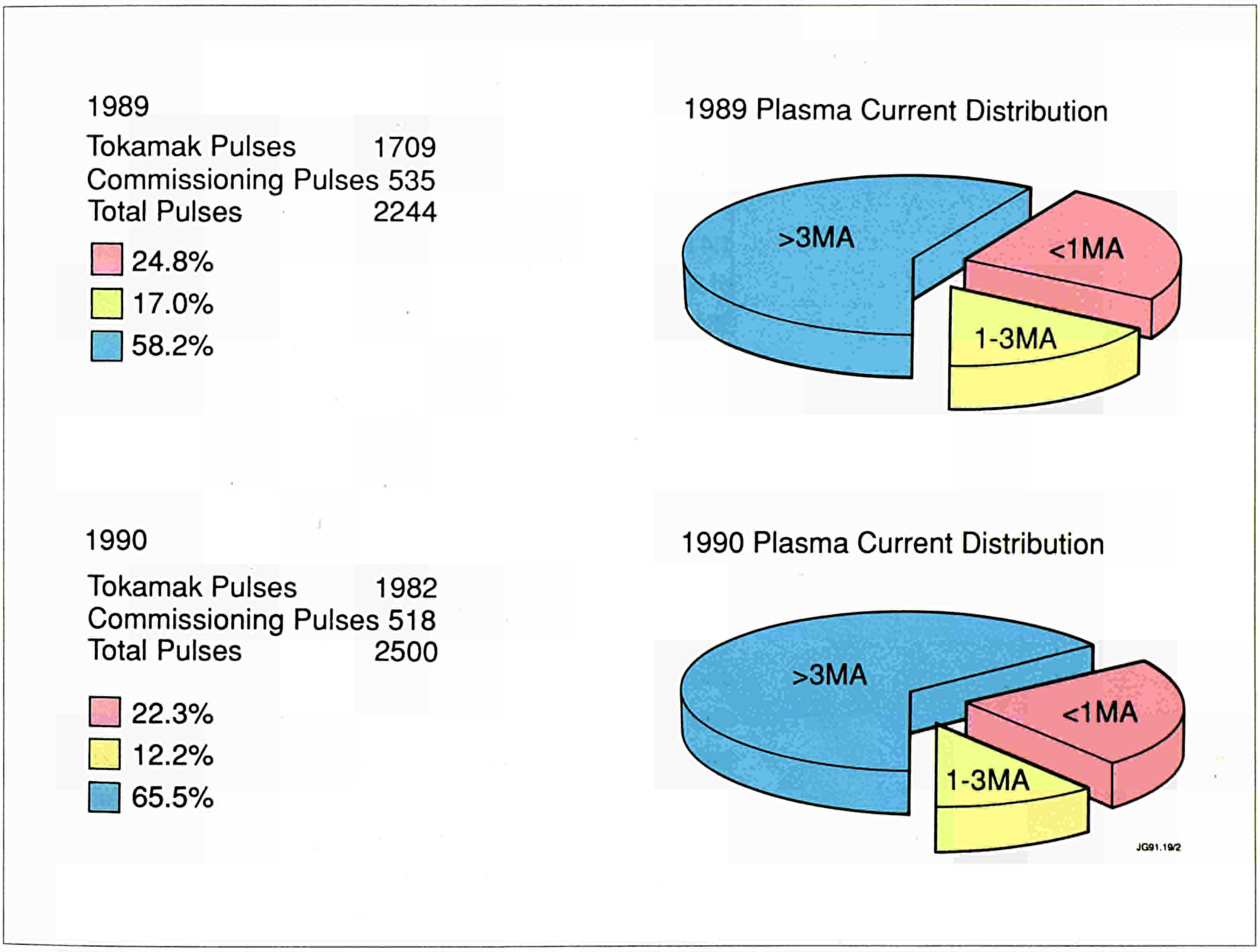


*Fig.24: Comparison of numbers of pulses and distributions of plasma currents for 1989 and 1990. The 1989 plasma current distribution differs from that in the 1989 Annual Report which was limited to technically successful pulses only. The present comparison is for **all** tokamak pulses, both non-successful (mainly <1MA) and successful.*

Technical Developments for Future Operations

Considerable effort was devoted during the year to the design and procurement of equipment for installation on the machine during future major shutdowns. Reference should be made to the section on the Future Programme of JET to relate these technical developments to the overall JET programme.

Lower Hybrid Current Drive

The Lower Hybrid Current Drive (LHCD) technique will be the main method of decoupling the plasma current and temperature profiles in JET. The main objectives of current drive and profile control are:

- to suppress sawteeth activity and to benefit from higher core reactivity by sustaining peaked profiles of both density and temperature;
- to modify local values of the current gradient and improve energy confinement in the plasma centre;
- to assess the current (and efficiency) required for non-inductive operation of large tokamaks.

The JET LHCD system will be powered by 24 klystrons operating at 3.7GHz. Each klystron has been uprated to 650kW and will produce a total power of 15MW. The launcher will produce a narrow wave spectrum with a parallel wave index which can be varied from 1.4 to 2.4. The horizontal row producing this spectrum is composed of 32 waveguides; with 12 rows, the total number of waveguides is 384. The system is summarized in Table.5.

The system will be installed in JET in two stages. The first prototype stage was installed and tested during 1990. The first stage was composed of two prototype launchers, one built using the same technique as foreseen for the final system and one built by CEA Cadarache, France, using the technique developed for Tore Supra. The prototype launcher compromising one third of the number of waveguides of the full system was tested and installed on the torus. The corresponding eight klystrons and associated drive, phase control and power transmission system were also installed and commissioned, and the system used in operation during the experimental campaign. In the limited experimental and commissioning period that was available, the prototype system operated at 1.5MW for 20s and 1.6MW for 10s and these initial experiments were performed with phase control of the klystrons at their output and with $\pm 180^{\circ}$ phase modulation of the klystron output to assess relative phase at the grill mouth. Initial coupling studies in X-point plasmas were also performed.

Manufacture of the final launcher is in an advanced state.

Table.5: LHCD System Parameters

	Final System	Prototype System
Generator		
Frequency	3.7GHz	
Number of klystrons	24	(8)
Power (generator)		
10s pulse	15 MW	(5)
20s pulse	12 MW	(4)
Duty cycle	1/30	
Efficiency	42 %	
Phase control	10 degrees	
Maximum VSWR	1.8	
Transmission line length	40m	
Estimated insertion losses	1dB	
Launcher		
Number of waveguides	384	(128)
(48 multijunctions)		
Waveguide material	stainless steel	
Coating	copper	(copper + carbon)
Maximum temperature	500°C	
Total weight	15 tonnes	(10)
Stroke	210 mm	
Response	12 mm/15 ms	
Pumping	100 000/s^{-1}	

Following a review of the programme, it is now planned to install this launcher with the pumped divertor in 1992. This has required some design changes to match the shape of the grill mouth to the larger plane profile, and has required some delay in manufacture pending completion of the design. The 48 multijunction units at the heart of the launcher are, however, complete apart from final internal machining to the revised design.

High Speed Pellet Injection

The injection of solid hydrogen pellets is one method of providing a particle source inside the recycling boundary layer of a future fusion reactor without simultaneously depositing excessive power. The ablation of the pellet by hot plasma electrons requires very high speed pellets, in order to penetrate beyond the q=1 surface to the plasma centre. So far in JET, measurements have only been carried out in a limited velocity range up to 1500ms^{-1}. JET plans an advanced multi-pellet injection system which will be installed during the 1992 shut-down and brought into operation in the 1993 operational period. The planned system presently comprises a high-speed multi-pellet Advanced Pellet Launcher (APL) incorporating two-stage gun technology; a new slightly upgraded version of the present ORNL Launcher for medium-speed pellets; and a pellet centrifuge for low-speed pellets at a high rate suitable for the requirements of the pumped divertor programme. The upgraded ORNL launcher will be a repetitive pneumatic single-stage launcher, JPL II, compatible with the geometry of the new APL and with the tritium, radiation, and remote handling requirements for the D-T Phase of JET. The envisaged spatial arrangement of the three pellet sources is shown in Fig.25. The APL and JPL II are attached to the Pellet Injector Box (PIB), which acts as a differential pumping system to remove the driver gas of the pneumatic guns. The centrifuge bypasses the Pellet Injector Box PIB, but connects into the same main horizontal port of Octant No.2.

As a first step towards the APL, JET is preparing experiments employing a 6mm single-shot, two-stage gun prototype launcher of its own development with a pellet velocity of ~4kms^{-1}. The complete first prototype launcher is assembled in the teststand. Its two-stage gun is commissioned and sabot-only-shots have been fired in liquid helium conditions. The in-flight separation of the sabot from the pellet trajectory has been proved. The solid pellet formation and storage commissioning is still continuing. However, it is expected that the launcher will be ready for operation in 1991. Once the gun is fully commissioned, its transfer to the Torus Hall and its re-commissioning on the machine can be accomplished speedily. A second Prototype Launcher has been manufactured and is ready for

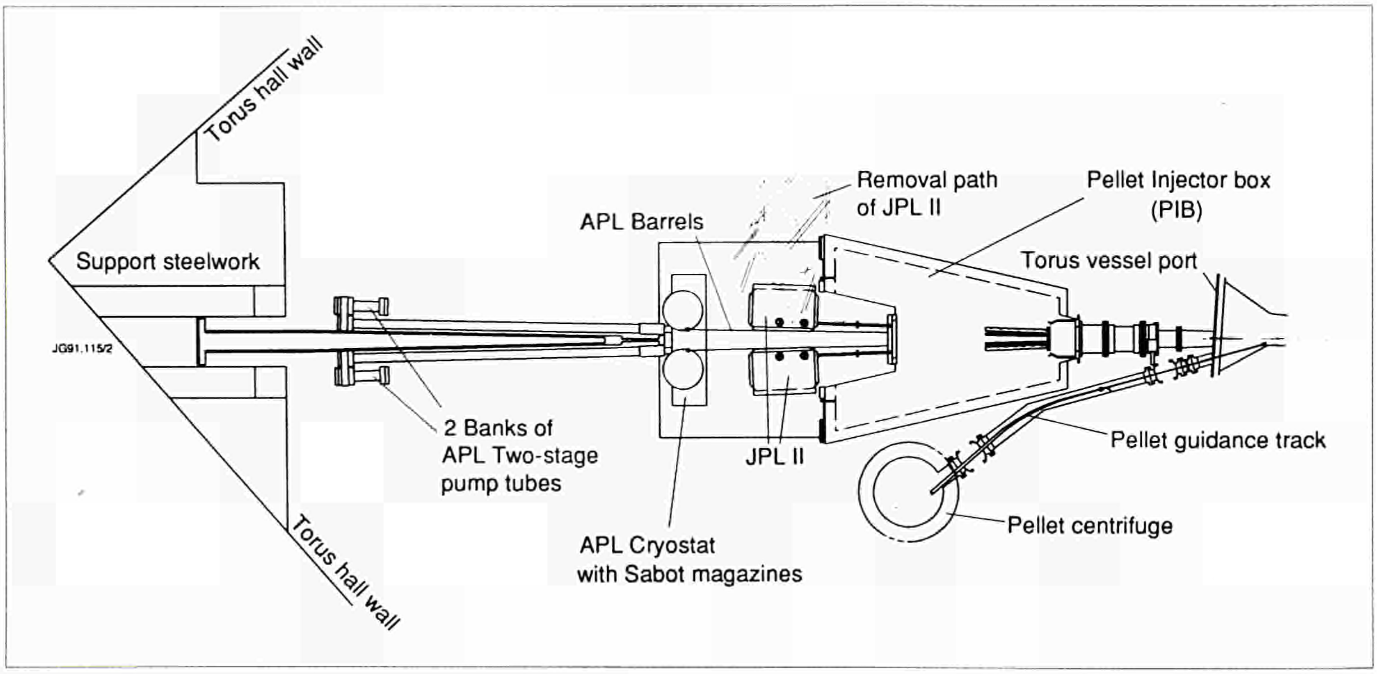


Fig.25: Conceptual view of future JET Pellet Injection (plan view).

assembly. Measures for the implementation of the existing ORNL Launcher and the prototype Launcher have always been guided by the principle that the interface to the torus (the PIB and its cryopump) should cope with the final requirements of an advanced launcher system. Thus, only modest upgrades can be expected, especially on the pellet characterising diagnostics. Since the results of the high-speed pellet experiments are not yet available, it is hard to settle on a firm specification for the APL. Desirable features now aimed for consist of: pellets in the 3-6mm range; velocities exceeding 5kms^{-1}; availability of ~10 pellets per tokamak pulse, some as close in time as a fraction of a second; and pellet material of deuterium, but tritium should not be ruled out. The two-stage gun should look similar to the prototype launcher but upgraded in several respects, such as higher pellet speeds.

The conceptual design of the JPL II is based on each gun of nominally 3, 4, 5 and 6mm pellet diameter and is essentially of the same proven design as that of the present ORNL launchers delivering pellets at speeds in the range 1.2-1.5kms^{-1}. Major elements in the design include: a major upgrade in liquid helium economy; extended pellet sequences of 160, 80, 40 and 20, respectively; increase of repetition frequency (10, 6, 2 and 1s^{-1}, respectively); and revision of sealing and joining technology towards even higher reliability and nuclear compatibility. The centrifuge should be capable of providing deuterium particles into the plasma beyond its recycling layer, to provide a minimum recycling flow into the pumped divertor configuration, which is sufficiently strong to sweep plasma impurities towards the divertor and to retain impurities from the dump plates in the divertor. The magnitude for the gas flow equivalent should approach 1000mbarℓs^{-1}. This can be produced by the injection of 1.5 to 3mm pellets in the plasma midplane at repetition frequencies up to 40s^{-1} and relatively slow speeds of 50 to 500ms^{-1}. Moreover, the centrifuge should be capable of maintaining these high gas flows for long pulses (~60s). A model of such a centrifuge is currently under construction for ASDEX Upgrade, Garching, FRG. JET has decided to use the ASDEX Upgrade centrifuge mechanical design with minor modifications and has placed a contract with the IPP Garching, FRG, to transfer the design and experience and to obtain advice on the systems expansion necessary to cope with the specifications for JET.

Tritium Handling

On original JET Programme planning, the Active Gas Handling System (AGHS) is still required to be functional for the D-T phase of JET set for May 1992. As a result of additional workload in the Project related to beryllium activities and extensive design and procurement efforts for the pumped divertor, progress on the upgrading of

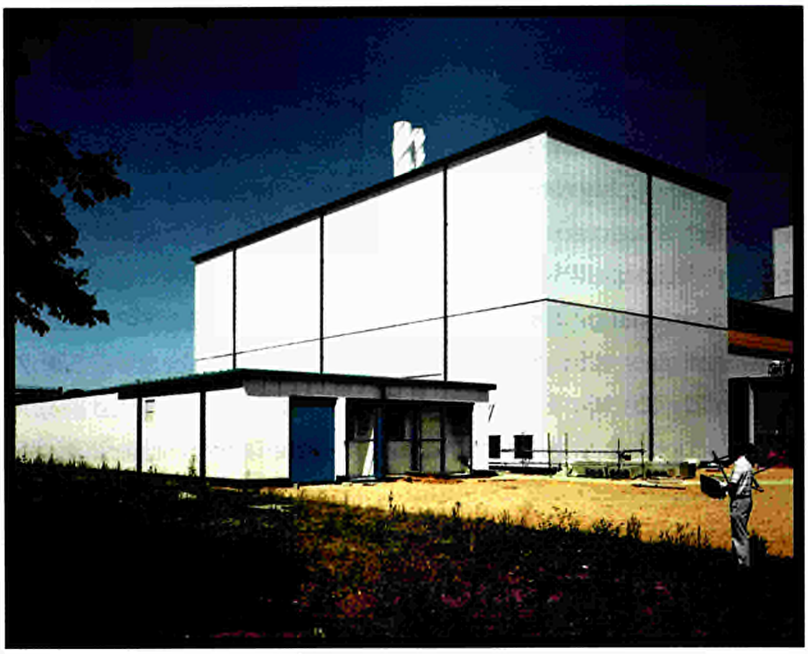


Fig.26: The Active Gas Handling System (AGHS) Building.

components for a full D-T phase has been slower than planned during the previous year. It is now unlikely that that the original programme of D-T shots will be carried out and a limited programme of up to 100 shots is currently envisaged. Nevertheless, before tritium injection into the torus can start, it will be necessary to demonstrate that the AGHS and safety systems essential for tritium operation have been fully commissioned with tritium and that sufficient operational experience has been accumulated. Several months of active commissioning/operation of the AGHS in isolation will be required plus a period with the AGHS providing exhaust and gas introduction for D-D operation to satisfactorily demonstrate torus interfaces. To meet this programme, the planning of tritium procurement and obtaining of official authorisations is based on the introduction of tritium into the AGHS in September 1991.

Preliminary investigation of the modifications required for a reduced D-T phase in 1992 have shown that:

a) The expected required modifications to the torus and subsystems are minor provided the tritium inventory in the machine can be kept very low;
b) The AGHS must be fully operational, although processing of impurities may not be required on a daily basis and the cryodistillation system would only be required for clean-up of discharged protium.

The AGHS Building (see Fig.26) was officially handed over in May 1990 and required some minor modifications, which were outside the building contract. With some dust still prevalent in the building due to some minor building modifications and installation of cable trays and other mountings into the concrete, designated clean areas have been established in a number of areas of the building. This will permit continual and timely progress of the interconnection of the various subsystem packages as they are available without contamination of the process with further dust. A preliminary seismic "walkdown" has been undertaken on the building to determine whether there were any seismically vulnerable design details. Apart from minor modifications, such as extra stops to prevent the cryodistillation modules swinging, the building is satisfactory. Delays have occurred in the assembly of the Active Gas Handling System (AGHS) due to the late completion of the building and due to serious delivery delays of a few key components. Plant design activities were nearly completed at the end of 1990. Only some interconnecting piping design was still underway.

JET is required under the Host Agreement to satisfy the United Kingdom Atomic Energy Authority (UKAEA) in advance that the arrangements for tritium operation conform to the standards in the UKAEA. As certain UKAEA sites are licensed by the NII under the Nuclear Installations Act 1965, JET has decided to adopt comparable standards. Formal permission is also needed from Her Majesty's Inspectorate of Pollution (HMIP) and JET must comply with various statutory requirements monitored by the UK Health and Safety Executive (HSE). The Safety and Reliability Directorate (SRD) of the UKAEA has granted JET permission to introduce up to 5 grams of tritium into the AGHS provided that the Fusion Safety Committee is satisfied that JET is ready to do so and that various agreed actions are carried out. JET must obtain the permission of the UK Department of the Environment, through Her Majesty's Inspectorate of Pollution (HMIP), before tritium may be brought onto site and before any discharges of radioactive material may be made. JET is already authorised to discharge the small amounts of radioactivity generated in the D-D phase and has been negotiating with HMIP on the conditions under which increased authorisations for the D-T phase would be granted. These include discharge monitoring arrangements; environmental monitoring; and demonstrating that "best practicable means" that are economically achievable have been used to limit the releases from the plant. HMIP have indicated that proposed arrangements should be acceptable and formal application for the use of tritium will be made early in 1991.

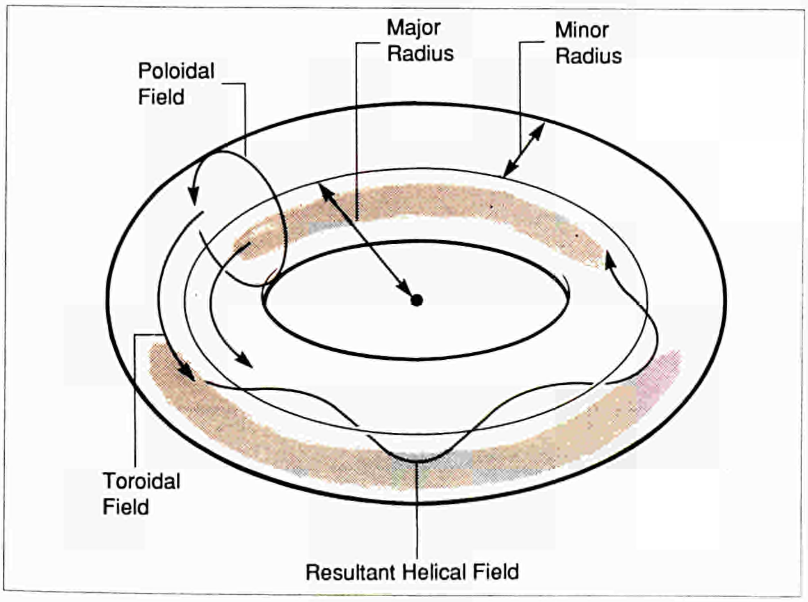

JET

Results of JET Operations in 1990

Introduction

The overall objective of the JET Project is to study plasma in conditions and with dimensions close to those that would be needed in a fusion reactor. The central values of temperature, density and energy confinement time needed for a reactor operating with deuterium and tritium must be such that their project ($n_i \tau_E T_i$), exceeds the value $5x10^{21}m^{-3}$skeV. Typical values for these parameters, which must be attained simultaneously in a reactor, are given in Table.6.

With ohmic heating alone in JET, values only reached 3keV and 4keV for the ion and electron temperatures respectively, $4x10^{19}m^{-3}$ for the plasma density and 1.0s or the energy confinement time. These parameters were obtained simultaneously during one discharge and result in a fusion product of $1.2x10^{20}m^{-3}$skeV. However, higher peak values of electron and ion temperature have been reached using additional radio frequency heating and neutral beam heating and combinations of these two methods. Even so, these substantial increases in temperature were associated with a fall in the energy confinement time as the heating power was increased. Thus, gains



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.

in plasma temperature have been offset by degradation in energy confinement time, and the fusion product obtained have not shown the full gains anticipated over conditions with ohmic heating only.

However, a substantial increase in the value of the fusion product has been achieved, by operating in the magnetic limiter (X-point) configuration in JET. During 1990, values of 8-9x$10^{20}$$m^{-3}$skeV were obtained using up to 18MW of additional heating.

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.

Table.6: Reactor Parameters

Central Ion Density, n_i	2.5x$10^{20}$$m^{-3}$
Global Energy Confinement Time, τ_E	1-2 s
Central Ion Temperature, T_i	10-20keV
Fusion Product, $(n_i\tau_E T_i)$	5x$10^{21}$$m^{-3}$skeV

Considerably 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 30keV, energy confinement times of up to 1.8s and central densities of up to 4x$10^{20}$$m^{-3}$.

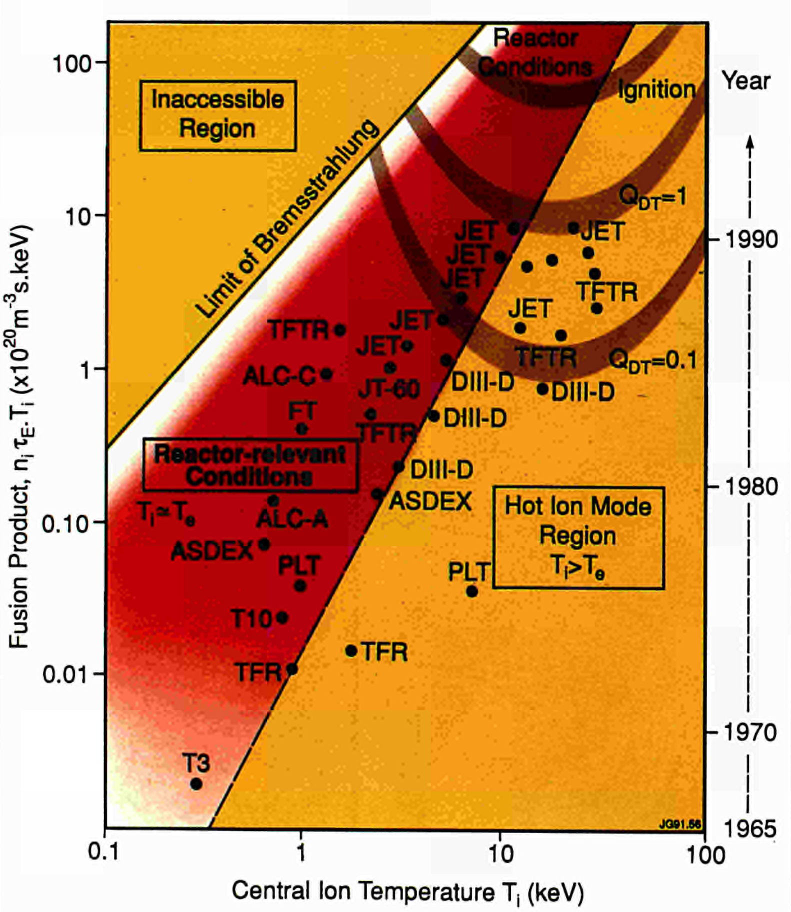


Fig.27: Fusion parameter ($n_D\tau_E T_i$) versus central ion temperature, $T_i(0)$, for a number of machines worldwide in the period 1965-1990.

Ignition

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

The highest value of the fusion product attained so far in JET is close to breakeven conditions. A factor of 5-8 increase would bring the conditions in JET to those required in a reactor. The increases in performance that have been achieved on JET and other tokamaks since 1965 are shown in Fig.27.

As the global energy confinement time scales favourably with plasma current in discharges with both magnetic and material limiters, the modifications carried out in JET, to increase the plasma current in both of these modes of operation, give confidence that significant alpha-particle heating will be observed when JET is operated in deuterium and tritium together.

Experimental Programme

The strategy of JET is to optimise the fusion product by building up a high density and 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 with 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 as shown in Fig.28. 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 of this phase, Phase IIA, had been completed. The machine then entered a planned shutdown for extensive modifications and enhancements before the start of the second part of the Additional Heating Studies, Phase IIB, in June 1987. The general objective of this phase, from

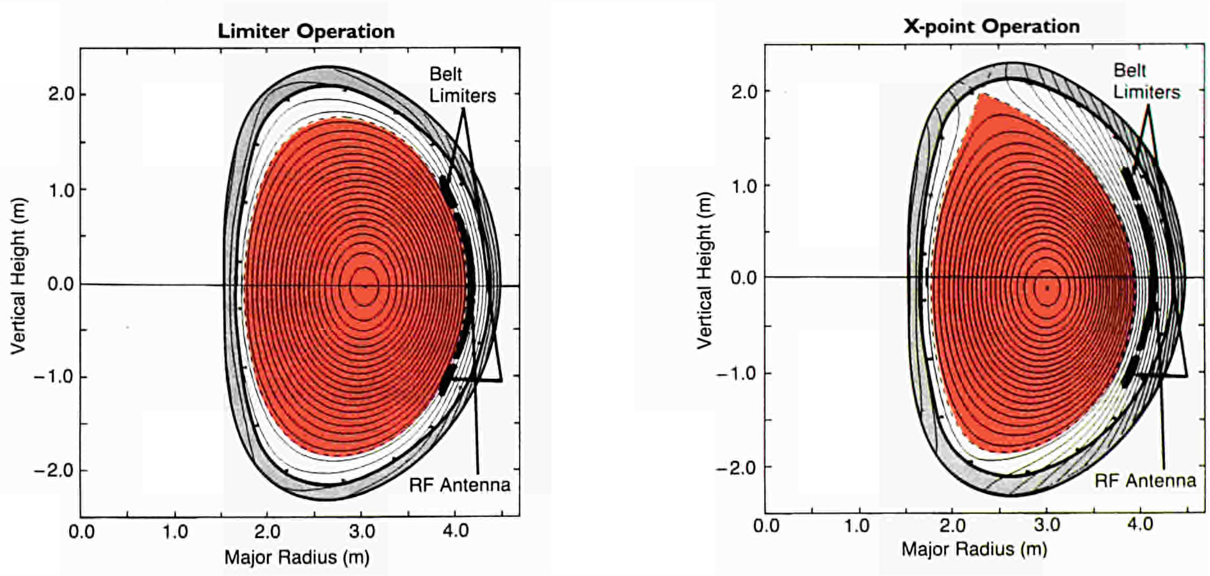
Operating Modes

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.



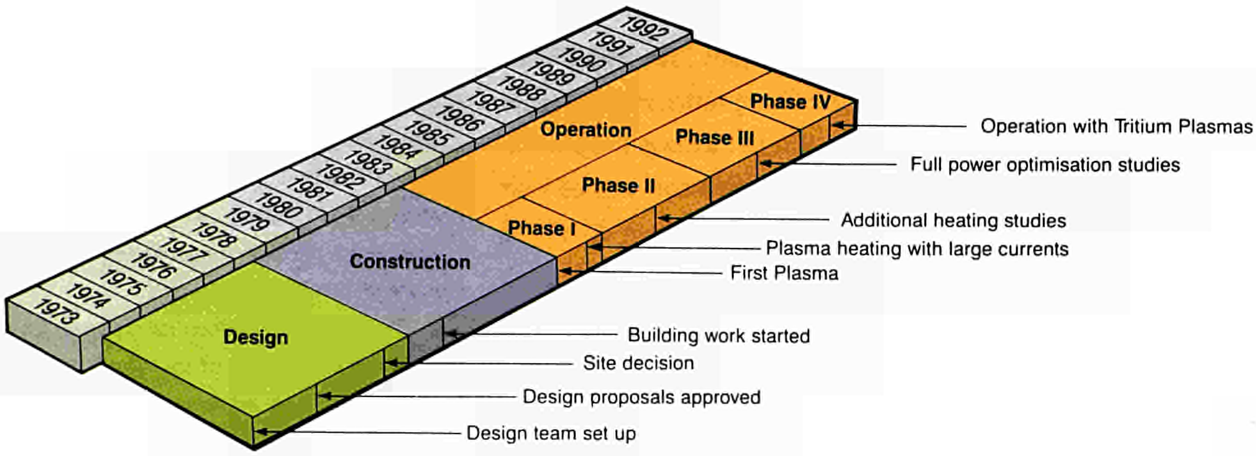


Fig.28: The original overall JET programme.

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 power 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 reached its midpoint in 1990.

The 1990 experimental programme was executed by three Task Forces, with the programme objectives divided into the following three main areas:

Task Force L: Performance Optimisation in Limiter Plasmas
(involving progression to full performance in material limiter configuration with currents up to 7MA, with high energy content; and including progression to the highest fusion product, long pulse operation, Beryllium optimization, etc.).

Task Force X: Performance Optimisation in X-Point Plasmas
(involving progression to full performance in magnetic limiter (X-point) configurations at high currents (up to 6MA) to explore the H-mode regime of operation both in the single and double-null configurations; and including progression to higher NB and RF powers and towards quasi-steady-state operation).

Task Force P: Profile Effects and Related Physics Issues
(involving a study of profile effects (using LHCD, RF, NB and high speed pellet injection, etc.); and including particle and energy transport studies in transient conditions, and disruption and sawtooth stabilisation).

Main Scientific Results

During 1990, the experimental programme concentrated on four main areas:

- introduction and exploitation of new facilities;
- further improvement in plasma performance;
- improvements in understanding in key areas of tokamak physics, such as: particle and impurity transport; physics of the H-mode; energy transport and confinement;
- experiments relevant to Next Step devices.

The main new facilities introduced in JET were beryllium tiles at the lower X-point, beryllium screens on the ion cyclotron resonance heating antennae, feedback control of the plasma position with respect to the ICRF antennae, prototype lower hybrid current drive (LHCD) system and helium neutral beam injection. Experiments aimed at improving the understanding of tokamak physics have covered a wide range of topics including detailed studies of thermal, particle and impurity transport, and various aspects of H-mode physics. Experiments to improve performance have concentrated on high current limiter and inner wall discharges, and on optimizing the fusion performance of X-point discharges. Impurity control in JET, as for other long-pulse high power tokamaks and Next Step devices, is of fundamental importance and therefore significant effort has also been devoted to this area of study.

The scientific results in these areas are described in the following sections, under the headings: Density Effects; Temperature Enhancement; Energy Confinement Studies; and Impurity Studies.

Impurities

Impurities present a major problem in tokamaks as they cause:

- large power losses from the plasma by radiation;
- dilution of the number of effective ions in the plasma available for productive fusion reactions, with a corresponding fall in thermonuclear yield;
- reductions in the density limit.

With carbon used as the first-wall material, the main plasma impurities were carbon (2-10%) and oxygen (1-2%). With beryllium evaporated inside the vessel on all surfaces to act mainly as a getter,

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.

Interactions between the plasma and vacuum vessel walls would result in the release of heavy metal impurities. To reduce this possibility, the edge of the plasma is defined by upper and lower belt limiters. These are cooled structures circling the outboard torus wall with carbon or beryllium tiles attached. Carbon and beryllium have a relatively low electric charge on the nucleus.

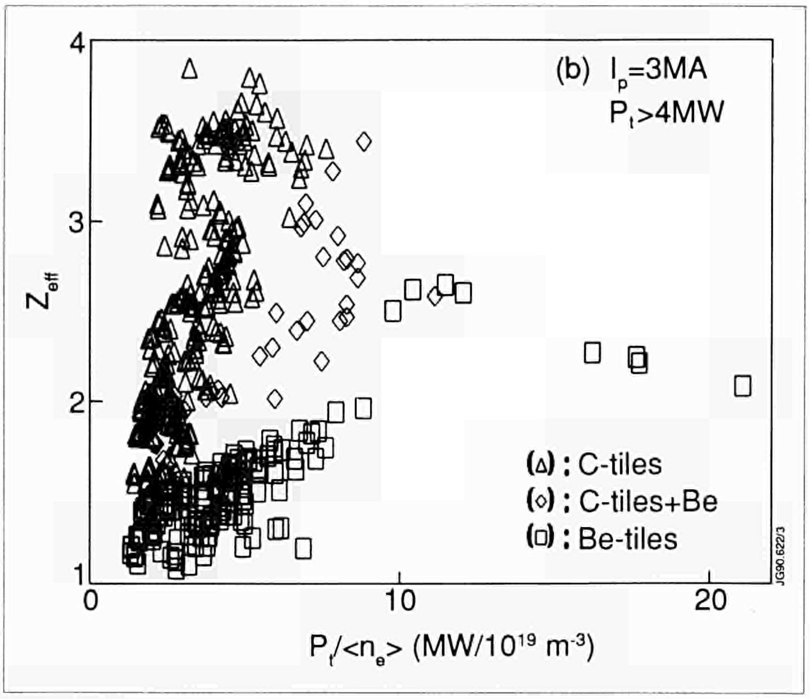


Fig.29: Fuel dilution factor (n_D/n_e) as a function of power per particle (P_t/<n>) for cases (a) carbon limiter; (b) beryllium gettering; (c) beryllium limiters.

oxygen was reduced by factors >20, and carbon by >2. Although beryllium increased, carbon remained the dominant impurity. With beryllium as the material of the limiters, the carbon concentration was reduced by a further factor 10, but beryllium levels increased by ~10, and became the dominant impurity. Due to the virtual elimination of oxygen and replacement of carbon by beryllium, impurity influxes were reduced significantly.

The parameter which provides a measure of the impurity content of a plasma is the effective ion charge, Z_{eff}, which is the average charge carried by an ion in the plasma. The global impurity content is monitored routinely throughout each pulse by measuring Z_{eff}. Due to the virtual elimination of oxygen, and the replacement of carbon by beryllium, the effective plasma charge, Z_{eff}, was reduced significantly, first with beryllium evaporated inside the vessel and then more so when beryllium belt limiters were installed, in addition.

Fig.29 shows the dilution factor, n_D/n_e, as a function of input power per particle, P_t/n_e. With carbon, it had not been possible to maintain (n_D/n_e), much above 0.6 for moderate power, but values greater than 0.8 were routinely achieved in beryllium discharges. Correspondingly, the effective plasma charge, Z_{eff}, was reduced significantly, first in the beryllium evaporation phase, and more so with beryllium limiters. Z_{eff} as a function of the input power per particle (P_t/n) for the three phases of operation is shown in Fig.30. Better plasma purity contributes significantly to improved fusion performance, which otherwise could be achieved only with a substantial increase in energy confinement.

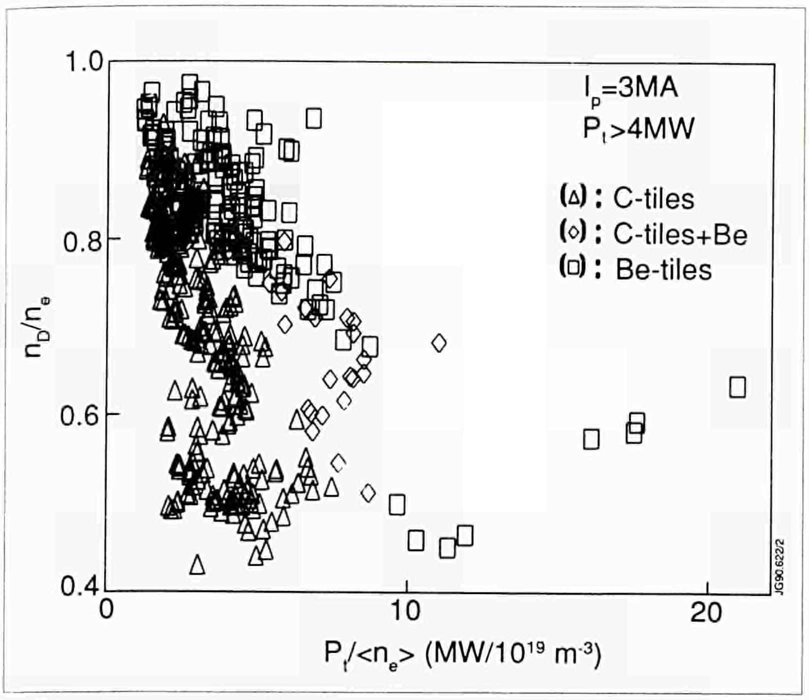


Fig.30: The effective charge, Z_{eff}, as a function of total power per particle, (P_t/<n>).

The impurity chlorine has been observed throughout 1989 and 1990 operation. Although its concentration, n(Cl)/n_e, is small (~0.1% or less), it has a significant effect on the plasma power balance. This is particularly evident during high density operation, when it can account for over 90% of the radiated power. In most cases, the chlorine radiation effectively determines the density reached in the plasma. Systematic spectral analysis enables radiated power components to be derived for the different impurity elements found in the plasma and this has allowed chlorine contributions to be monitored regularly. An understanding of the behaviour and factors which affect chlorine release have been gained from this study. Most notably, the presence of fluorine in the vessel significantly increases the chlorine content, whereas suppression of the chlorine release was correlated with a reduction in vessel temperature. A different in chlorine behaviour was noted when the plasma limiting surfaces were either carbon or beryllium, the carbon surfaces leading to a faster depletion of chlorine inventory. This is thought to be due to the higher vapour pressure of carbon-chlorine compounds compared to beryllium-chlorine compounds. During 1990, the conditioning of the vessel was improved and the chlorine content of the plasma was low, resulting in a record line-averaged density of 4.3×10^{20}m^{-2} in a 5MA plasma.

The use of beryllium as a first wall material also produced a marked improvement in the ability to control the plasma density in JET. This arose in part from the reduction in the amount and charge of the dominant impurity, but also depended strongly upon the fact

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.

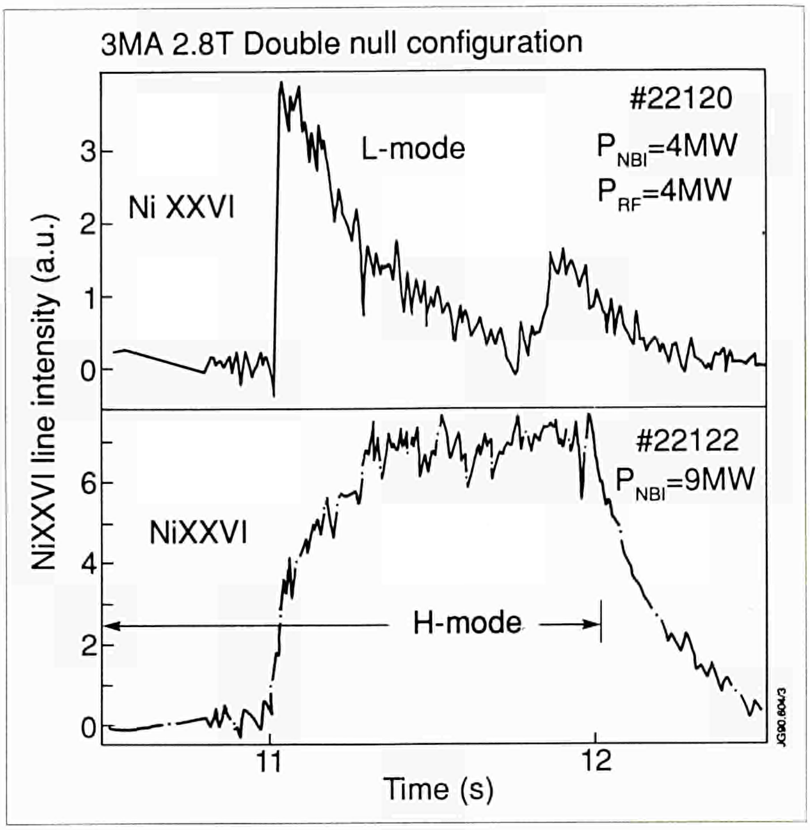


Fig.31: (a) temporal evolution of NiXXVI emission in (a) the L-phase and (b) the H-phase of two similar discharges with ~9MW of additional heating.

that beryllium pumped deuterium and helium very effectively during a discharge. On longer time scales (minutes to hours), beryllium also retained very little deuterium compared to carbon. Greater than 80% of the neutral gas admitted to JET was recovered, compared to about 50% with a carbon first wall. This has important advantages for the tritium phase in JET.

An important observation made during 1990 was that test impurities introduced into the plasma showed evidence of better confinement during H-modes. Fig.31 shows the temporal evolution of nickel impurities in the L- and H-phases of two similar discharges with ~9MW of additional heating. In contrast to the decaying signal of the L-phase, the signal rises rapidly to a steady value in the H-mode and persists to the end of the H-phase. This shows that impurities have considerably longer confinement times in the H-phase. This suggests that the H-mode might be a disadvantage in a reactor, where impurities and helium ash could be retained leading to increased fuel dilution in the plasma centre.

Density Control

Increasing the density can be achieved by introducing additional gas into the vacuum vessel, by the injection of energetic neutral atoms (neutral beam heating) and by solid pellet injection.

Increasing the input power to the plasma through additional heating raises the electron density limit. However, problems can occur when this heating power is switched off, if the electron density is too high. To overcome this problem, the plasma is moved, prior to the switch-off point, so that it bears on the carbon tiles covering the inner wall. The tiles have been found, to provide a pumping mechanism for removing particles so that the density can be reduced below the critical limit.

Density Effects

Density Limits and Disruptions

In most tokamaks, disruptions can occur under certain circumstances. Disruptions are dramatic events in which plasma confinement is suddenly lost, followed by a complete loss of current in the plasma. Disruptions pose a major problem for tokamak operation as they can impose a limit on the density range in which stable plasmas can be achieved and their occurrence leads to large mechanical stresses and to intense heat loads on the vacuum vessel.

Fig.32 shows a diagram of the stable operating regime (without disruptions) constructed by mapping the normalised current I/q ($\propto I_p/B_t$ where q is the safety factor, I_p the plasma current and B_t the toroidal field) as a function of the normalised density <n>R/B_t (where <n> is the average density and R the major radius). The density limit is dependent on plasma purity and a the power to the plasma. In ohmically heated plasmas with carbon limiters, the density limit was n_c(OH)(m^{-3}) = 1.2 x $10^{20}B_t$(T)/qR(m), as shown by the line marked OH(C). With neutral beam injection, the plasma impurity was improved and the limit was increased substantially, to n_c(AH) (m^{-3}) = 2.0 x $10^{20}B_t$(T)/qR(m), as shown by the line marked NB(C).

Various experiments have explored the mechanism for the density limit. With a carbon first-wall, the plasma density was limited, in general, when the radiated power reached 100% of the input power. This led to the growth of MHD instabilities in the plasma and ended in a major disruption. With a beryllium first-wall, the maximum density increased significantly by up to a factor of 2.

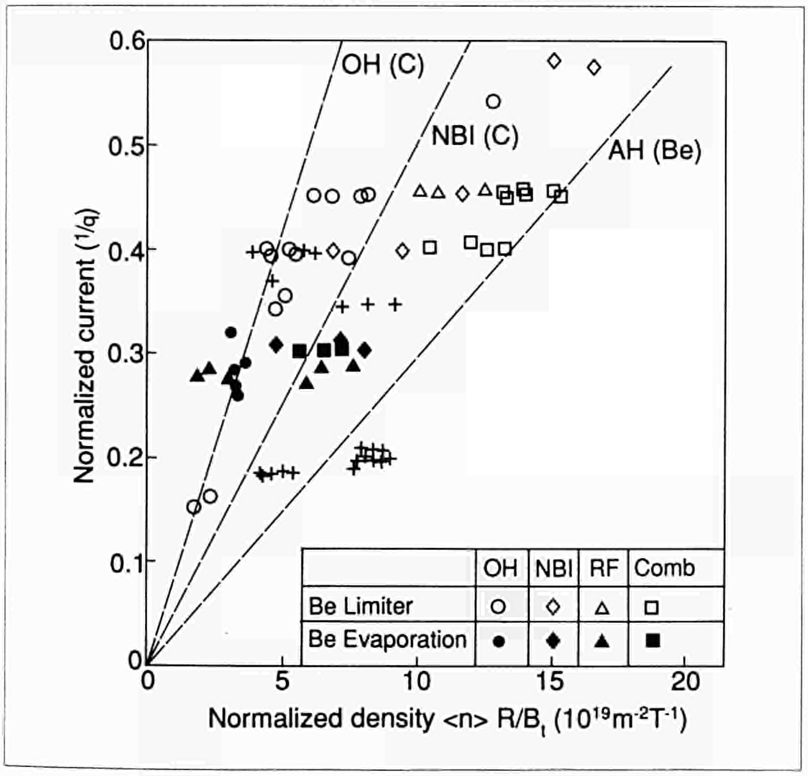


Fig.32: Normalized current (I/q) versus normalized density (<n>R/B_t). The points show the results with a beryllium first-wall. The lines show the density limits achieved with carbon walls using ohmic heating (OH(C)), with additional heating (NB(C)), and the maximum line with beryllium AH(Be).

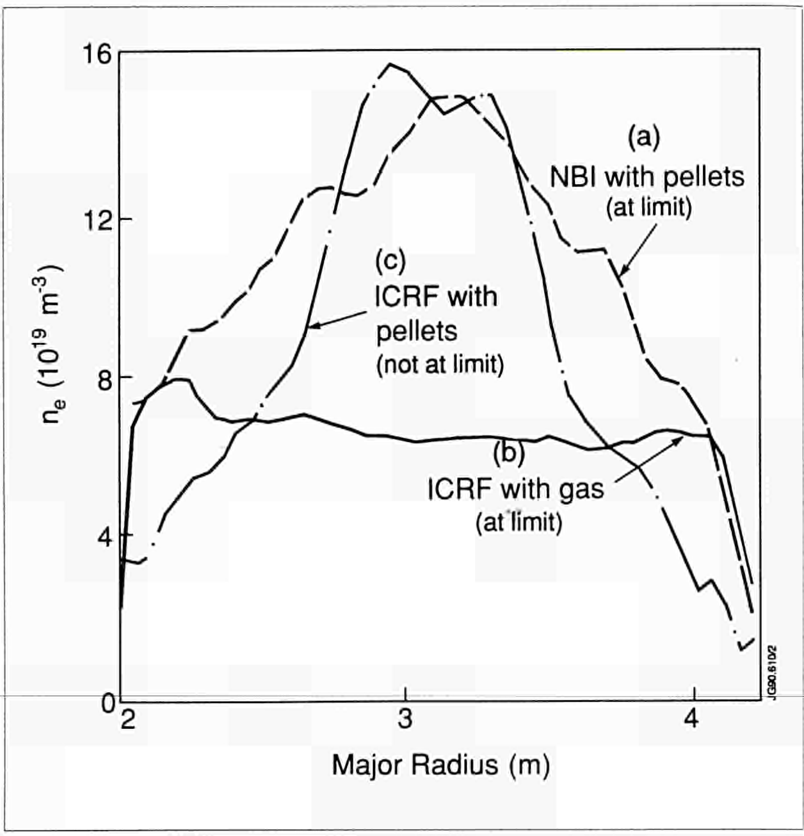


Fig.33: Electron density profiles for different fuelling and heating methods.

Furthermore, the nature of the density limit changed and the frequency of disruptions at the density limit were much reduced. Disruptions did not usually occur, and the limit was associated rather with the formation of a poloidally asymmetric, but toroidally symmetric radiating structure (a "MARFE"). This limited the plasma density to within the stable operating domain, but did not cause a disruption. These results constitute a substantial enhancement of JET's operating capability.

Heating and fuelling have been varied systematically in JET, in which both gas and pellet fuelling have been studied. With deep pellet fuelling and either neutral beam or RF heating, peaked profiles were obtained (Fig.33). Just before a density limit MARFE occurred, pellet fuelled discharges reached the same edge density as gas fuelled discharges, but the central densities were considerably higher. The central density was dependent, on the fuelling methods used. The profiles are similar near the edge, but are remarkable flat with gas fuelling. These observations suggested that the edge density may be correlated with the density limit and it is found to increase approximately as the square root of the input power (see Fig.34). This endorses the view that the density limit is determined by a power balance at the plasma edge and the cause of disruptions is related to radiation near the q=2 surface. Thus, under beryllium conditions, when the radiation is low, or confined to the outermost edge, there are no density limit disruptions.

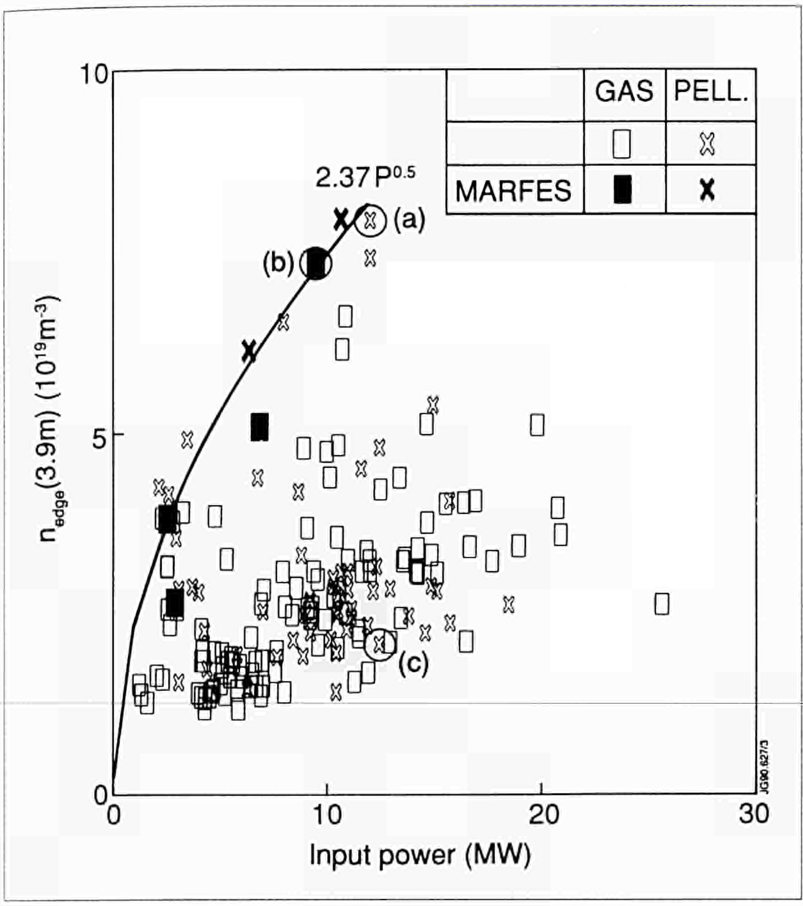


Fig.34: The edge electron density (n_{edge}) versus input power (P_t) showing that the density limit occurs at the boundary of the operational domain close to the curve n_{edge} ($x10^{19}m^{-3}$) = 2.37 $P^{1/2}$(MW). The profiles shown in the previous figure correspond to the three data points circled.

Pellet Fuelling

For a reactor, it is important to obtain an optimum central density, n(0), while minimizing the edge density in contact with cool material surfaces. This optimizes the number of useful nuclear fusion reactions whilst providing good insulation of the hot plasma from its surroundings. This means that a large density peaking factor, n(0)/<n>, (where <n> is the average density) is desirable for optimum performance. An effective method of achieving this aim is to inject solid pellets of hydrogen or deuterium into the plasma centre.

The injection of multiple 2.7, 4mm and 6mm diameter solid deuterium pellets has been undertaken into JET plasmas under various conditions including material limiter and magnetic limiter (X-point) discharges, with plasma currents up to 6MA in ohmic, neutral beam and RF heating situations. This has been undertaken since 1988 as a collaborative effort between JET and a US team, under the umbrella of the EURATOM-USDoE (US Department of Energy) Fusion Agreement on Pellet Injection. A jointly built three-barrel, repetitive multi-injector has been used to inject pellets at a maximum frequency of several per second with nominal speeds up

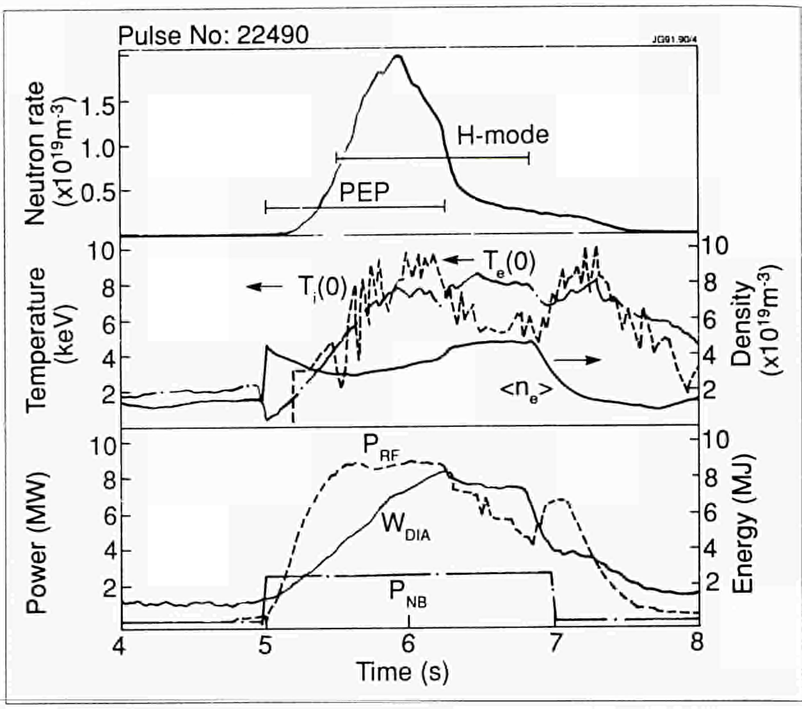


Fig.35: Combination of peaked profiles (PEP mode) produced by pellet injection and RF central heating with the good global energy confinement of the H-mode. The maximum neutron rate occurs when the two modes overlap.

to 1500ms^{-1}. A record central density of $4x10^{20}m^{-3}$ was achieved by strongly peaking the density profile using a sequence of 4mm solid deuterium pellets injected at intervals throughout the current rise phase of a X-point discharge.

To improve the overall plasma performance in JET, two regimes of enhanced performance have been combined. This takes advantage of the good global confinement properties of the H-mode together with peaked profiles produced by pellet fuelling and central heating of the pellet-enhanced performance mode. A typical discharge is shown in Fig.35. A peaked density profile produced by injecting a string of pellets is heated by a mixture of neutral beams and RF power to produce peaked temperature profiles with central ion and electron temperature of ~10keV. Although transient, these temperatures persist into the H-mode phase. The neutron production rate peaks at $10^{16}s^{-1}$, corresponding to a $Q_{DD} \approx 10^{-3}$ and is estimated to be about 90% thermal during the period when the peaked profiles and H-mode phases overlap. The fusion triple product $n_D T_i \tau_E$ reached $8x10^{20}m^{-3}$keVs. The enhancement in neutron yield due to peaked profiles is shown in Fig.36.

Temperature Enhancements

Sawtooth Oscillations

In most tokamak discharges including JET, the central temperature and density is modulated by sawtooth-like oscillations. This is due to

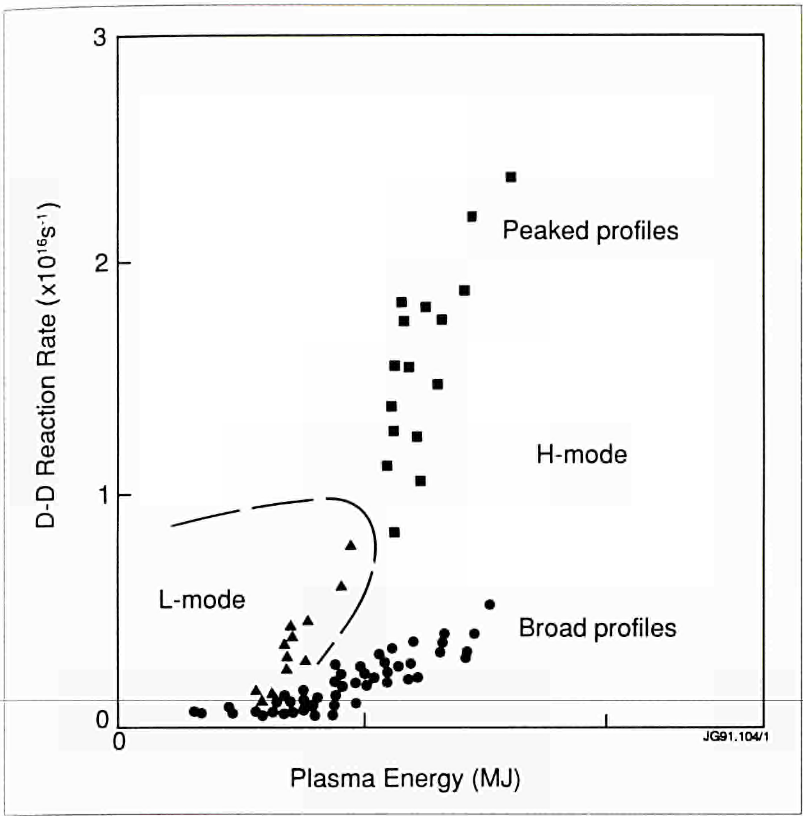


Fig.36: Enhancement of the neutron rate for H-modes with peaked profiles compared to those with broad profiles for the same plasma kinetic energy.

the periodic occurrence of magnetohydrodynamic (MHD) perturbations associated with the plasma surface whose safety factor, q, has a value of unity. Heating in the plasma centre leads to a gradual rise in the central temperature, which is terminated suddenly by the rapid growth of the MHD instability. The principal effect is to flatten the temperature and density profiles across the region inside the so-called mixing radius, which can range from about one to two-thirds of the plasma radius. As a consequence, high energy particles, produced by the auxiliary heating or by fusion reactions, can be expelled from the plasma centre to larger radii where they may be lost rapidly to the plasma periphery.

The consequences of the sawtooth instability are detrimental in two respects. This instability flattens the central plasma temperature and density, and it can expel energetic particles (injected by the neutral beam system, accelerated by the ICRF fields, or produced in fusion reactions) from the plasma core. Therefore, the repetitive occurrence of this instability can significantly limit the fusion power produced by the plasma. However, a number of techniques have been developed for the suppression of these instabilities and the resultant improvements in performance explored in some detail. In particular, it is planned to control the current profile directly, and hence to eliminate the q=1 surface. This will be achieved by the injection of lower hybrid (LH), radio-frequency (RF) waves or neutral

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.

Current Profile Control

The highest current density exists at the centre of the plasma, as this is the hottest region and the electrical resistivity decreases as the temperature increases. Without sawteeth, which occur on the q=1 surface, this high current density region would be squeezed or pinched inwards. Selective heating outside the central region would remove the q=1 surface from the plasma and so avoid the onset of the sawteeth. Another way is to decouple the plasma current and temperature profiles. On JET, it is intended that an electric current, additional to that generated by transformer action, should be produced by neutral beams and by radio-frequency power at 3.7GHz (called Lower Hybrid Current Drive (LHCD)).

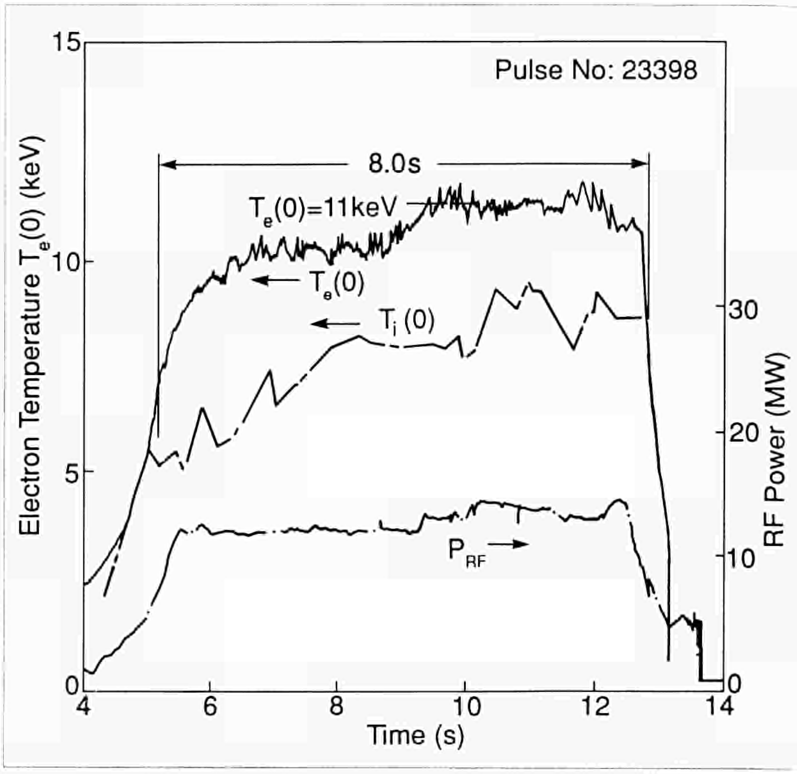


Fig.37: Evolution of the central electron temperature, $T_e(0)$, and the central ion temperature, $T_i(0)$, during a 'monster sawtooth'. P_{RF} is the ICRF heating power.

beams in the plasma. In addition, a spontaneous stabilization process was discovered during additional heating experiments in JET, which has resulted in the production of long sawtooth-free periods (called 'monsters').

Various studies have been performed in the so-called 'monster-sawtooth' regime. One of the longest monster sawteeth lasting for 8 seconds is illustrated in Fig.37. In this case, central ICRF heating was applied during the current ramp-up of a 3.5MA plasma. This resulted in a monster sawtooth lasting throughout the whole period (~8 seconds) of the RF power application. The central electron temperature reached 11keV and the ion temperature attained ~9keV by the end of the pulse. This regime of operation has been extended up to plasma currents of 5MA. To explain this phenomenon, it has been proposed that sawteeth are stabilized by fast particles, principally those accelerated by the ion cyclotron radio-frequency (ICRF) heating system. In other experiments, it has been found that peaked temperature profiles (with both central ion and electron temperatures above 10keV) can be maintained for periods of several seconds, which would, in a D-T mixture, result in a significant enhancement in the time-averaged fusion reactivity compared to a sawtoothing discharge. In addition, similar enhancements in plasma performance have been achieved by suppressing sawteeth via the injection of deuterium pellets. Ablation of these pellets by the plasma broadens the temperature, and hence the current profile, and raises q(0) above unity, which results in suppression of the sawteeth.

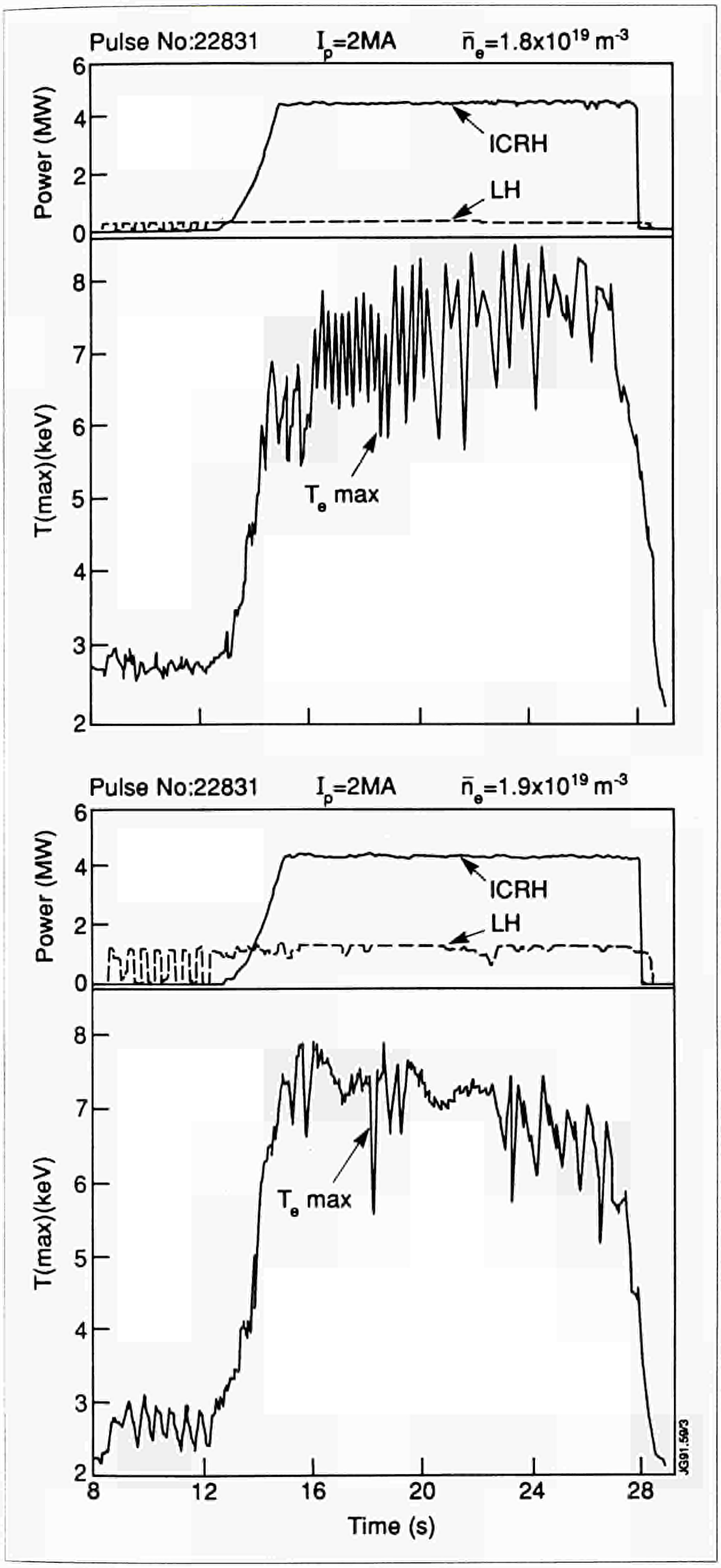


Fig.38: Long pulse LHCD and ICRF heating showing enhanced monster sawtooth duration as the non-inductive current drive is increased.

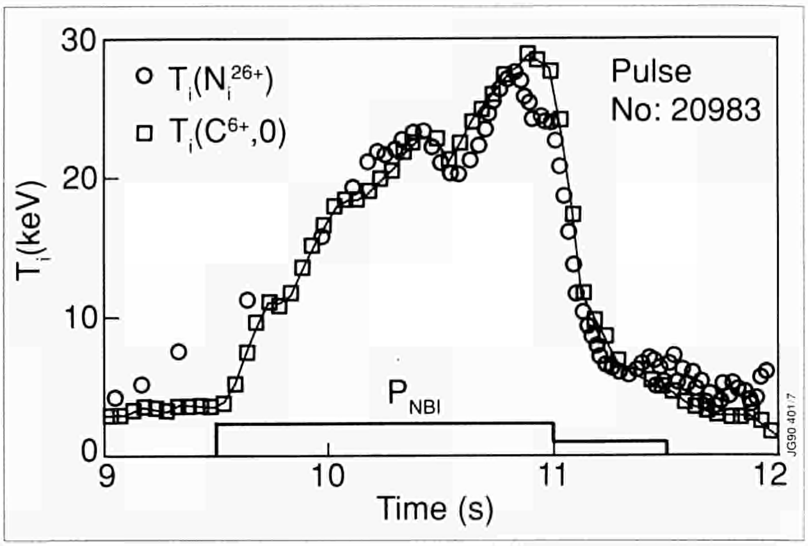


Fig.39: Ion temperature as a function of time during NB heating showing that temperatures of ~30keV are reached.

Current drive studies on JET have shown that long pulses are required to achieve substantial current profile modification, as the current diffusion time is ~10 seconds. The prototype lower hybrid wave system has provided 1.3MW for 20s which has enabled current profile modification during monster sawteeth. This is shown in Fig.38, in which 4MW of ICRF power is able to create only short monsters towards the end of the pulse. The addition of 1.3MW of lower hybrid current drive power increases the duration of monsters by a factor x2 and they appear earlier in the heating pulse.

Neutral Beam Injection

The two neutral beam injectors on the JET machine inject high energy neutral beams into the plasma tangential to the torus from diametrically opposite positions at Octant No.4 and Octant No.8. Originally, both injectors operated at 80kV energy and in 1988 deposited up to 21.6MW power in the plasma. During 1989 and 1990, the Octant No.4 system was converted to 140kV operation with deuterium beams and during 1990, the Octant No.8 system was upgraded to 85kV operation. This provides greater penetration of the neutral beams into denser plasmas and deposits more power near the plasma centre. In this configuration, the total power was slightly reduced to ~19MW of neutral beam power.

If densities are not too high, the neutral beams penetrate to the centre of the plasma and deposit their energy there. In these conditions, the beam energy is transferred mainly to the plasma ions, causing large increases in ion temperature. This is the so-called 'hot-ion mode' of operation. With the introduction of the beryllium first-wall, improved density control was possible. This coupled with the increased neutral beam penetration at higher beam energy (140kV) allowed high ion temperatures to be obtained. Record ion temperatures were achieved up to 22keV with material limiter plasmas and up to 30keV in magnetic limiter plasmas, with input powers up to 18MW. A typical example is shown in Fig.39 in which the ion temperature reached ~30keV for about 15MW input in a magnetic limiter configuration. In this mode, the ion temperature profile is sharply peaked and the electron temperature is significantly lower than the ion temperature by a factor of 2-3.

During 1990, the Octant No.4 injector was also adapted to produce He^3 and He^4 beams at 120kV, as required. The advantages with helium beams are that they avoid the production of beam-plasma neutrons which complicate the measurement of thermonuclear neutron production and result in activation of the vessel. Helium beams proved to be an efficient heating method and high heating was observed. He^3 beams (5MW) were combined with deuterium beams (10MW) to produce high ion temperatures up to 25keV in an H-mode plasma. Further improvements are expected during 1991 when the He^3 beam energy is increased up to 155kV.

Radio Frequency Heating

The ion cyclotron resonance frequency (ICRF) heating system is used for highly localized heating of the JET plasma. The wide frequency band (23-57MHz) allows variation in the radial heating position at which the ion cyclotron resonance frequency matches the local magnetic field position (which varies across the radius of the machine). A minority ion species (H or ^3He(1-10%), at present, and D in the future D-T phase) is injected into the plasma for this purpose, and absorbs the RF power at the local resonance position. These high energy localized ions collide with the main plasma electrons and ions, transferring energy to them and causing a rise in the local electron temperature (T_e) and ion temperature (T_i) of the main plasma.

The original design power of the ICRF heating system was 15MW for 20s. However, an upgrade of the system was completed in 1990, in which each of the eight generators was enhanced from 3MW to 4MW each. Subsequently, a maximum power of about 22MW for 1.75 seconds has been coupled to the plasma. The maximum pulse length was restricted due to energy dissipation limitations on the vessel.

For monster sawtooth discharges, the scaling of the central electron temperature with the RF power per particle has been investigated and is shown in Fig.40. The central electron tem-

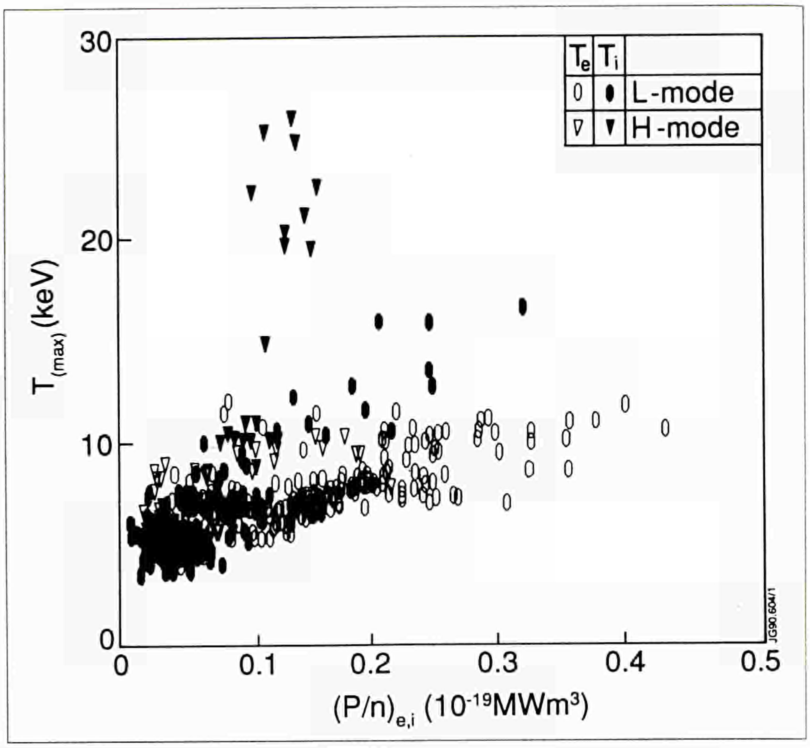


Fig.40: Central ion (T_i) and electron (T_e) temperatures as functions of power per particle $(P/n)_{e,i}$ to either species.

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 L(low)-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 H(high)-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.

perature, $T_e(0)$, increases with increasing power per electron up to a certain value but then appears to saturate for higher values. The maximum central temperature achieved is ~12keV. The ion temperatures achieved as a function of power per particle is also shown for comparison in Fig.40 and it is seen that the ion temperature increases approximately linearly with power per particle up to the highest temperatures. This indicates that ion confinement degrades little with input power. On the other hand, with the central electron temperature saturating at ~12keV, it seems that the electron confinement degrades strongly with increased heating power, although it might be that the saturation is due to a broadening of the RF deposition profile or an increase in losses of the energetic of the minority ions. These effects are being investigated.

Energy Confinement

The global energy confinement time in all JET plasma configurations, is defined by the relationship:

$$\tau_E = W_k/(P_t - dW_k/dt)$$

where W_k is the kinetic energy and P_t is total input power to the plasma without subtracting radiation losses. The values of τ_E reported here are such that $(dW_k/dt) << P_t$ and so are quasi-stationary.

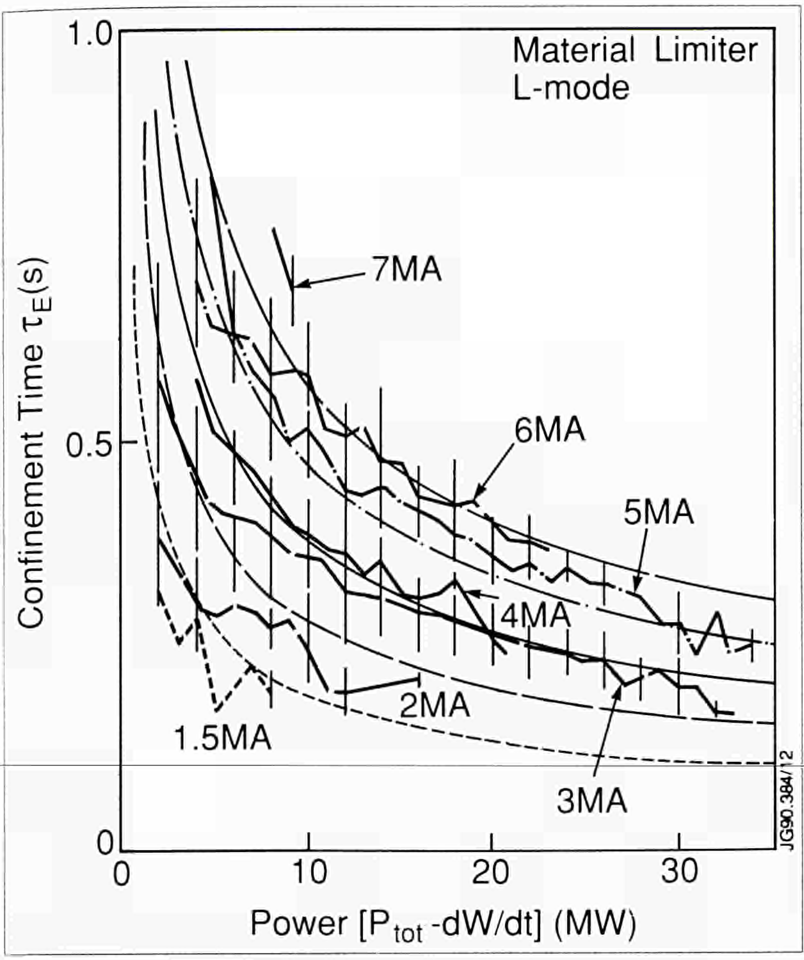


Fig.41: Confinement time as a function of input power for material limiter conditions, for different plasma currents.

Material Limiter Configuration

In JET ohmically heated discharges, energy confinement time values up to 1.8 seconds have been attained. However, the temperatures achieved in these cases are too low for a future fusion reactor, so that it is important to study confinement in additionally heated plasmas.

With carbon limiters, the energy confinement time on JET falls with increasing heating power independent of the type of heating, whether neutral beam injection, radio frequency heating or a combination of the two methods as seen in a number of experiments. This effect is repeated with a beryllium first-wall and global energy confinement times are similar. However, the advantages with the use of a beryllium first-wall is that improved density control is achieved due to high wall pumping and the impurity content (and plasma radiation) is reduced. These factors allowed higher plasma densities and result in improved fuel concentrations (n_d/n_e). This permits improved fusion performance (which will be described in more detail in the following section).

The decrease of energy confinement time with increasing heating power in material limiter cases is shown in Fig.41. The energy confinement time shows only a weak dependence on plasma density, but improves favourably as the plasma current increases. The global energy confinement time results can be fitted by a simple power law relationship. JET has contributed to an ITER L-mode energy confinement database, which has compiled data from various tokamaks around the world, including: JT-60 (Japan), TFTR (USA), JET (EC), T-10 (USSR), JFT-2M (Japan), DIII-D (USA), DIII (USA), ISX-B (USA), DITE (UK), ASDEX (FRG), TFR (France), PDX (USA) and PLT (USA).

An analysis of the ITER L-mode energy confinement database has resulted in two scaling laws. The recommended power law scaling (ITER89-P) is given by:

$$\tau_E(\text{ITER89-P}) = 0.048\ A^{0.5}\ I_p^{0.85}\ R^{1.2}\ a^{0.3}\ \kappa^{0.5}\ (n/10)^{0.1}\ B^{0.2}\ P^{-0.5}$$

The recommended offset-linear scaling law (ITER89-02) is:

$$\tau_E(\text{ITER89-02}) = 0.064\ A^{0.2}\ I_p^{0.8}\ R^{1.6}\ a^{0.6}\ \kappa^{0.5}\ (n/10)^{0.6}\ B^{0.35}/P + 0.04\ A^{0.5}\ I_p^{0.5}\ R^{0.3}\ a^{0.8}\ \kappa^{0.6}$$

where A is the atomic number, I_p(MA) is the plasma current, R(m) is the major radius, A(m) is the minor radius, κ is the elongation, B(T) is the magnetic field, n($10^{19}m^{-3}$) is the density, and P(MW) is the total input power. Both scalings fit equally well the JET L-mode confinement data, although the scatter is large.

Magnetic Limiter Configuration

In the magnetic separatrix (X-point) configuration, the plasma is detached from both the limiter and inner wall and recycling occurs in an open divertor region near the X-point. With heating power applied above a certain threshold value, a transition occurs to an improved plasma confinement (H-mode) regime, which is dependent upon the toroidal magnetic field. Fundamental characteristics include a rise in the energy content and plasma density, as well as an increase in electron temperature near the separatrix, which produces a pedestal in the temperature profile, and a flatter density profile with a steep gradient near the separatrix. The global energy confinement time in the H-mode exceeds that obtained with limiter discharges by more than a factor of two, as shown in Fig.42.

Stable discharges with a magnetic separatrix have been maintained in JET for several seconds at plasma currents over 5MA in the single-null configuration and up to 4MA in the double-null

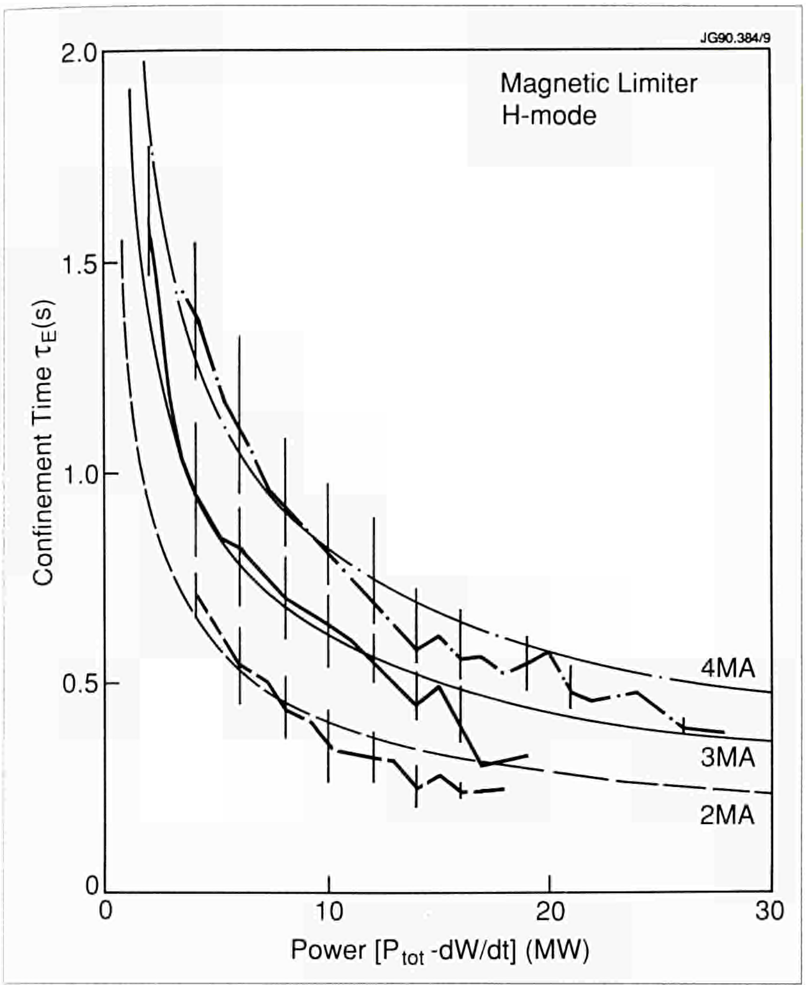


Fig.42: Confinement time as a function of input power for magnetic limiter conditions, for different plasma currents.

MARFE

A MARFE (Multifaceted Asymmetric Radiation From the Edge) is a toroidally symmetric band of cold, highly radiating plasma which normaly forms at the plasma inner wall. It can occur when the plasma edge density is high and results from of an imbalance between the power flowing along magnetic field lines in the edge and the power lost locally due to radiation. A MARFE grows rapidly, on a timescale of ≈10-100 milliseconds, but it can persist for several seconds. In some cases, the MARFE leads to a disruption, but in others the main consequence is a reduction in the edge density.

situation. Operation in these configurations has been undertaken to compare global confinement characteristics with those with limiter discharges, as well as to study the operation of preliminary beryllium target plates; the effect of changing the toroidal field direction; impurity retention; H-modes with RF Heating; and edge ion temperatures.

Plasma purity is improved by the use of a beryllium first-wall, and central values of the fuel concentration (n_d/n_e) were in the range 0.7 to 0.9. Use of beryllium also improved the control of plasma density, with its high deuterium pumping rate. The confinement times were unchanged from the carbon limiter cases, but the fusion performance improved substantially. The global confinement time scaled with power, P, as $P^{-0.5}$, with both ICRF and NB heating in the range 4-25MW, confirming results found in 1989. Even so, these experiments were still carried out with the upper X-point target plates. However, to obtain initial evidence of the influence of beryllium as a target material for X-point plasmas, a preliminary target was devised which used tiles of a non-optimum design, originally intended for use in the ICRF

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.

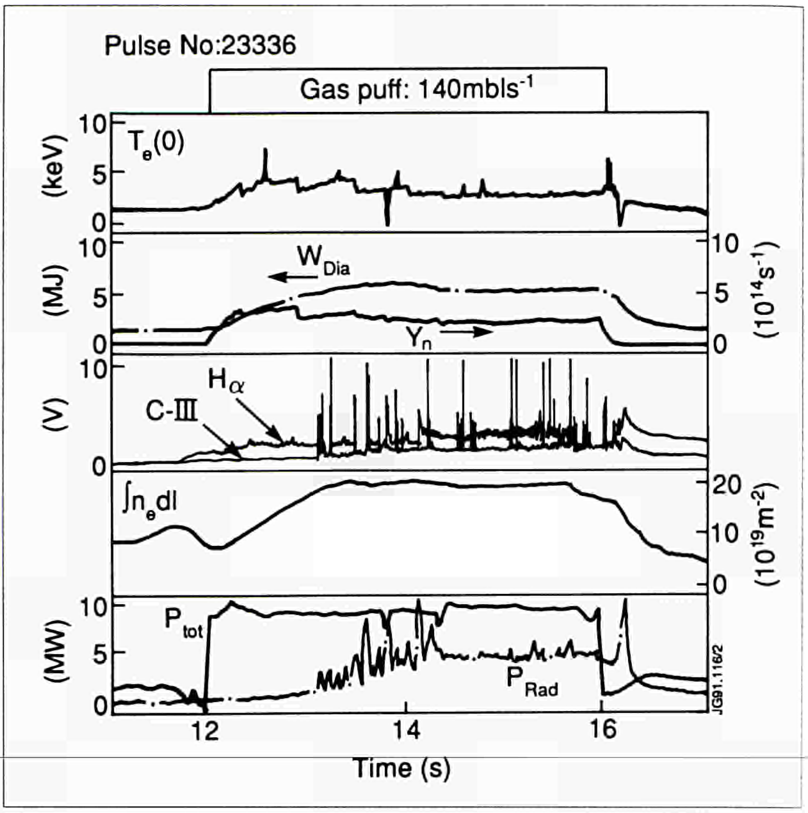


Fig.43: Overview of an elmy H-mode, at moderate NBI power, in which plasma parameters were held constant for 2-3s by the ELM's. This regime was established by gas puffing into the midplane of a hydrogen target plasma heated by deuterium neutral beams.

antenna protective frame. H-modes were obtained with similar power thresholds and comparable confinement properties to discharges on the upper set of carbon tiles. As with carbon, H-modes on the beryllium tiles were terminated by a sudden influx of impurities (or 'bloom') due to the formation of localized "hot-spots" on the tiles. Various techniques to delay the onset of the blooms have been explored, including sweeping the X-point radially in order to distribute the power over a larger tile area. A high recycling regime can suppress the 'bloom' and this can be established by gas puffing either before or during the H-mode but it is more stable when started before the heating is applied. This regime is improved when the X-point is well inside the vacuum vessel.

A quantitative comparison between H-modes with carbon and beryllium tiles is inconclusive at the present time, as the beryllium tiles became badly melted during the first series of experiments (these beryllium tiles was not optimized for the X-point power flux) and subsequently, it was not possible to establish good H-modes on the damaged tiles. These experiments will be continued during 1991 using new carbon and beryllium tiles specifically designed for the X-point region.

During some H-modes, Edge Localized Modes (ELM's) of instability appear at the plasma edge, leading to some loss of confinement. The majority of JET H-modes are free of ELM's. In this situation, the density rises throughout the H-mode and it is usually terminated by a high level of radiation (or, at the highest powers, by an impurity 'bloom'). However, impurity influxes can be reduced, and the H-mode duration extended, by heavy gas puffing. Even so, in these cases, the density continues to rise and the regime never achieves stationary conditions. Recent experiments have shown that, under certain conditions, a steady-state H-mode can be achieved in which the particle and impurity influxes are controlled by regular ELM's. These have been produced reliably by gas puffing from the midplane in a hydrogen plasma. Results are shown in Fig.43, in which, after an initial phase of ~1 second, ELM's appear and in spite of continuous gas puffing, the plasma density, radiated power, impurity contact, stored energy and neutron production remained consistent for the duration of the H-mode. Although the confinement time was not as high as the H-mode without ELM's, it was still a factor of 1.8 higher than that of the L-mode scenario for similar power input.

Evidence from several tokamaks has shown that significant changes occur in some aspects of H-mode behaviour when the direction of the toroidal field is reversed, so that the ion drift in the field gradient is away from rather than towards the X-point. Specifically, the H-mode power threshold can double and the distribution of power on the inner and outer X-point strike zones can change substantially. A series of experiments was performed to investigate such differences in JET H-modes.

When the ion drift was towards the X-point, the temperature rise at the outer strike point was larger than at the inner strike point. When the toroidal field was reversed, so that the ion drift was away from the X-point, the tile temperatures at both strike points were lower and nearly equal. The impurity 'bloom' was delayed significantly. Measurements of the ion currents to the plates showed similar asymmetry (typically a factor of 3 greater current to the outer strike point compared to the inner strike point), when the ion drift was towards the X-point, whereas the currents at each strike point were almost equal when the drift was reversed. The radiated power is greater at the inner strike zone when the drift was towards the X-point and at the outer strike zone when the drift was away from the X-point. The power threshold for the H-mode was lower by a factor of ≈ 2 when the drift was towards the X-point (as observed in other tokamaks) and increased more slowly with toroidal field. In practice, this is

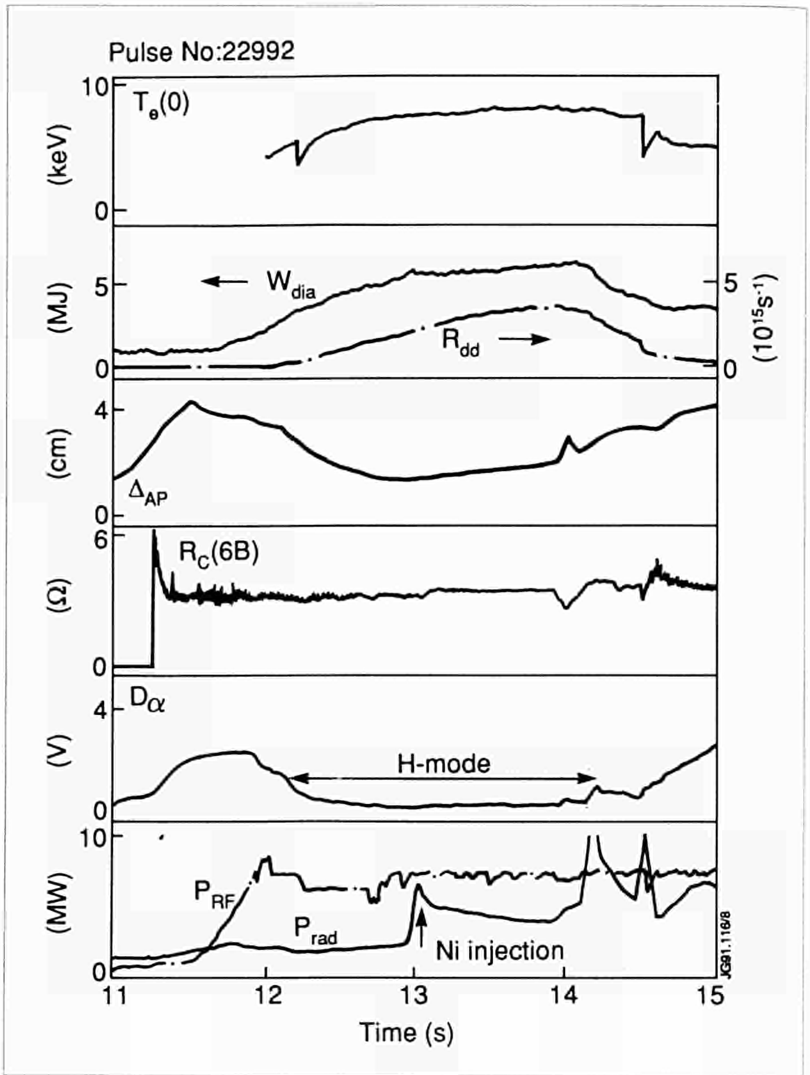


Fig.44: Overview of an ICRF-only H-mode in a 3MA/2.8T double-null X-point plasma. Note the slow change in plasma to antenna distance, Δ_{AP}, as the new position feedback control system maintains a constant coupling resistance, R_c.

unimportant when the emphasis is on high power discharges that are well above the power threshold. The confinement properties and impurity behaviour appeared to be independent of the field direction.

The first H-modes in JET with ICRF heating alone were obtained during 1989, primarily from using beryllium gettering to reduce impurity generation from the ICRF antennae screens. A major limitation had been the change in antenna coupling resistance to the plasma at the H-mode transition. This caused difficulties in maintaining the RF power to the plasma during the H-mode. To eliminate this problem, a new position control system was installed, which via a feedback loop, controlled the position of the plasma to maintain constant coupling resistance during changes in the plasma edge (e.g. the L-to H transition). In addition, to further reduce RF specific impurity generation, the nickel screens were replaced by beryllium screens. Fig.44 shows an overview of an

ICRF-only H-mode in this situation. This discharge was a 3MA/ 2.8T double-null deuterium plasma using hydrogen minority heating. The coupling resistance was kept almost constant during the L-to-H and H-to-L transitions. The power threshold for the H-mode transition in such plasmas was ~5MW, slightly lower than the threshold for similar neutral beam heated plasmas. The confinement is similar to that in neutral beam heated plasmas with an enhancement factor of ~2 relative to the material limiter situation.

Energy confinement predictions for H-mode operation in Next Step tokamaks require a scaling law based on tokamaks of difference sizes. Throughout 1990, work at JET proceeded on an H-mode database for global confinement scaling at the request of the ITER Project. The work was performed as a combined effort from JET and from several other tokamaks (DIIID (General Atomics, USA), ASDEX (IPP Garching, FRG), JFT2M (JAERI, Japan), PBXM and PDX (PPPL, USA)). A database consisting of measurements from neutral beam heated H-modes from these tokamaks was assembled from 979 discharges. The fit to the ELM-free data set gives:

$$\tau_E = 0.082\, I_p^{1.02} B_T^{0.15} P^{-0.47} A^{0.5} R^{1.6} \kappa^{-0..19}$$

where τ_E(s) is the energy confinement time, I_p(MA) is the plasma current, P(MW) is the loss power, A is the atomic number, R(m) is the major radius and κ the plasma elongation. A thermal offset-linear H-mode energy scaling has been obtained, in which the fast ion contribution due to the injected NB ions was excluded. The resolution scaling is

$$W_{th} = 0.183\, R^{1.9}\, I_p^{1.1}\, B_T^{0.91}\, A^{0.5} + 0.029\, I_p\, R^{0.87}\, A^{0.5}\, P_L$$

where W_{th}(MJ) is the thermal energy.

Progress Towards a Reactor

Beta Limits

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). To date, the maximum value of β_t obtained in JET is 5.5%. This limit is close to the value expected theoretically, which is the so-called Troyon limit $\beta_t(\%) = 2.8\ I_p(MA)/B_t(T)\ a(m)$, where I_p is the plasma current and a is the minor radius.

Recently, further considerations of plasma beta have suggested a von Gierke β_t limit given by $\beta_t(\%) = 4\ell_i I_p(MA)/B_t(T)\ a(m)$, where ℓ_i is the plasma inductance. In JET, $\ell_i \approx 0.7$, which is low and is thought to be due to the presence of a large bootstrap current which reduces the plasma inductance. Using this value of ℓ_i, the consistency is good in JET between the Troyon and von Gierke limits. The limit in JET is found to be disruption free. A range of magnetohydrodynamic (MHD) instabilities occur and these limit the maximum beta value without causing a disruption.

Alpha-Particle Simulations

The behaviour of alpha-particles has been simulated in JET by studying energetic particles such as 1MeV tritons, and ^3He and H minority ions accelerated to a few MeV by ICRF heating. The energetic population has up to 50% of the stored energy of the plasma and possesses all the characteristics of alpha-particles in an ignited plasma, except that in the JET experiments, the ratio of the perpendicular to parallel pressure was above three, while in a reactor plasma the distribution will be approximately isotropic. The mean energy of the minority species was about 1MeV, and the relative concentration of the ^3He ions to the electron density was 1-2%, which is comparable to the relative concentration of alpha-particles in a reactor (≈7%). Under conditions with little MHD activity, no evidence of non-classical loss or deleterious behaviour of minority ions was observed, even though the ratio of the fast ion slowing down time to the energy confinement time in JET is greater than that expected in a reactor.

Fusion reactivity measurements have been undertaken on the D-He^3 reaction, in which minority He^3 ions were accelerated to energies in the MeV range using ICRF heating. RF powers in excess of 15MW have been coupled to the deuterium plasma in the He^3 minority regime. Best results were obtained in a 3.5MA discharge in double-null X-point configuration, in which a reaction rate of $4.6\times10^{16}s^{-1}$ was achieved. This corresponded to 140kW of fusion power and a $Q(=P_{fus}/P_{rf})$ value of 1.25% was reached. This was carried out with a beryllium first-wall and benefitted from an improved fuel concentration of n_D/n_e up to 0.7. Typical results are shown in Fig.45, which shows the fusion power as a function of the ICRF input power. The fusion power is greater by a factor x2 with the beryllium first-wall compared with the carbon case. At RF powers greater than 10MW, the fusion yield seemed to saturate, possibly caused by excessive impurity generation and/or an acceleration of the minority ions above their

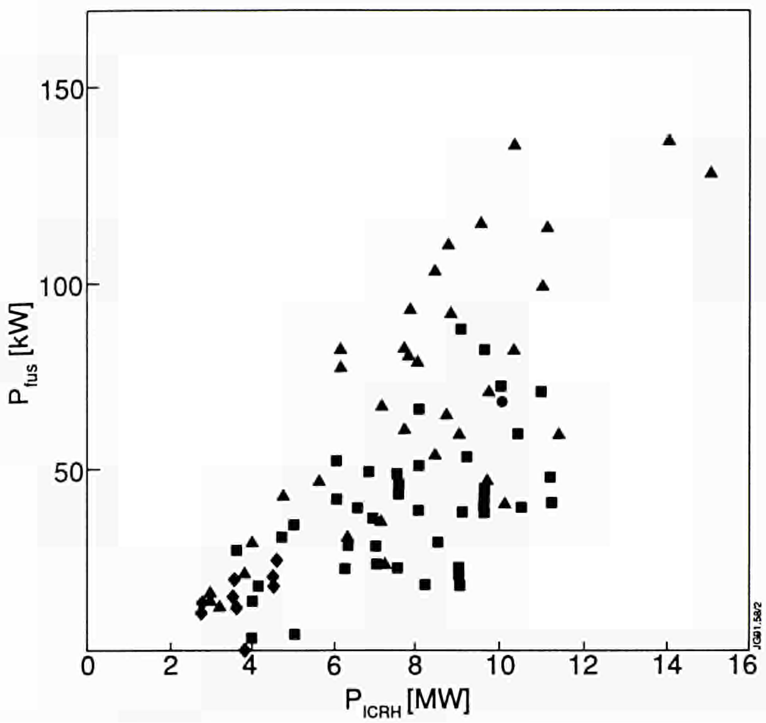


Fig.45: Fusion power as a function of ICRF input power.

optimal energy. Comparison of the measurements with theoretical predictions suggest that the trapping and slowing down of the fast particles are close to classical expectations.

Fusion Performance

The figure of merit which determines the fusion performance is the triple product, $n_D T_i \tau_E$, and how close this approaches the value required for a fusion reactor. In a reactor operating with deuterium and tritium, this product must exceed the value $5\times10^{21}m^{-3}$keVs for ignition conditions. The general performance obtained in JET and other tokamaks is shown in Fig.27.

Significant improvements were achieved in the material limiter configuration, due to the better purity and pumping obtained with beryllium as the first-wall. With high NB heating to low density deuterium target plasmas, it was possible to achieve L-mode hot ion regimes in up to 5MA currents plasmas. Typical parameters achieved were: n_i=$2.5\times10^{19}m^{-3}$, T_e=9.0keV, T_i=22.0keV, n_D/n_e=0.85 and τ_E = 0.6s. In these conditions, the best value of the fusion product for limiter discharges was $3\times20^{20}m^{-3}$skeV and, at the same time, the best value of Q_{DD} was 1.4×10^{-3}. Further development of higher current beryllium limiter discharges has continued with the aim of combining peaked profiles with the favourable scaling of global confinement time with current. Sawteeth have been suppressed well into the flat-top of a 6MA

Table.7: Summary of Plasma Parameters obtained in JET

Experimental Programme	Peak Density $n_i(0)$ ($\times10^{19}m^{-3}$)	Energy Confinement τ_E (s)	Ion Temperature $T_i(0)$ (keV)	Fusion Product $\{n_i(0)\tau_E T_i(0)\}$ ($\times10^{20}m^{-3}$skeV)	Q_{DT} Equivalent	Plasma Current I_p (MA)
Ohmic (4.6MW)	4.0	1.0	3.1	1.2	0.010	5
ICRF (16MW)	3.8	0.4	8.0	1.2	0.025	3
NBI (16.5MW) Low n:	3.0	0.55	20	3.3	0.35*	4.7
Combined NBI+RF (22MW)	4.5	0.5	8.1	2.0	0.30*	3.5
X-point NB-(18MW)	4.6 4.0	1.0 0.85	19 28	8.7 9.0	0.8* 0.8*	4.2 3.6
X-Point (PEP) Pellet + ICRF (9MW)	8.0	1.0	8.5-10.5	7-8.6	0.4	3

(* Beam-plasma reactions are dominant)

discharge and during the current rise of a 7MA discharge. A central electron temperature $T_e \approx 9$keV was obtained in both cases. The ions have been heated by neutral beams in a 6.5MA discharge, giving $T_i \approx 7.5$keV, $T_e \approx 8.0$keV and $n_i \approx 5\times10^{19}m^{-3}$. The confinement time was 0.65s, which together gave a fusion product of $2.1\times10^{20}m^{-3}$skeV. This phase of high fusion performance was terminated by a sawtooth crash with a subsequent strong density rise and influx of beryllium.

The inner wall of JET is still protected by carbon tiles. When operating with plasma in contact with the inner wall, the plasma shape must be carefully matched to the curvature of the inner wall to avoid carbon blooms due to localized overheating of the tiles. In optimized discharge conditions, neutral beam heating powers up to 16.5MW have been applied to plasmas in contact with the inner wall for up to 2s, without a strong carbon influx. Evaporation of beryllium onto the carbon tiles gave significant improvements in plasma purity and density control. Neutral beam injection into low density ($n_e \approx 3.0\times10^{19}m^{-3}$) target plasmas with I_p=4.7MA gave hot-ion ($T_i \approx 20$keV, $T_e \approx 9$keV) L-mode discharges with a confinement time of 0.45s. This gave a fusion product $2.3x10^{20}m^{-3}skeV$ and $Q_{DD} \approx 1.0x10^{-3}$.

Improved fusion performance was obtained in magnetic limiter configurations (X-point) plasmas during H-mode operation. In particular, when the good confinement properties of the H-mode were combined with the peaked profiles produced by pellet fuelling and central heating, good performance was obtained. A particular example has given a peaked density profile produced by injecting a string of pellets, which is heated by a mixture of neutral beams (2.5MW) and ICRF waves (9MW) to produce peaked temperature profiles with central ion and electron temperatures of ≈10keV which, although transient, persist into the H-mode phase. The neutron production rate peaked at $10^{16}s^{-1}$ corresponding to $Q_{DD} \approx 10^{-3}$ and is estimated to be about 90% thermal during the period when the peaked profiles and H-mode phases overlap. The fusion product reached a value of $8x10^{20}m^{-3}keVs$.

The best route so far is the hot-ion H-mode scenario. This is obtained when powerful neutral beams are injected into a low density target plasma. In the best discharge, a single null, 3.5MA discharge at a central density of $4.6x10^{19}m^{-3}$ was heated by 18MW of D° (10MW at 80keV and 8MW at 140keV). The central ion temperature reached ≈ 28keV for a confinement time of 0.85 seconds. The resulting plasma energy was 11.3MJ. This discharge obtained $Q_{DD} = 2.4x10^{-3}$ and a fusion product of $9x10^{20}m^{-3}skeV$. A full D-T simulation shows that ≈13MW of fusion power would have been obtained transiently, in this case. The fusion product is within a factor 5-8 of that required in a reactor.

The achieved values of the fusion product in the various configuration are tabulated in Table.7.

Summary of Scientific Achievements

Substantial progress has been made using beryllium as a first-wall material. Reduced impurity levels have resulted and have allowed prolonged operation at higher densities. Consequently, the general JET performance has improved, as follows:

- the pumping of deuterium with beryllium was more efficient than with carbon walls and provided improved density control. This permitted low density and high temperature (up to 30keV) operation for times exceeding 1 second;
- the maximum density of stable operation (or density limits) in various configurations have increased, with a peak density of $4x10^{20}m^{-3}$ achieved with pellet fuelling. The density

limit was found to be principally a fuelling limit and not a disruption limit, as shown with carbon limiters;

- sawtooth free periods up to 8 seconds were achieved. Further investigations have been undertaken on the stabilisation mechanism, but this is still not yet clear;
- a prototype lower hybrid current drive system has been operated on JET at up to 1.6MW for 20 seconds duration. Preliminary experiments have shown current drive values up to 1MA and the ability to stabilize sawteeth;
- with the introduction of beryllium RF antennae screens and a feedback system to maintain constant RF coupling to the plasma, improved and reliable RF-only H-modes have been achieved for periods exceeding 1 second. The confinement characteristics were similar to those with neutral beam heating alone;
- β values up to the Troyon limit were obtained in double-null X-point plasmas;
- a new mode of operation was introduced in which the pellet enhanced performance (PEP) (with peaked profiles) was combined with the good confinement properties of the H-phase. Fusion product values up to $8\times10^{20}m^{-3}keVs$ were obtained;
- the hot-ion H-mode scenarios was further enhanced to produce fusion products of $\approx 9\times10^{20}m^{-3}keVs$;
- the neutron yield was improved to $3.8\times10^{16}s^{-1}$ and the equivalent fusion factor Q_{DT} reached $\approx$ 0.8-0.9. This is near breakdown conditions and within a factor 5-8 of that required in a reactor.

However, these results were obtained in a **transient** state and could not be sustained in a steady state. Ultimately, the influx of impurities caused a degradation in plasma parameters.

At the start of 1991, further modifications will be incorporated including: uncooled separatrix dump plates with beryllium protection at the bottom, and graphite at the top; gas injectors in the X-points regions; the prototype high-speed pellet launcher; and the second neutral injector box converted to 140kV operation. The 1991 operational programme aims to exploit these new additions to complete and obtain maximum performance in 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 or carbon dump plates.

Preparations for D-T operations will also continue during this period, including commissioning of the Active Gas Handling System with tritium gas (subject to consent of the approving bodies) with the aim of undertaking a limited number of tritium pulses at an early stage.

In the longer term, a New Phase is proposed for JET, aimed at demonstrating effective methods of impurity control in operating conditions close to those of a Next Step tokamak in an axisymmetric pumped divertor configuration. This is described in further detail in the following section.

Future Programme

Introduction

The initial JET objectives still remain valid and continue to provide the focus of the Project's plans. These original objectives were set out in the JET Design Proposal in 1978, 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 α-particle production, confinement and consequent plasma heating.

The problems of plasma-wall interaction and of heating the plasma must, in any case, be solved in order to approach the conditions of interest.

An important part of the experimental programme will be to use JET to extend to a reactor-like plasma, results obtained and innovations made in smaller apparatus as a part of the general tokamak programme. These would include: various additional heating methods, first wall materials, the control of the plasma profiles and plasma formation."

At the start of 1990, the JET Project was midway through its planned Phase III - Full Power Optimization Studies. The original design specifications of JET had been achieved and in many cases exceeded. Two of the main programme objectives of the JET programme - the study of plasma heating and of the confinement of plasma - had to a large extent been met, in that the results from JET have made it possible to define with confidence the main parameters of a Next Step device. Some aspects of α-particle heating had also been studied in simulation experiments.

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;*
4. *Alpha-particle production, confinement and consequent plasma heating.*

During 1990, emphasis within the programme was further directed towards the fourth area of study, that of plasma-wall interactions, particularly the control of impurities in high performance plasmas. The Project has now demonstrated clearly the benefits to be derived (albeit transiently) from passive impurity control by using beryllium as a first-wall material for plasma-facing components.

The most recent experiments on JET achieved plasma parameters approaching breakeven values for about a second, resulting in a large burst of neutrons. These neutrons indicate that fusion D-D reactions are taking place. 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 is due to the poisoning of the plasma by impurities. This has further emphasised the need to provide a scheme of impurity control suitable for a Next Step device.

The JET aims clearly state that JET is an experimental device and that, to achieve its objectives, the latest developments in Tokamak physics must be allowed to influence its programme. However, within a JET programme to 1992, it would not be possible to tackle thoroughly problems associated with impurities. In view of the central importance of impurity control for the success of a Next Step device, the JET Council unanimously supported in 1989 a proposal to add a new phase to the JET programme, the objective of which would be to establish effective control of impurities in operating conditions close to those of the Next Step. This involved providing JET with a new magnetic configuration, including principally the installation of a pumped divertor. A prolongation of four years from the current end date of 31st December 1992 is needed to carry out the changes and then to allow sufficient experimental time to demonstrate the effectiveness of the new configuration in controlling impurities. This would provide for deuterium operation up to the end of 1994, followed by tritium operations in 1995 and 1996.

The JET Council agreed the proposed prolongation of the Project. In addition, a recent European Fusion Programme Evaluation Board (under the Chairmanship of Prof. U. Colombo) has recommended that fusion should be maintained as a priority in the Community's energy research strategy and supported the proposal to prolong JET's lifetime. The Project extension has been incorporated into the 1990-1994 Euratom Fusion Programme proposal and transmitted to the Council of Ministers for a decision.

During 1990, much of JET's efforts have been directed to preparations for the future, in particular to pursuing in parallel the two programme paths;

- preparations for the new pumped divertor phase in the frame of a proposed programme to 1996;
- completion of a JET programme by the end of 1992 with the final phase of D-T operations.

In the context of preparing for D-T operations, the Active Gas Handling Building was completed. Installation of the main sub-systems of the active gas handling system has proceeded as the components have been delivered and sub-system commissioning has started. Some important components have suffered delays and this has put back the date at which overall plant process commissioning can start. At present, it is still considered possible to undertake a limited campaign of D-T operations before the end of 1992. At the same time, the Project has pressed ahead strenuously with design and procurements for the new pumped divertor phase. The design of the main components - the divertor elements and the internal coils - evolved during the course of the year.

The Project has thus been able to maintain the dual programme stance required pending the decision of the Council of Ministers on the 1990-1994 Fusion Programme and in particular on the proposed prolongation of the JET Programme. However, this position cannot be maintained during 1991 without adverse effects on both the scientific programme and resource management.

JET Strategy

Present achievements show that the main objectives of JET are being actively addressed and substantial progress is being made. The overall aim for JET can be summarised as a strategy "to optimise the fusion product (n_i T_i τ_E)". For the energy confinement time, τ_E, this involves maintaining, with full additional heating, the values that have already been reached with ohmic heating and in the H-mode with the X-point configuration. For the density and ion temperature, it means increasing their central values $n_i(0)$ and $T_i(0)$ to such an extent that D-T operation would produce a-particles in sufficient quantity to be able to analyse their effects on the plasma.

The enhancements to JET aim to build up a high density and high temperature plasma in the centre of the discharge (with minimum impurity levels) where α-particles could be observed, while maintaining an acceptably high global energy confinement time, τ_E. The mechanisms involved are to decouple the temperature profile from the current density profile through the use of lower hybrid current drive and neutral beam injection to ensure that, at higher central temperatures, the current density in the centre does not reach the critical value that causes sawteeth oscillations.

This will involve the following:

a) Increasing the Central Deuterium Density, $n_D(0)$, by:
- injecting high speed deuterium pellets and higher energy deuterium neutral beams to fuel the plasma centre and dilute impurities;
- injecting pellets to control the influx of edge material;
- stabilising the m=2, n=1 magnetic oscillations present at the onset of a disruption with magnetic perturbations produced from a set of internal saddle coils which will be feedback controlled;

b) Increasing the Central Ion Temperature, $T_i(0)$ by:
- trying to lengthen the sawtooth period;
- controlling the current profile (by lower hybrid current drive in the other region, and by counter neutral beam injection near the centre) to flatten the profile;
- on-axis heating using the full NB and ICRF additional heating power (24MW, ICRF, and 20MW, NB);

c) Increasing the Energy Confinement Time, τ_E, by:
- increasing up to 7MA the plasma current in L-mode operation;
- increasing up to 6MA the plasma current in the full power, H-mode operation in the X-point configuration.

d) Reducing the impurity content, by:
- using beryllium as a first-wall material;
- controlling new edge material with the pumped divertor configuration.

In parallel, preparations for D-T operation are proceeding at full speed to ensure that the necessary systems for gas processing, remote handling, radiological protection, active handling and operational waste management are fully commissioned and operated satisfactorily in good time before the introduction of tritium into the JET device. In addition, the tritium neutral injection system at 160kV and α-particle diagnostics are being developed for this phase.

The New Phase of JET: Pumped Divertor

The following sections describe developments which are underway on JET to implement the proposed pumped divertor configuration in the New Phase.

Motivation and Status

Plasma dilution is a major threat to a reactor. The entainment of impurities in a forced flow of plasma towards the divertor target plates is a candidate concept for impurity control in Next Step tokamaks. This form of **active** impurity control is the focus of the

New Phase of JET: planned to start in JET in 1992. First results should become available in 1993 and the Project should continue to the end of 1996. The aim of the New Phase is to demonstrate, prior to the introduction of tritium, effective methods of impurity control in operating conditions close to those of a Next Step tokamak, with a stationary plasma (10s-1minute) of 'thermonuclear grade' in an axisymmetric pumped divertor configuration. Specifically, the New Phase should demonstrate:

- the control of impurities generated at the divertor target plates;
- a decrease of the heat load on the target plates;
- the control of plasma density;
- the exhaust capability;
- a realistic model of particle transport.

The New Phase of JET should demonstrate a concept of impurity control; determine the size and geometry needed to realise this concept in a Next-Step tokamak; allow a choice of suitable plasma facing components; and demonstrate the operational domain for such a device.

Key Concepts

The key concept of the proposed JET pumped divertor is that since sputtering of impurities cannot be suppressed at the target plate of a divertor, these impurities should be confined in the vicinity of the target plate itself. This confinement can be achieved by maintaining a strong directed flow of plasma particles along the divertor channel towards the target plates, to prevent back diffusion of impurities by the action of a frictional force. A most important feature of the configuration is the connection length, along the magnetic field lines, between the X-point region and the target plates. This distance should be long (~5-10m) to achieve effective screening of the impurities. In other words, the X-point should be well separated from the target plates and in JET this can only be achieved by **coils which are internal to the vessel**.

The formation of a **target plasma** in the divertor channels is another essential feature of the pumped divertor. The cold (radiatively cooled) and dense plasma, which is expected to form in front of the target plates, plays a number of key roles:

- radiating a significant fraction of the plasma input power, thus reducing the heat load on the target plates;
- reducing the impurity production by screening the target;
- reducing the probability of the impurities diffusing back to the plasma.

In the vicinity of the outer target plate, a pumping chamber with a cryogenic pumping system is planned to control **the main plasma**

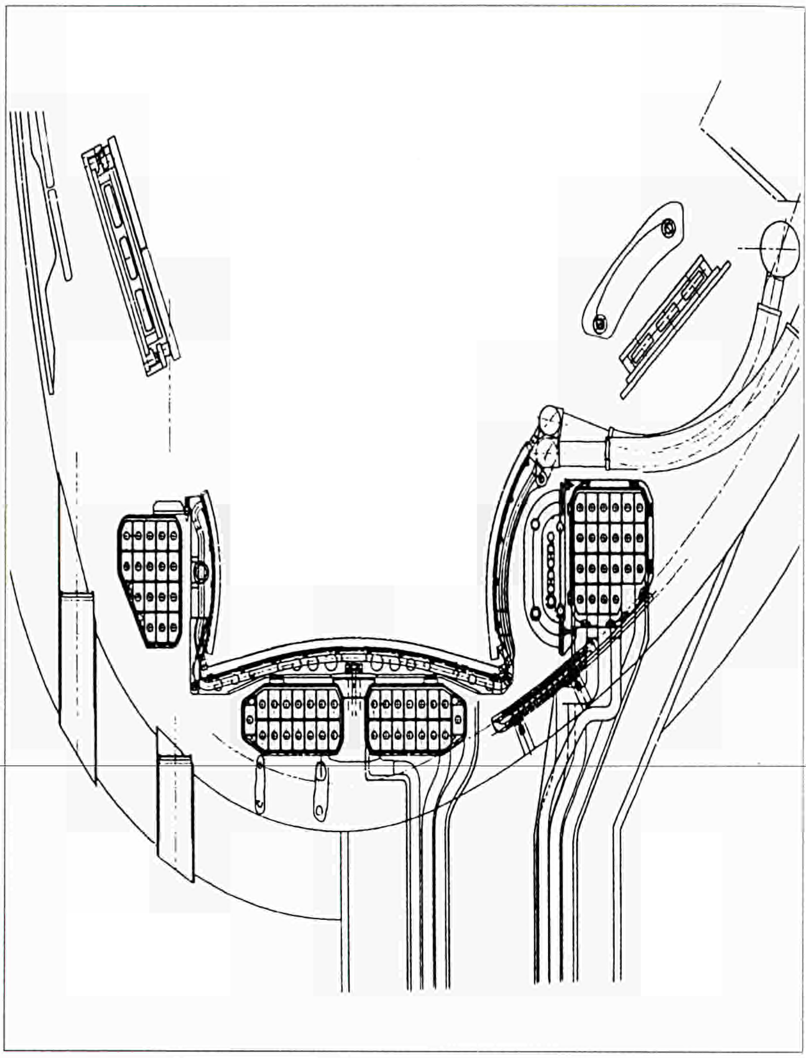


Fig.46: Details of four divertor coil arrangement.

density. It should be noted that only a small fraction of the hydrogenic neutrals generated at the target plate are expected to be pumped. Some of these neutrals will be able to recycle towards the X-point region, re-enter the scrape-off plasma there and enhance the plasma flow to the target plate. This local recirculation of hydrogenic particles should improve the impurity confinement. If required, gas can also be injected near the X-point to further increase the particle flow in the divertor channels.

Evolution of engineering aspects

Although basic designs and engineering principles are similar to the 1989 design, significant changes have occurred in certain areas, principally the magnetic configuration and the divertor coils, the design of target plates and certain features of ICRF antennae and limiters.

Magnetic Configuration and Divertor Coils

The main modification was the move to a four divertor coils configuration (see Fig.46). The initial motivation for this change was the

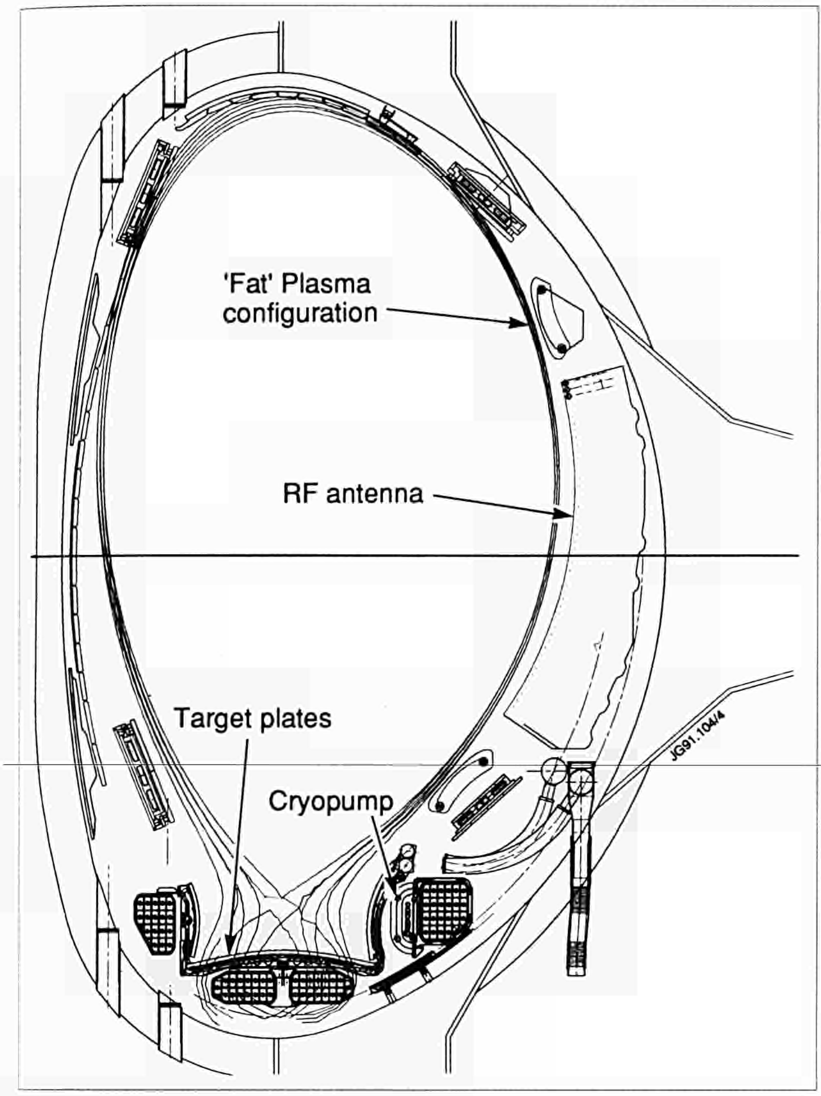


Fig.47: Configuration with so-called 'fat' plasma.

need to increase the connection length (length of field lines) between the X-point region and the target plates to provide better impurity confinement. The new multicoil configuration has proven to be much more flexible and versatile than the original single coil design, and will allow investigation of a range of plasma and divertor configurations. The range of configurations is illustrated by the two typical cases, the so called, fat and slim plasmas (Figs.47 and 48) obtained at plasma currents of 6MA. This much needed experimental flexibility fully warrants and justifies the design change. Since all four coils will have independent power supplies, great operational flexibility can be achieved:

- A "fat" plasma can be made using only the central bottom coils. This has a large volume, moderate elongation but short connection lengths;
- A "slim" plasma can be produced by adding currents in the side coils. Longer connection lengths are achieved at the expense of a smaller plasma volume. In addition, the elongation is larger and the vertical stability margin is reduced.

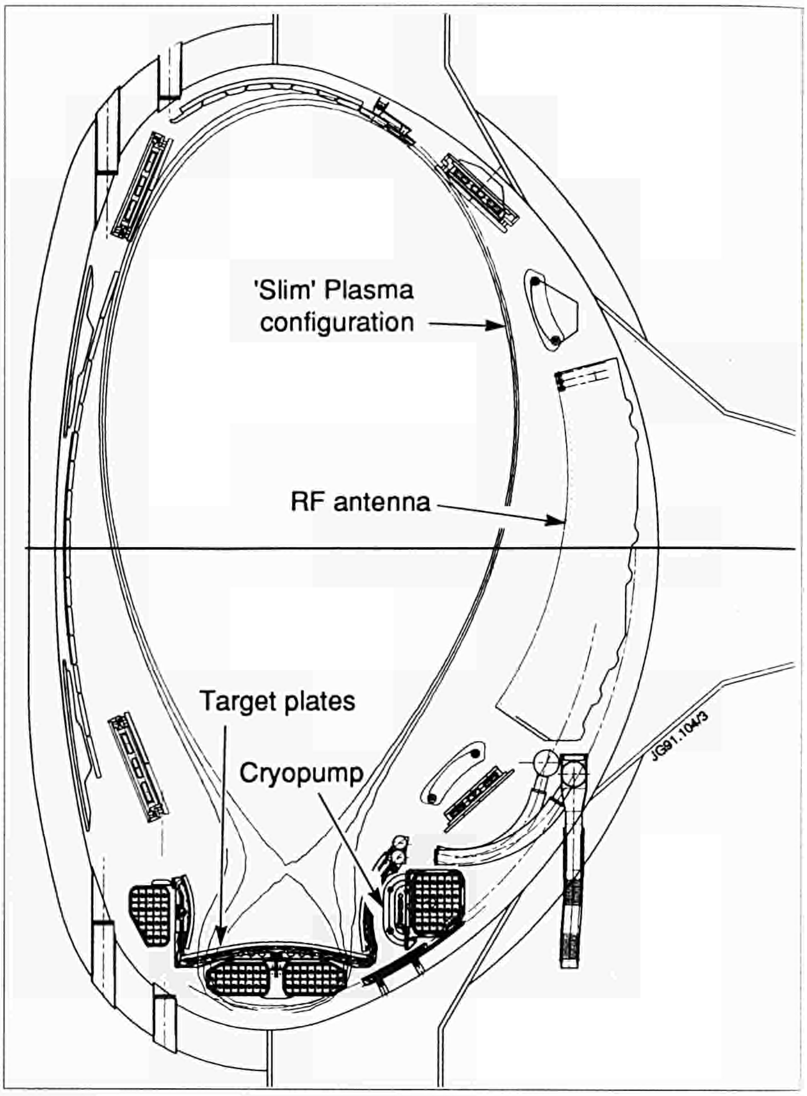


Fig.48: Configuration with so-called 'slim' plasma.

Typically the "slim" plasma has a connection length of 7m and the "fat" plasma has a connection length of 3m, both at a plasma current of 6MA. This gives the possibility of studying the effect of the connection length on the confinement of impurities and select the optimum configuration. Moreover, the side coils allow the connection lengths to be adjusted independently of the plasma current, and separately on the inboard and outboard sides of the X-point. In addition, the strike zone of the separatrix and scrape-off layer can be swept across the target plates to reduce the power deposition profile to an acceptable time averaged value.

Target Plates

The layout of target plates has been modified to take into account the new magnetic configuration. The target plates feature three elements (see Fig.49) in a U-configuration to accommodate the new plasma and divertor contours. Horizontal plates at the bottom intersect the heat flux conducted along field lines. Therefore, these bottom plates are subjected to a severe power deposition. Vertical

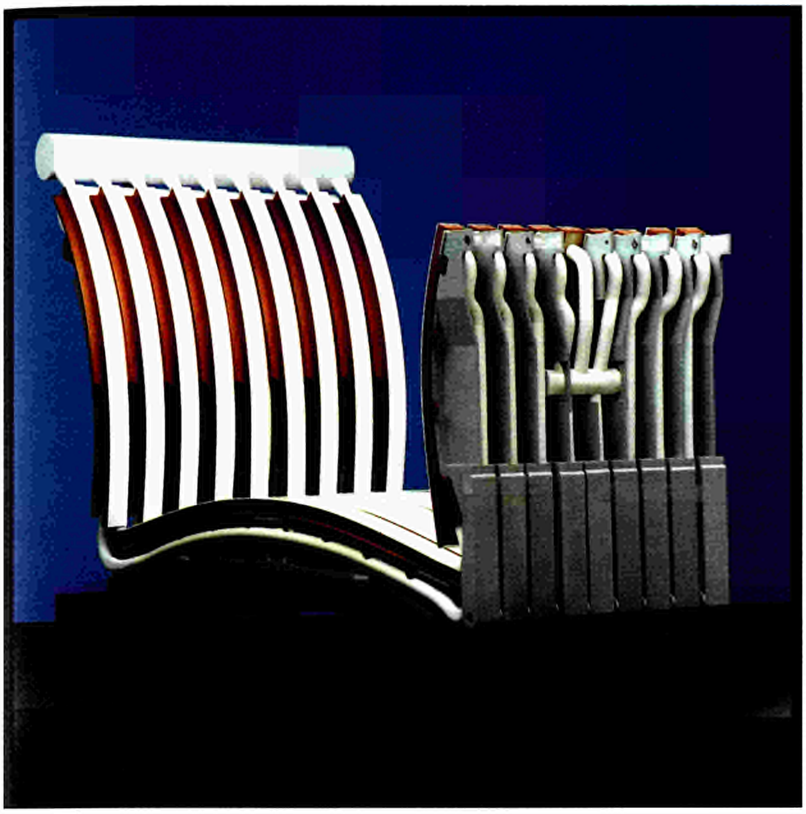


Fig.49: Layout of target plates.

plates on either side intersect the power radiated from the divertor plasma, and receive only a modest heat load. The horizontal and vertical plates are split into 384 radial elements grouped into 48 modules of eight elements each.

In this configuration, the peak power density on the bottom target plates would be unacceptably high even for the most advanced heat sinks. Consequently, sweeping the field lines is essential. Then the load can be accommodated by hypervapotrons of the type used on the JET neutral beam systems. In contrast to the bottom elements, the side elements receive only modest radiative heat load from the divertor plasma, and should not cause difficulties.

The surface of the hypervapotrons facing the plasma must be clad with a low Z-material. The choice of beryllium is natural in view of the results achieved on JET, although it is recognised that beryllium impurities generated in the divertor plasma will radiate only a negligible fraction of the incident power. However, the choice of material other than beryllium would entail the risk of impurities migrating back to the plasma and jeopardising the benefits of a beryllium first wall.

Installation of the target plates will proceed in two steps. During 1993, Step 1 will use solid radiatively cooled beryllium blocks as target plates. In 1994, Step 2 will use water-cooled beryllium clad hypervapotrons. This approach was motivated by the desire to start pumped divertor operation with a robust and simple design. The

Fig.50: The full scale model of one quadrant of the A2 antenna to be used for high power RF tests.

development of beryllium clad hypervapotrons has also proven to be more difficult than anticipated and additional time was required for the full qualification of manufacturing processes.

ICRF Antennae and LHCD Launcher Developments

The ion cyclotron resonance frequency (ICRF) antennae require close proximity to the plasma to achieve adequate coupling. With decreasing coupling, the voltage required to couple the full generator power is increased beyond that sustainable by the antennae. In both the 'flat' and 'slim' configurations, plasmas would be too far from the existing (A1) antennae to couple significant power. However, the much increased clearance available between the plasma and the wall allows the design of new antennae with improved coupling. A new set of antennae (to so-called A2 antennae) optimised to the new plasma configuration is therefore being produced. Initially, these will be set-up to match the 'fat' plasma; operation with the slim plasma will require the antenna to be moved to a new position in the torus.

One difficulty of the ICRF antennae design was the large force generated by eddy currents flowing in the antennae structure during plasma disruptions. To minimise these currents, the antennae structures and conductors use thin metal sheets and stiffness is provided by corrugations on double walls. Resistive elements offering high resistance to eddy currents but low resistance to RF currents have also been incorporated.

The "slim" plasma configuration requires that the ICRF antennae should be moved radially and tilted to match the plasma profile and achieve good RF coupling. The new design features spacer blocks for the antenna support structures and extension pieces for the RF conductors which allow this radial displacement. The toroidal layout of the antennae has also been modified to allow neutral injection in all possible plasma configurations.

A full scale model of one quadrant of the antenna has been constructed (Fig.50), and is presently being prepared for high power RF testing under vacuum. This model includes all critical features of the antenna and can be tested in open and short-circuit configurations to fully evaluate the design. These tests will commence shortly and are a critical element in the programme for completion of the prototype antenna by the end of 1991.

The LHCD launcher must be located close to the plasma to achieve good matching. Consequently, the grill mouth must be reshaped to suit either the large or small plasmas, and the launcher structure must be modified to enable the launcher to be moved sufficiently into the torus. The present LHCD launcher (L1) is being modified to suit the larger pumped divertor plasma, and will now be installed for the first time in the pumped divertor phase. The launcher will not couple to the 'slim' plasma; an alternative approach to the construction of the launcher is being explored for the slim plasma campaign.

The revised L1 version will re-use from the existing launcher the side protection, disruption supports and hangers for allowing movement of the launcher. Some modification of these items is required to support the additional disruption loads in the new configuration. With the reduced duty cycle, no active cooling is being incorporated apart from the RF window, as in the existing launcher. An alternative approach, for which a feasibility study is underway, utilises quasi-optical transmission between the 48 input waveguides and the 384 reduced section output waveguides. This would enable matching to the small plasma by the rebuilding of a simplified waveguide mouth.

Limiters

In the divertor configuration, a limiter is required for plasma start-up and also as a protection for the ICRF antennae. The initial design used two fixed belt limiters located above and below the antennae, but in the new configuration, the wide range of plasma shapes makes it impossible to use belt limiters which are at a fixed radial location. The new limiter design comprises six discrete poloidal limiters which extend from the top to the bottom saddle coils. These limiters will carry beryllium or graphite tiles and can be adjusted radially and tilted to provide adequate protection for the antennae.

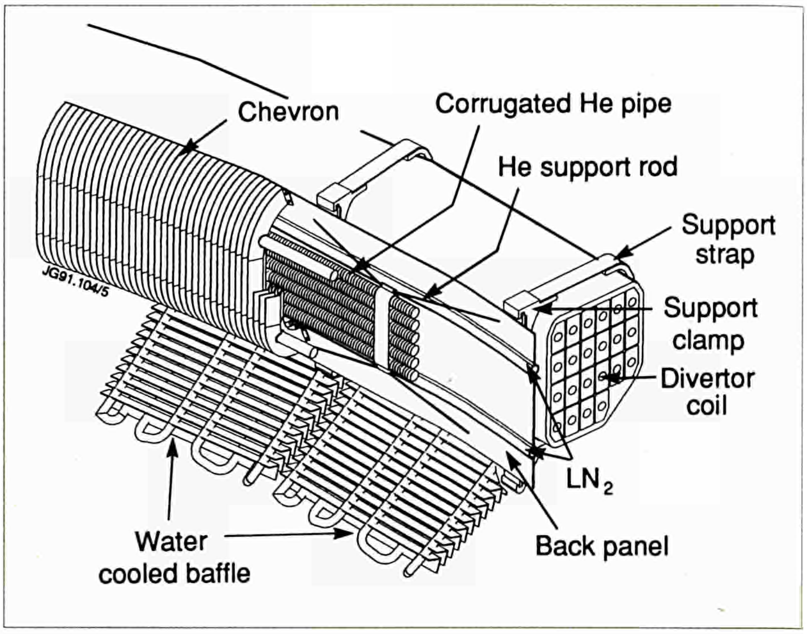


Fig.51: Divertor cryopump

Cryopump

An integral part of the divertor is a large cryocondensation pump with a nominal pumping speed of $5\times10^5 \ell s^{-1}$. The pump shown schematically in Fig.51 extends over the full toroidal length of the outermost divertor coil which also acts as the mechanical support. The design is somewhat conventional utilizing a liquid nitrogen cooled chevron baffle to protect the liquid helium condensing surface, which consists of corrugated stainless steel pipes, from high temperature gas molecules and thermal radiation. A water cooled chevron baffle ensures that the liquid nitrogen chevron is protected from direct line-of-sight to the high temperature of the vacuum vessel. The design is compatible with extreme conditions of up to 10^{23} particles per second and, in the D-T phase, a neutron flux of $10^{19}ns^{-1}$ for a 10s pulse. Manufacturing contracts have been placed with European industry and provision of the cryosupplies is underway.

Diagnostics

Definition of plasma diagnostics for the divertor, and engineering design and integration into the divertor have continued during the year. Magnetic geometry, electron density and temperature of the divertor plasma, radiative and conductive heat loading of the targets, and dynamics of impurity and hydrogen ions in the divertor plasma are the main measurement goals. Detailed engineering is underway for the diagnostic systems and the present status is detailed in Table.8.

Planning

The overall pumped divertor planning calls for a start of installation inside the JET vessel at the end of 1991. An important element is the

Table.8: Diagnostics for the New Phase of JET

System	Diagnostic	Purpose	Association	Status
KB2X	X-point bolometer	Time and space radiated power from X-point region	JET and IPP Garching	Commissioning
KB3D	Divertor bolometer	Time and space resolved radiated power from divertor region	JET	Design
KC1D	Magnetic diagnostic for divertor	Identification of flux surface geometry	JET	Design
KD1D	Calorimetry for divertor	Poloidal temperature distribution on target	JET	Design
KE4	Fast ion and alpha-particle diagnostic	Space and time resolved velocity distribution	JET	Under construction
KE5	q-profile Thomson scattering	Measurement of q-profile	JET	Under development
KE7	Lidar Thomson scattering	Higher spatial resolution, n_e and T_e in plasma edge	JET	Design
KE9D	Lidar Thomson scattering	T_e and n_e profile in divertor region	JET	Design
KF1	High energy neutral particle analyser	Ion energy distribution up to 3.5MeV	Purchased from Ioffe Leningrad	Under construction
KG5X	X-point reflectometer	Peak n_e in X-point	JET	Under development
KG6D	Microwave interferometer	$\int n_e ds$ in divertor region	JET	Design
KG7D	Microwave reflectometer	Peak n_e in divertor region	JET	Design
KJ3	Compact soft X-ray cameras	MHD instabilities, plasma shape	JET	Design
KJ4	Compact soft X-ray camera	Toroidal mode number determination	JET	Design
KK4D	Electron cyclotron absorption	n_e T_e profile in divertor region	JET	Design
KL3	Surface temperature	Surface temperature of target tiles	JET	Commissioning
KM2	14MeV neutron spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distributions	UKAEA Harwell	Under construction
KM5	14MeV time-of-flight neutron spectrometer		SERC Gothenberg	Awaiting installation
KS6	Bragg rotor X-ray spectrometer	Monitor of low and medium Z impurity radiation	UKAEA Culham	Design
KS7	Poloidal rotation	Multichannel spectroscopic measurement of poloidal rotation	UKAEA Culham	Design
KT3X	X-point target spectroscopy	Impurity and H spectra spatially resolved	JET	In preparation
KT5D	Toroidal view	Flow velocity	JET	Design
KT6D	Periscopes	Impurity density in divertor	JET	Design
KT7D	VUV and XUV spectroscopy	Impurity survey in the divertor region	JET	Design
KY4D	Fixed Langmuir probes for divertor	Plasma parameters at target	JET	Design
KY5D	Fast pressure gauges for divertor	Neutral particle fluxes on target	JET	Design
Kα1	Escaping alpha-particle detector	D-T alpha-particle confinement	JET	Design

winding of the four coils internal to the JET vacuum vessel. The manufacturing contract was placed in August 1990, design and documentation is almost complete and the main materials have been ordered. The coil parts should be ready for delivery to JET in early 1992 and in-vessel assembly is expected to take about four months. Overall, the time schedule is tight and is shown in Fig.52.

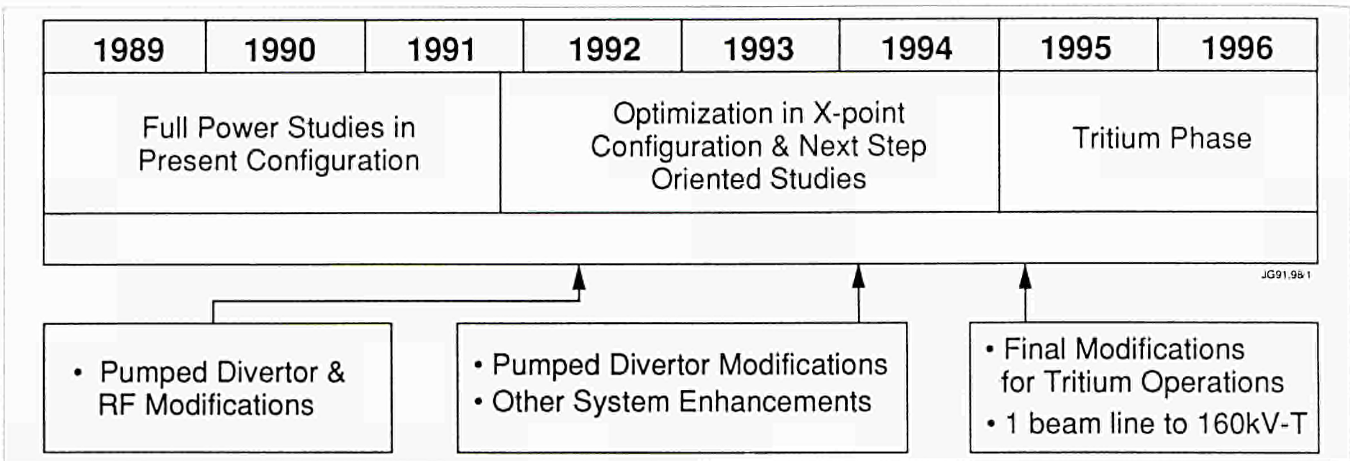


Fig.52: Overall plan for the JET New Phase.

The modifications for the tritium phase take place early in 1995, with conclusion of the Project at the end of 1996, following the D-T phase of operation in 1995-96.

Future Plans

The JET programme was divided into phases governed by the availability of new equipment and fitting within the accepted lifetime of the Project. At the beginning of 1990, the planned programme was as set out in Table.9. Taking account of the adjustments to the shutdown schedule and the need to allow for

Table.9: JET Programme to 1992.

1983-1984	1985-1986	1987-1988	1988-1989	1990-1991	1991-1992
PHASE I	PHASE IIA	PHASE IIB	PHASE IIIA	PHASE IIIB	PHASE IV
Ohmic Heating Studies	Additional Heating Studies		Full Power Optimisation Studies		Tritium Phase

Ohmic Systems	5MA	Vessel restraints and improved volt-seconds for 7MA operation	Vessel reinforcements			
Separatrix		Additional P1 coils	Separatrix dump plate supports		Separatrix dump plates	
Limiters	Eight carbon mid-plane limiters	Carbon belt limiters	Beryllium belt limiters	Modifications to Beryllium tiles		
Pellets	Single pellet injector	ORNL multiple pellet injector (1.5kms^{-1})			High speed pellet injector	
NBI	First NBI line (80kV)	Second NBI line (2x80kV)	One line modified to 140kV D		Second line modified to 140kV D	One line modified to 160kV T
ICRH	Three A_0 antennae	Eight A_1 antennae		Be antennae screens		
LHCD			Install Vacuum Chamber	Prototype system		Full system*
Disruption control						Saddle coils*
Tritium and Remote handling					Tritium plant and main RH modifications	Final modifications

* To go ahead only if New Phase of JET approved

sensible periods of operation to establish high reliability in preparation for the active phase of operation, the period remaining for D-T operation was no more than eight months. However, with the advent of the proposal for a New Phase for JET until the end of 1996, the planned programme is now as set out in Fig.52.

On the JET programme, Phase I, the Ohmic Heating Phase, was completed in September 1984, and Phase II (Additional Heating Studies) was completed in October 1988. The present Phase III (Full Power Optimization Studies) is underway, with Phase IIIA completed and Phase IIIB just started. Future phases are set out in the following paragraphs.

Full Power Optimisation Studies - Second Part - Phase IIIB (Oct. 1990 - Dec. 1991)

After the shutdown at the start of this phase, the following are planned to be operational:

- uncooled separatrix dump plates (with beryllium protection at the bottom, and graphite at the top);
- gas injectors in the X-points regions;
- prototype high-speed pellet launcher;
- second neutral injector box converted to 140kV operation;
- in-vessel preparation for the fast ion and α-particle diagnostic.

The scientific aims of the operational period in this configuration will be to exploit these new additions in order to complete and obtain maximum performance in limiter configuration (currents up to 7 MA) and to optimise X-point operation (currents up to 6 MA), including a comparison of H-modes in X-point configuration using beryllium or carbon dump plates.

Preparations for D-T operations will also continue during this period, including commissioning of the Active Gas Handling System (AGHS) with tritium gas (subject to consent by the approving bodies).

New Phase Programme-Phase IVA (Dec 1991 - Dec 1993)

At the end of 1991, the Project will enter an extended shutdown, which will last until Spring 1993, in order to install the components relevant to the new pumped divertor phase. This will involve intensive in-vessel work to install the following equipment:

- lower divertor structure with inertially cooled beryllium target plates;
- pumping chamber and cryopump;
- internal poloidal divertor coils and corresponding power supplies;
- modified limiters;

- new ICRF heating antennae (A2);
- full lower hybrid current drive (LHCD) system with its modified launcher;
- divertor diagnostics;
- multiple high-speed pellet launcher;
- disruption control system using internal saddle coils.

The single-null X-point pumped divertor configuration should enable JET to progress towards extended high power operation with 40MW additional heating made of neutral beam and ICRF power (eg plasma currents of 6MA for up to 3s, 3MA for up to 5s). The control of disruptions using saddle coils system and the control of sawteeth using the full power LHCD system should also be studied.

The first operating period should focus initially on establishing reliable operation in this new configuration. Subsequently, attention should be devoted to the study of performance and effects of the pumped divertor in controlling impurities, plasma density and exhaust, and power loading on the target plates.

New Phase Programme-Phase IVB (Dec 1993-Dec 1994)

The proposed shutdown (~4 months) in late 1993 would be to provide an opportunity, in the light of information from the experimental programme and elsewhere, to implement modifications to the pumped divertor (eg. enhanced cooling of the target plates). In addition, it should be possible to install other enhancements aimed at improving performance in the new configuration or for the D-T Phase (eg enhanced pellet injection or fuelling system, modifications to LHCD or additional heating systems, etc.).

The primary objective of this period of the new phase (to end-1994) would be to provide information necessary to demonstrate steady divertor operation with 40 MW power and to establish with confidence the key design features of the Next Step in relation to:

- impurity control;
- fuelling;
- helium transport and exhaust of ashes.

Another objective would be to optimise reliability and plasma performance in the divertor configuration in preparation for D-T operations. In parallel, active commissioning of the Active Gas Handling System and Remote Handling preparation should be completed.

Tritium (D-T Operations) - Phase V (Jan 1995-Dec 1996)

Subject to the approval of the JET Council and to necessary official consents, and when it is clear that the results in deuterium and general levels of system reliability justify it, the D-T phase would start in 1995, after a short shutdown to complete final modifications required for active operations.

During D-T operations, it would be possible to study in depth the physics of α-particle production, confinement and heating and thermal excursions. In addition, the real experience of tritium operation in a relevant scale tokamak (ie tritium handling and recovery, fuel mixture control, confinement properties of D-T plasmas, and remote maintenance and plasma diagnostics with large neutron and gamma backgrounds) will provide essential information for the Next Step.

JET Programme with 1992 as the end date

As noted previously, for the present, the Project is proceeding in a manner compatible both with pursuing the New Phase programme towards 1996 and with completing its experimental life with D-T operations in 1992. Plans have been developed for a campaign of D-T pulses which could be managed with a minimum of modification to the machine and existing subsystems. In order to keep the tritium inventory low, the plans involve a limited number of D-T pulses at the end of each operating day, immediately followed by cryo-panel regeneration. The exhaust would be collected in the Active Gas Handling System and isotopically separated for re-use after a few weeks of operation. This would entail the full operation of the AGHS, albeit not on a continuous basis and not using its capacity.

Work necessary to prepare for such a campaign is proceeding, including:

- preparation for formal submission to the UKAEA Safety and Reliability Directorate of an overall safety analysis;
- activation and shielding calculations for the limited D-T scenario;
- modifications to diagnostic and ancillary systems, (eg conversion of one NB box for tritium injection, reduction of diagnostic windows, etc.).

It is unlikely that, in the time available, multiple high-speed injection of tritium pellets could be brought into operation.

The proposed 1992 and 1996 JET Experimental programmes diverge at the end of 1991. However, as the JET Council has recognised, it is becoming increasingly difficult to maintain both options within the constraints of staff, money and time available. Before mid-1991, the Project will be forced, in the absence of a decision on the extension of the Project, into making choices which will adversely affect one or probably both paths.

Members and Organisation

Members

The JET Joint Undertaking has the following Members:

The European Atomic Energy Community (EURATOM);

The Belgian State, acting for its own part ('Laboratoire de Physique des Plasmas of the École Royale Militaire') and on behalf of the Université Libre de Bruxelles' ('Service de Chimie-Physique II de l'ULB'); and of the 'Centre d'Études de l'Energie Nucléaire (CEN)/'Studiecentrum voor Kernergie' (SCK);

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

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

The Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy;

The Hellenic Republic, Greece;

The Forskningscenter Risø (Risø), Denmark;

The Grand Duchy of Luxembourg, Luxembourg;

The Junta Nacional de Investigaçao Cientifica e Tecnológica (JNICT), Portugal;

Ireland;

The Kernforschungsanlage Jülich GmbH (KFA), Federal Republic of Germany;

The Max-Planck-Gesellschaft zur Förderung der Wissenschaften eV - Institut für Plasmaphysik (IPP), Federal Republic of Germany;

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

The Swiss Confederation, Switzerland;

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

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

Management

The JET Joint Undertaking is governed by Statutes which were adopted by the Council of the European Communities on 30 May

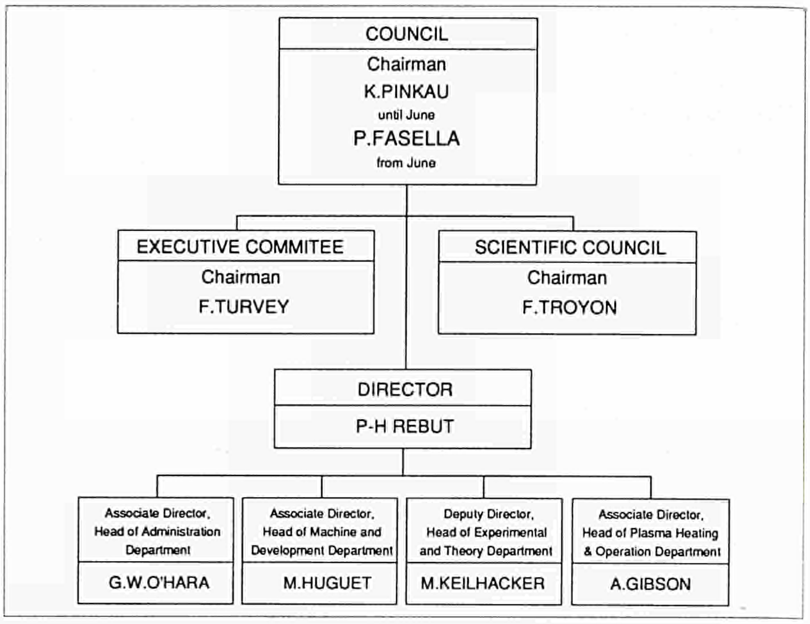


Fig. 53: Overall Project Structure

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 (see Fig.53).

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:

- The 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;
- The approval of the annual budget, including staffing, as well as the Project Development Plan and the Project Cost Estimates;
- Ensuring the 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 29th-30th March, 14th June and 1st November 1990. 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 the year on 20th-21st February, 24th-25th April, 19th-20th July, 18th-19th September, 8th November and 14th December 1990.

JET Scientific Council

The JET 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 membership of the JET Scientific Council is shown in Appendix III. The Scientific Council met twice during the year on 16th-17th May and 17th-18th October.

The main work of the JET Scientific Council in 1990 was to assess and advise the JET Council on:

- The New Phase of JET, including: the evolution of the pumped divertor concept; components for the pumped divertor; diagnostics for the New Phase; and modelling the edge plasma;
- JET planning to 1996;
- The status of the 140GHz gyrotron development;
- An active charge-exchange diagnostic for fast ions with energies in the range 0.5-3MeV;
- A new fast radial field amplifier system.

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' 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. P-H. Rebut, 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 Scientific 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 four Departments and the Coordinating Staff Unit. The four Departments are:

- Plasma Heating and Operation Department;
- Experimental and Theory Department;
- Machine and Development Department;
- Administration Department.

The overall Project Structure is shown in Fig.53.

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.

In addition, there are three groups. One contains Scientific Assistants who assist and advise the Director on scientific aspects of JET operation and future development. Another group contains the Technical Assistant who assists and advises the Director on organisational and technical matters related to JET operation and who also acts as Leader of the Publications Group. A third section contains the Press and Public Relations Group.

Plasma Heating and Operation Department

The Plasma Heating and Operation Department is responsible for heating the plasma, the organisation of experimental data and the day-to-day operation of the machine. The main functions of the Department are:

- heating of the plasma and analysis of its effects;
- centralising the interpretation of experimental results and investigating their coherence;
- organising data acquisition and computers;
- preparing and co-ordinating operation of the machine across the different Departments.

The Department is composed of four groups (Machine Operations Group, Physics Operations Group, Data Management Group and Health Physics Group) and three Divisions:

(1) Control and Data Acquisition System Division (CODAS), which is responsible for the implementation, upgrading and operation of the computer-based control and data acquisition systems;

(2) Neutral Beam Heating Division, which is responsible for the operation of the neutral beam injection system. The Division also participates in studies of the physics of neutral beam heating;

(3) Radio Frequency Heating Division, which is responsible for the design, construction, commissioning and operating the RF heating and Lower Hybrid (LH) systems during the different stages of their development to full power. The Division also participates in studies of the physics of RF heating and Lower Hybrid Current Drive.

Experimental and Theory Department

The main functions of the Department relate to the measurement and validation of plasma parameters and the theory of tokamak physics. The major tasks are:

- to conceive and define a set of coherent measurements;
- to be responsible for the construction of necessary diagnostics;
- to be responsible for the operation of the diagnostics, the quality of measurements and the definition of the plasma parameters;
- to play a major role in the interpretation of data;
- to follow the theory of tokamak physics.

The Department consists of two Groups (Diagnostics Engineering Group and Data Processing and Analysis Group) and three Divisions:

(1) Experimental Division One (ED1), which is responsible for specification, procurement and operation of approximately half of the diagnostic systems. ED1 undertakes electrical

measurement, electron temperature measurements, surface and limiter physics and neutron diagnostics;

(2) Experimental Division Two (ED2), which is responsible for specification, procurement and operation of the other half of the diagnostic systems. ED2 undertakes all spectroscopic diagnostics, bolometry, interferometry, the soft X-ray array and neutral particle analysis;

(3) Theory Division, which is responsible for predictionof JET performance by computer simulation, interpretation of JET data and application of analytic plasma theory to gain an understanding of JET physics.

Machine and Development Department

The Machine and Development Department is responsible for the performance capability of the machine as well as for equipment for the active phase, together with enhancements directly related to it (excluding heating) and the integration of any new elements on to the machine. In addition, the Department, which is composed of three divisions, is responsible for maintenance and operation of the coil systems, structural components and machine instrumentation. The three Divisions are:

(1) Magnet and Power Supplies Division, which is responsible for the design, installation, operation, maintenance and modification of all power supply equipment needed by the Project. It is also responsible for the maintenance and operation of the coil systems, structural components and machine instrumentation;

(2) First Wall Division, which is responsible for the vital area of plasma-wall interactions. Its main tasks include the provision and maintenance inside the vacuum vessel of conditions leading to high quality plasma discharges. The Division develops, designs, procures and installs first wall systems and components, such as limiters, wall protections, internal pumping devices and pellet injection systems. The area of responsibility encompasses the vacuum vessel as a whole, together with its associated systems, such as pumping, bake-out and gas introduction;

(3) Fusion Technology Division, which is responsible for the design and development of remote handling methods and tools to cope with the requirements of the JET device, and for maintenance, inspection and repairs. Tasks also include the design and construction of facilities for handling tritium.

Administration Department

The Administration Department is responsible for providing Contracts, Finance and Personnel services to the Project.

Coordinating Staff Unit

The Coordinating Staff Unit is responsible for the provision of engineering services to the whole project and for the implementation of specific coordinating tasks at the Project level.

It comprises four groups:

- Technical Services Group;
- Planning and Safety Group;
- Drawing Office;
- Quality Assurance Group.


FOR USE IN

Administration

Introduction

The three main aspects of JET's administration - Finance, Contracts and Personnel - are reported on in this section. In addition, there are contributions on Safety, Public Relations and Publications Group.

Finance

The initial budgets for 1990 were approved at 94.17 MioECU for Commitments and 103.27 MioECU for both Income and Payments. The Commitments and Payments Budgets are each divided into two phases of the Project - Extension to Full Performance and Operational Phase; subdivisions distinguish between investment, operating, and personnel costs, each with further detailed cost codes.

During the year, the Project continued its efforts to achieve economies particularly in operating and personnel expenditure. These economies were necessary in order to:

- ensure that the funds required by the Project up to 31st March 1992 do not exceed the appropriations available from the current Pluriannual European Fusion Programme;
- find within the current Pluriannual Programme the initial investment capital required for the New Phase;
- maintain the pattern of decreasing Annual Budgets in real terms.

Commitments

Of the total appropriations in 1990 of 132.16 Mio ECU (including 37.99 Mio ECU brought forward from previous years), 100.53 Mio ECU was committed and the balance of 31.63 Mio ECU was available for carrying forward to 1991. The details of the commitment appropriations available (Table.10) and of the amounts committed in each Phase during the year (Table.11) are summarised as follows:

- In the extension to Full Performance Phase, 4.07 Mio ECU was committed leaving 11.74 Mio ECU commitment appropriations not utilised at 31 December 1990, to be carried forward to 1991;

Table.10: Commitment Appropriations for 1990

	Mio ECU
Initial Commitments Budget for 1990	94.17
Amounts brought forward from previous years	37.99
	132.16
Commitments made during the year	100.53
Balance of appropriations at 31 December 1990 available for use in 1991	31.63

Table.11: Commitments and Payments for 1990

	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	15.81	4.07	15.24	11.54
Phase 3 Operational				
Title 1 Project Investments	18.84	9.55	15.63	12.15
Title 2 Operating Costs	51.10	46.25	49.90	45.74
Title 3 Personnel Costs	46.41	40.66	44.44	40.89
Total Phase 3	116.35	96.46	109.97	98.78
Project Total - all phases	132.16	100.53	125.21	110.32

- In the Operational Phase, 96.46 MioECU was committed leaving a balance of 19.89 MioECU to be carried forward to 1991.

Income and Payments

The actual income for 1990 was 105.31 Mio ECU, to which was added 0.20 Mio ECU appropriations brought forward from previous years, giving a total of 105.51 Mio ECU. This total compares with the 1990 Income Budget of 103.27 Mio ECU. The excess of 2.24 Mio ECU, mainly generated by higher interest revenues, is carried forward to be offset against future contributions of Members. From the total

Table.12: Income and Payments for 1990

	Mio ECU	
Income		
Budget for 1990		103.27
Income received during 1990		
(i) Members' Contributions	101.06	
(ii) Bank Interest	4.07	
(iii) Miscellaneous	0.18	
(iv) Unused Appropriations brought forward from 1988	0.20	
Total Income		105.51
Excess of budgeted income carried foward for off-set against Members' future contributions	2.24	
Payments		
Budget for 1990		103.27
Amounts available in the Special Account to meet outstanding commitments at 31 December 1989		21.94
Total Available Appropriations for 1990		125.21
Actual payments during 1990	110.32	
Amounts from the Special Account transferred to income	0.71	111.03
Unutilised appropriations at 31 December 1990 carried foward in the Special Account to meet outstanding commitments at that date		14.18

payment appropriations for 1990 of 125.21 Mio ECU, payments made were 110.32 Mio ECU and 0.71 Mio ECU was transferred to income leaving a balance of 14.18 Mio ECU, which was transferred to the Special Reserve Account to meet commitments outstanding at 31 December 1990. (Payments are summarised in Tables.12 and 13).

Contributions from Members

The budget for Members' contributions was 101.06 MioECU, 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 financial participation by Euratom in the total cost of the Associations. Table.13 gives the percentage contribution from Members for 1990.

Table.13: Percentage Contributions to JET for 1990

Member	%
Euratom	80.0000
Belgium	0.2239
CIEMAT, Spain	0.1616
CEA, France	1.8508
ENEA, Italy	2.0322
Risø, Denmark	0.0882
Luxembourg	0.0016
KFA, Germany	0.6772
IPP, Germany	2.1569
KfK, Germany	0.9188
NFR, Sweden	0.1552
Switzerland	0.4377
FOM, Netherlands	0.3992
UKAEA	10.8967
	100.0000

Bank Interest

During the year, funds are normally received on a quarterly basis in respect of Members' contributions and intermittently in respect of other items. Therefore, the Project has funds which are not immediately required for the discharge of its commitments and these funds are placed on deposit accounts at market interest rates. During 1990, earned interest amounted to 4.07 MioECU.

Unused Payment Appropriations from Earlier Years

The unused payment appropriations of 0.20 MioECU arising in 1988 and held for reduction of Members' future contributions were transferred to income in 1990.

Table.14: Summary of Financial Transactions at 31 December 1990

	MioECU
Cumulative commitments	1117.2
Cumulative payments	1074.2
Unpaid commitments	43.0
Amount carried forward in the Special Account	14.2
Amount available from 1989 and 1990 for set off against future contributions from Members	5.3

Summary

Table.14 summarises the financial transactions of the JET Joint Undertaking as at 31 December 1990, which have yet to be audited. The final audited accounts for 1990 will be published in due course.

Contracts

Contracts Activity

147 tender actions covering supply, service and personnel requirements were issued in 1990. 15,519 contracts were placed, which represents an increase of 27% in volume compared with 1989. Of the 111 major contracts placed (value greater than 75,000 ECU), a significant proportion were for New Phase (pumped divertor) related plant and for services. Many of the larger contracts involve advance and retention payments for which bank guarantees are required by JET. The total value of guarantees held at 31 December 1990 was 7.2 MioECU.

4,782 minor contracts (value between 500 and 75,000 ECU) were issued in 1990. 10,626 Direct Orders (value between 0 and 500 ECU) were issued in the year which amounted to 68% of the total orders placed, whilst their aggregate value amounted to only 2.1% of the total value of all orders, including amendments, in that period.

Imports & Exports Services

Contracts Service is also responsible for the import and export of JET goods. The total number of imports handled in 1990 was 1,277, while the total exports amounted to 348. There were also 1,072 issues of goods to UK firms. The total value of issues to all countries for the year was 9.9 MioECU.

Stores Organisation

In July 1990, the JET Stores Organisation came under the control of the Contracts Service. Since April 1989, the bulk of JET material is procured on a "just-in-time" basis and Stores provide a receipts and delivery service for this material to the Project. The total number of such receipts in 1990 amounted to 16,414. Other services include:

- a conventional stock issue and control service for special beryllium work materials, consumable items for the Main Assembly Contract (MAC), cable, inconel and protective clothing;
- hiring of scaffolding, cranes and general equipment;
- a care-and-custody service for special equipment;
- scrap disposal and equipment despatch;
- general handyman service, covering such items as site clearance, furniture removal, conference room preparation, etc.

Administration of Contracts

The distribution of contracts between countries is shown in Tables 15 and 16. Table.15 includes all contracts with a value of 10,000 ECU and above placed prior to 1984, together with all contracts placed during the period 1984-90. Table.16 is an allocation of "high-tech" JET contracts, which is based on the figures shown in Table.15, but excludes all contracts below 5,000 ECU and contracts concerning civil works, installation, pipework, consumables (including gases), maintenance, operations and office equipment (including PCs).

Table.15: Allocation of JET Contracts

Country	Total of kECU Values	% of Total
UK	393,996	50.73
Germany	145,070	18.68
France	71,983	9.27
Italy	67,593	8.70
Switzerland	38,949	5.02
Denmark	12,589	1.62
Netherlands	10,602	1.37
Belgium	9,419	1.21
Sweden	5,961	0.77
Ireland	381	0.05
Others	20,064	2.58
TOTALS	776,607	100.00

Table.16: Allocation of JET "High-Tech" Contracts

Country	Total of kECU Values	% of Total
UK	121,805	27.81
Germany	124,612	28.47
France	55,812	12.75
Italy	63,020	14.40
Switzerland	30,636	7.00
Denmark	7,332	1.68
Netherlands	9,792	2.24
Belgium	4,849	1.11
Sweden	4,176	0.95
Ireland	330	0.08
Others	15,350	3.51
TOTALS	437,714	100.00

Personnel Service

The activities of the JET Personnel Service during 1990 were concentrated in three main areas: recruitment and staffing; training and conditions of service; and general administration.

Recruitment and Staffing

This was the most important activity following the Director's decision that the Project in its later phase should concentrate more on the recruitment of young physicists and engineers and less on experienced professional staff, which had been the aim of JET's recruitment campaign since the mid-1980's. This change of emphasis was designed to provide the next generation of fusion scientists able to contribute to the work of the Project up to the end of 1996 and capable of taking a leading role in fusion research in the future. With the help of JET's partners, links have been established with European academic institutions and, by making presentations of JET's work at these institutions, younger candidates have been attracted to apply for posts in the JET team. At the same time, other opportunities for undergraduates to work at JET on short term assignments in support of the new recruitment strategy have been created by the introduction of a more attractive scheme for students and an improved JET Fellowship scheme.

It is hoped that many of these young scientists will be recruited at the end of their studies for posts at JET.

Team Staff

As a result of the increased recruitment activity during the year, 77 new team staff have joined the Project, an increase of 58% compared to 1989. However, taking departures of staff into account, the net increase in Euratom staff was 15 and in UKAEA staff, 39. The number of posts filled against the approved complement is shown in Table.17 and Fig.54 shows the composition of team staff by nationality. The co-operation of the Associations in continuing to undertake to employ such staff at the end of their assignments to JET has been an important factor in the success of the recruitment campaign in 1990.

The trend for contract staff to join the JET team, which was noted last year, continued during 1990, when four contract staff were appointed to team posts.

Students

Student appointments rose sharply during 1990. The Project used an employment agency instead of the UKAEA's student assistant scheme, under which students had previously been recruited to JET. This has

Table.17: Posts Filled Against Complement
(situation as at 31st December 1990)

Team Posts	Complement	In Post
Temporary Euratom Staff	191	180
UKAEA Staff	260	247
DG XII Fusion Programme Staff	19	8
	470	435
Contract Personnel	219	218.5
TOTAL	689	653.5

enabled an increase in appointments of students from partner countries other than the UK and altogether 93 appointments were made, representing an increase of 52% compared to 1989.

JET Fellowships

Since the mid-1980s the number of JET Fellows undertaking post-graduate and post-doctoral research had gradually risen to 19 in 1990, of whom 13 were physicists and 6 were engineers. In order to exploit more fully the potential staffing resources of the scheme, the number of JET Fellow appointments available was increased to a maximum of 25, divided equally between scientific and engineering disciplines, with a third of the entrance places earmarked for PhD students. As the number of young scientists and engineers applying for fellowships at JET had increased, a more rigorous selection process was implemented, through a JET Fellowship Selection Board comprising senior JET scientists and engineers.

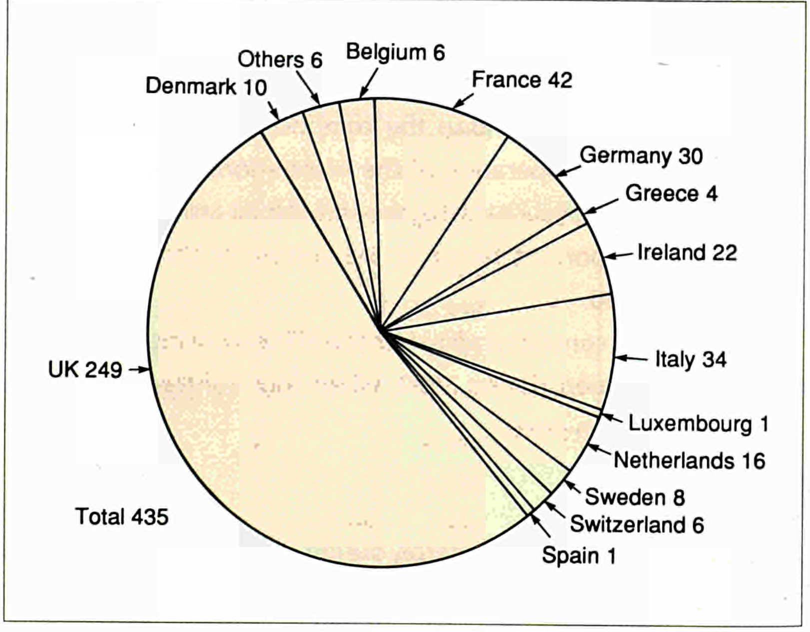


Fig.54: Composition of Team Staff by Nationality

Table.18: Contributions from Association Laboratories during 1990

Associate Laboratory		Man-Years
UKAEA	(UK)	12
IPP	(Federal Republic of Germany)	4
FOM	(The Netherlands)	2.8
NFR	(Sweden)	3
CEA	(France)	2.5
CIEMAT	(Spain)	1.7
CRPP	(Switzerland)	1.6
JNICT	(Portugal)	1
Risø	(Denmark)	2
KfA	(Federal Republic of Germany)	0.9
ENEA	(Italy)	0.8
	TOTAL	32.3

Table.19: Assigned Associate Staff within the Project during 1990

Division	Man-Years
Fusion	1.4
ED1	16.7
RF	0.9
ED2	9.7
Theory	2.9
Directorate	0.7
TOTAL	32.3

In addition to the increased manpower from the various sources during the year, the work of the Project continued to be supported by the assignment of staff to JET from Associated Laboratories and by other staff on attachment from other laboratories under various agreements. Table.18 shows the contribution from the partners to the Project as a whole, which was similar to that of 1989, and Table.19 shows the distribution of assigned staff within the Project.

Other scientific staff involvement reflected the world-wide interest in fusion, and include eleven JET Visiting Scientists from laboratories in USA, China and USSR. In addition, there have been exchanges of staff under the Tripartite Agreement between JET, JT-60 in Japan and TFTR in USA and between JET and other US laboratories as a result of specific collaborative agreements within the framework of the US Dept. of Energy and Euratom Bilateral Agreement.

An important task of the JET Personnel Service in this area has been to continue to monitor divisional expenditure by means of monthly budgetary reports to management to ensure that staffing levels approved by the JET Council are not exceeded. In addition, divisional budgets have also been allocated for the costs of travel and subsistence of staff which were previously funded centrally, with the aim of achieving economies wherever possible.

Training and Conditions of Service

Training

Changes in the provision of training primarily for JET team members were introduced during the year in such areas as the integration of new staff, safety induction, language tuition, and professional training. New staff are now provided with information designed to enable them to become familiar quickly with the organisation and working arrangements at JET. This has replaced the one day induction course of previous years. A new safety induction scheme informing staff through their line supervisor and safety representative of the basic safety requirements of working at JET was introduced and more than 600 persons (including contractors) working at JET had been through this scheme by the end of the year. In addition, courses involving several hundred persons covering basic safety, resuscitation, fire-fighting and working with radiation and beryllium were organised initially by the Joint Safety Services and latterly by the newly formed JET Safety Group.

The scheme for tuition in Community languages continued to be available but group classes were restricted to the lunch period to minimise the impact of such tuition on the work of the Project.

Attendance at training courses to supplement on-the-job training and to update the professional knowledge of staff has been supported by the Project to an increasing extent. The provision of advice on suitable training courses and the organisation of on-site group training, for example in the use of new computer software, is now an important role of the Personnel Service.

A comprehensive safety training programme has been operated for staff and contractors. Over 20 subjects have been covered ranging from basic induction courses to specialist safety training. In total, there have been some 3000 attendees.

Conditions of Service

Staff conditions of service are determined by the conditions of service of the two employers. Where possible these have been modified in consultation with the employers to meet the unique conditions of JET.

During the year, the UKAEA introduced a special bonus scheme for beryllium workers and 23 UKAEA team members received bonus payments based on the nature of the work carried out in beryllium controlled areas. UKAEA shift workers have continued to receive the special shift allowance for Saturday working introduced in 1989 by the UKAEA in recognition of the typical pattern of JET shift working.

The Retention of Experience Allowance payable to UKAEA team members was modified by the UKAEA to enable previous work for JET to count for payment and as a result the allowance was paid to 208 UKAEA team members, an increase of 8% compared to last year.

In addition, the working conditions at JET were considered jointly by management and staff representatives at three meetings during the year. Topics covered were the working arrangements in the Torus Hall during shutdowns, beverage facilities, the provision of a creche and the introduction of a JET Suggestions Scheme.

General Administration

Following the reduction in the services provided by Culham Laboratory under the Host Support Agreement, a number of activities were taken over and reviewed by the JET Personnel Service. As a result, the contract cleaning service and the contract beverage and catering service were introduced with the aim of reducing costs.

Safety

Organisation and Committees

The JET 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 legislation and, in accordance with the Host Support Agreement, JET complies with the safety regulations of the host organisation. This is monitored by the UKAEA Joint Safety Services.

During 1990, two new groups, previously part of the Joint Safety Services, were transferred to the Project: the JET Safety Group and Health Physics Group. The JET Safety Group provides a general safety service, including safety training, monitoring of the organisation of safety, co-ordination of emergency services and planning. The JET Health Physics Group provide a comprehensive radiological protection and occupational hygiene service, dosimetry service, beryllium analysis and environmental monitoring both on and off site.

There are currently four committees on safety related matters:

- The JET Safety Policy Board, chaired by the Director of JET meets once a year to review safety policy and define new actions;
- The JET Health and Safety Committee, chaired by the Head of Administration Department, consists of representatives of management and staff and reviews all matters which affect the health and safety of all employees on the JET site. It receives reports of Safety Audits, inquiries into accidents, and accounts of activities of the JET Safety Working Group;
- The JET Fusion Safety Committee, chaired by the Head of Coordinating Staff Unit, keeps under review the safety aspects of the Project during design, commissioning and operation, which arise from the use of tritium;
- The JET Safety Working Group, which is chaired by the Head of the Coordinating Staff Unit with members drawn from JET, Joint Safety Services and the Patrol Service, has continued to review all aspects of day-to-day safety. Comprehensive procedures controlling the use of beryllium on-site have been endorsed, and a review of all safety documentation has been carried out. Special attention was paid to improving safety training, particularly basic safety instructions to new staff and to contractors.

Radiation and Beryllium Data

The 1989/90 shutdown was completed by early June with a total collective radiation dose of 0.045man-Sv, of which 47% was accrued during 1990. D-D fusion neutron yield continued to be rigorously controlled during 1990 operations. This limited activation of the vacuum vessel so that the general radiation dose rate in-vessel was 60μSv/h at the start of the 1990/91 shutdown. The 1990/91 shutdown started in early November and the collective dose incurred from in-vessel work during the period to the end of December was 0.03 man-Sv. The total collective radiation dose for the Project during 1990 was 0.071 man-Sv, this is a 45% reduction on 1989.

Beryllium safety measures continued to be applied in the vacuum vessel and other Beryllium Controlled Areas. All work in Beryllium Controlled Areas was subject to Personal Air Sampling, the results of which, during 1990, demonstrated compliance with the requirements of the UK's 'Control of Substances Hazardous to Health Regulations 1988'.

Press and Public Relations

Following the restructuring of the UKAEA in April, JET set up its own Press and Public Relations Group, bringing to an end the 10-year joint service provided by the Host Organisation.

The Project continues to attract a wide range of visitors from both the scientific community and the general public. Amongst the more notable scientists visiting JET were Dr. Edward Teller - often described as the father of the H-bomb - and Professor Ernest Walton, who was awarded the Nobel Prize for Physics in 1951 for his pioneering work on nuclear physics. On the diplomatic front, a group of Ambassadors from OECD countries visited JET in June whilst from the political field, five Members of Parliament, from the UK, Germany and Japan received briefings on fusion during their visits to JET. The Fusion Programme Evaluation Board, set up by the Commission of the European Communities to conduct an independent review of the Fusion Research Programme, visited JET in March and took evidence from senior staff. Amongst their recommendations was the proposal to extend the operational period of JET until the end of 1996. From the media, eight journalists were given briefings on the progress of nuclear fusion, and two television crews, one from Italy and one from the UK, recorded interviews and general shots of JET. About 80 groups from schools, universities, professional bodies and the general public were given presentations on JET and guided tours of the laboratories. In addition, JET staff gave lectures on the research activities to various universities and professional groups.

JET provided display material and hardware for the Commission's stand at an exhibition in Rome held under the auspices of the Italian Presidency of EUREKA. Italian Team members manned the stand.

A major activity of the Group was the organisation of two major international conferences. The first was the 9th International Conference on Plasma Surface Interactions in Controlled Fusion Devices held in Bournemouth, UK, from 21st - 25th May 1990, which attracted an international audience of 200 delegates. The second event was the 16th Symposium on Fusion Technology, held in the Queen Elizabeth II Conference Centre, London, from 3rd-7th September 1990. A record attendance of 556 delegates representing all major fusion laboratories worldwide and some industrialists involved in fusion participated. Both programmes included visits to JET.

Publications Group

Following the restructuring, which took place in the UKAEA, JET set up its own Publications Group in early 1990. The Group provides a Graphics, Phototypesetting, Photographic and Reprographics service for the Project. The Group is lead by the Publications Officer, who is also responsible for the clearance, production and distribution of all JET documents. In addition, the Group arranges JET attendance at major International Conferences, and prepares papers and posters for these Conferences and Meetings.

Conferences

1990 was a particularly busy year, not only in setting up and organising the new Publications Group inside JET, but also in the number of major fusion Conferences held during that year. In particular, JET provided major contributions to the following Conferences:

- 9th International Conference on Plasma Surface Interactions (PSI) in Controlled Fusion Devices, Bournemouth, U.K., 21st-25th May 1990 (4 Invited Papers, 3 Oral Contributions and 18 Posters);
- 17th European Conference on Controlled Fusion and Plasma Physics, Amsterdam, the Netherlands, 25th-29th June 1990 (3 Invited Papers, 7 Oral Contributions and 38 Posters);
- 16th Symposium on Fusion Technology (SOFT), London, U.K., 2nd-7th September 1990 (3 Invited Papers, 3 Oral Contributions and 33 Posters);
- 13th IAEA Meeting on Plasma Physics and Thermonuclear Research, Washington, U.S.A., 1st-6th October 1990 (9 Oral Contributions and 4 Posters);
- 32nd Meeting of the Division of Plasma Physics of the American Physical Society (APS), Cincinnati, U.S.A., 12th-16th November 1990 (2 Invited Papers and 8 Posters).

In total, the Group prepared 183 Papers and 90 Posters for presentations to 27 different Conferences throughout the world. Arrangements were also made by the Group for 219 participants to attend these major meetings during the year.

In addition, the Group provided the Scientific Secretariat for the 9th International Conference on Plasma Surface Interaction (PSI) and for the 16th Symposium on Fusion Technology (SOFT), for which the Project was the Host Organisation. Considerable effort was expended in reprographics work in preparation for these meetings, and subsequently in compilation and editing of the Proceedings of both Conferences.

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 1990, 491 publications were cleared for external presentation.

During the year, 293 documents were published from the Project and the full list is included as an Appendix in the JET Progress Report, 1990. This total included 7 JET Reports, 76 JET Preprints, 7 JET Internal Reports, 4 JET Technical Notes and 6 JET Divisional Notes. All these JET documents are produced and disseminated by the Group on a wide international distribution.

APPENDIX I
The JET Council

Member	Representative
The European Atomic Energy Community (EURATOM)	P. Fasella (Vice-Chairman to June) (Chairman from June) C. Maisonnier
The Belgian State acting for its own part (Laboratoire de Physique des Plasmas - Laboratorium voor Plasmafysica, Ecole Royale Militaire - Koninklijke Militaire School) and on behalf of the Université Libre de Bruxelles (Service de Chimie-Physique II of the UBL); and of the 'Centre d'Étude de l'Energie Nucléaire' (CEN)/'Studie-centrum voor Kernenergie' (SCK)	P.E.M. Vandenplas T. van Rentergem
The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain	A. Grau Malonda
Commissariat à L'Énergie Atomique (CEA), France	D. Cribier (to June) J. Tachon (from June) R. Aymar
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	R. Andreani P. Longo (to October) C. Mancini (from October)
The Hellenic Republic (Greece)	A. Katsanos
The Forskningscenter Risø (Risø), Denmark	H. von Bülow J. Kjems
The Grand Duchy of Luxembourg (Luxembourg)	J. Hoffmann J.P. Zens
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal	J.A. da Costa Cabral (to June) J.T. Mendonça (from June) Mrs. M.E. Manso
Ireland	D. Byrne (to January) M. Brennan (from October) F. Turvey
The Kernforschungsanlage Jülich GmbH*, Federal Republic of Germany (KfA)	A.W. Plattenteich (Vice Chairman from June)
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	K. Pinkau (Chairman to June)
The Swedish Natural Science Research Council (NFR), Sweden	M.O. Ottosson (from January) H. Wilhelmsson
The Swiss Confederation	F. Troyon P. Zinsli
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	M.J. van der Wiel K.H. Chang
The United Kingdom Atomic Energy Authority (UKAEA)	J.R. Bretherton (from February) D.R. Sweetman

Secretary: J. McMahon, JET Joint Undertaking

* name changed to Forschungszentrum Jülich GmbH in January 1990.

APPENDIX II
The JET Executive Committee

Member	Representative
The European Atomic Energy Community (EURATOM)	J.P. Rager P.J. Kind
The Belgian State acting for its own part (Laboratoire de Physique des Plasmas - Laboratorium voor Plasmafysica, Ecole Royale Militaire - Koninklijke Militaire School) and on behalf of the Université Libre de Bruxelles (Service de Chimie-Physique II of the UBL); and of the 'Centre d'Étude de l'Energie Nucléaire' (CEN)/'Studie-centrum voor Kernenergie' (SCK)	R. Vanhaelewyn
The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain	F. Manero
Commissariat à L'Énergie Atomique (CEA), France	C. Gourdon (Vice-Chairman from June) R. Gravier
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	A. Coletti M. Samuelli
The Hellenic Republic (Greece)	A. Theofilou
The Forskningscenter Risø (Risø), Denmark	F. Øster V.O. Jensen
The Grand Duchy of Luxembourg (Luxembourg)	R. Becker
The Junta Nacional de Investigação Cientîfica e Tecnológica (JNICT), Portugal	J. Bonfim F. Serra
Ireland	F. Turvey (Chairman) D. Taylor
The Kernforschungsanlage Jülich GmbH*, Federal Republic of Germany (KfA)	V. Hertling
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	K. Tichmann
The Swedish Natural Science Research Council (NFR), Sweden	E. Hellstrand (to December) G. Leman
The Swiss Confederation	A. Heym P. Zinsli
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	H. Roelofs L.T.M. Ornstein
The United Kingdom Atomic Energy Authority (UKAEA)	D.M. Levey W.M. Lomer (to February) D.C. Robinson (from February)

Secretary: J. McMahon, JET Joint Undertaking

* name changed to Forschungszentrum Jülich GmbH in January 1990.

APPENDIX III
The JET Scientific Council

Members appointed by the JET Council:

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Staff Secretary: M.L. Watkins, JET Joint Undertaking