JOINT EUROPEAN TORUS JET

JET
JOINT
UNDERTAKING

ANNUAL
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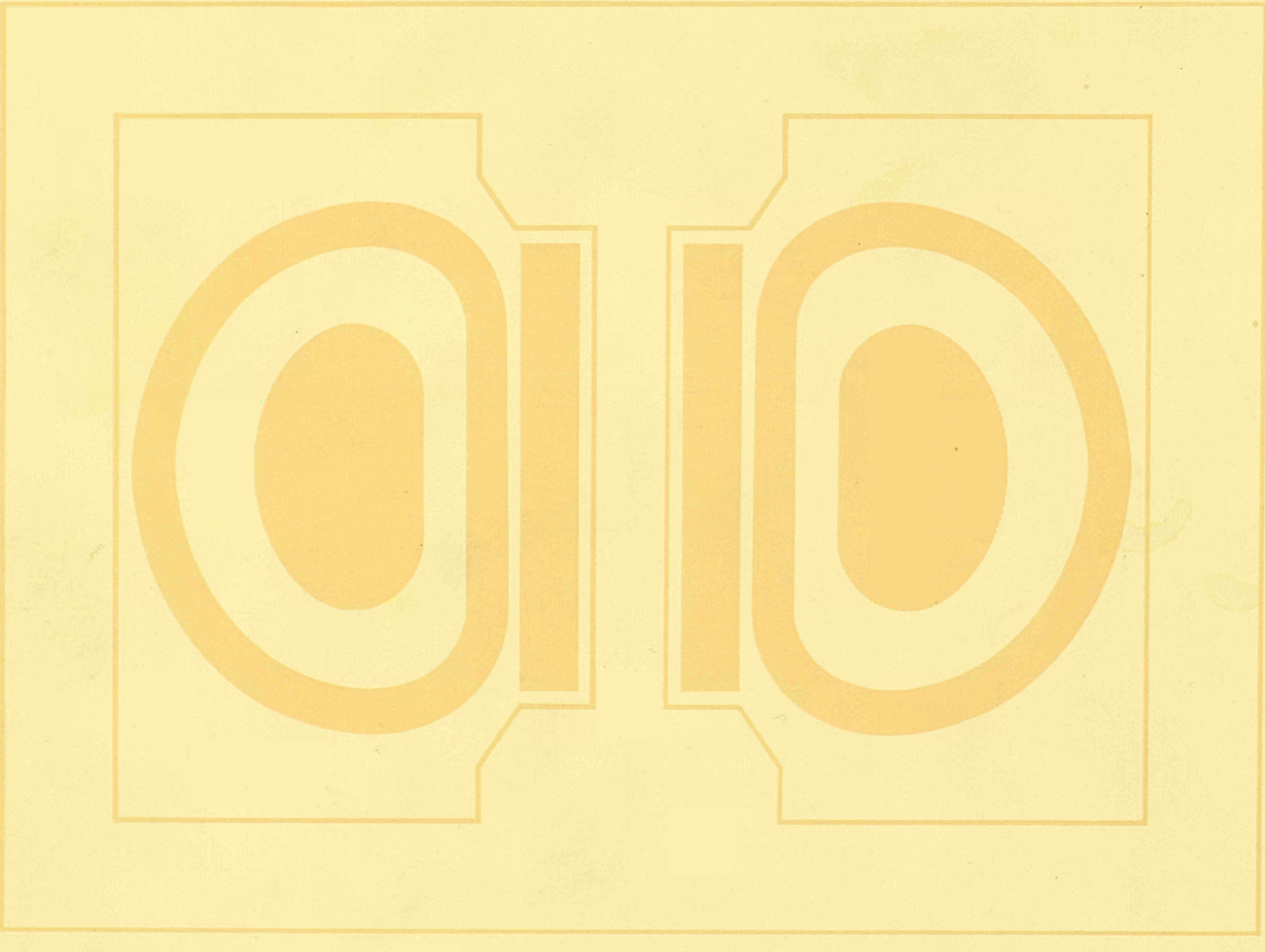
1993



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EUR-JET-AR16

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Preface

The year 1993 saw the virtual completion of the longest and most difficult shutdown since the machine was first assembled. By then the components for the new pumped divertor phase were installed, transforming completely the interior of the JET machine. Thus, JET achieved all its work programme targets, enabling the new experimental programme to start as planned early in 1994.

Plasma impurities continue to be a major obstacle to steady-state operation which is desirable in a fusion reactor. The decision to extend JET until the end of 1996 was taken to allow the Project to establish reliable methods of plasma purity control and plasma exhaust in operational conditions relevant for the Next Step tokamak, and to make preparations for the final phase of JET with deuterium-tritium plasmas. At the beginning of 1992, JET embarked on a two-year reconstruction of the vacuum vessel to provide a pumped divertor channel to control power exhaust and to screen plasmas from impurities which cool the plasma and reduce the number of energy producing reactions.

Despite additional work not envisaged when the shutdown was being planned, the original tight time schedule was maintained. This was achieved by the very detailed planning of the work, increased working hours and the dedication of everyone involved. The in-vessel work was performed round the clock for seven days a week. By the end of the shutdown 40,000 man-hours of working time had been spent in the vessel and 80 tonnes of new components had been installed giving the vessel an overall weight of about 200 tonnes in the new divertor configuration.

The first experiments in the new experimental programme will concentrate on establishing and characterising plasma behaviour in the pumped divertor configuration. The full programme will be directed at establishing reliable operation in the new configuration; studying the control of impurities, plasma exhaust and power handling using the complete range of ancillary equipment; extending performance to high power operations; and studying specific physics issues relating to the Next Step tokamak.

JET is the largest and most powerful fusion experiment in the world and has the capacity to facilitate the study of reactor relevant problems and the provision of further important information for the design of the International Thermonuclear Experimental Reactor (ITER) project.

ITER is a collaborative agreement between Euratom and the Governments of Japan, the Russian Federation and the USA whose basic objective is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes. ITER would accomplish this objective by "demonstrating controlled ignition and extended burn of deuterium-tritium plasmas, with steady state as an ultimate goal, by demonstrating technologies essential to a reactor in an integrated system, and by performing integrated testing of high heat-flux and nuclear components required to utilise fusion energy for practical purposes". The quadripartite agreement specifies that the Engineering Design Activities (EDA) of ITER should be implemented by two or more Protocols. Protocol 1 which led to the Outline Design for ITER was followed by the signing of Protocol 2 on 21 March 1994, which will end in 1998.

The former Director of JET, Dr. P-H Rebut, was appointed Director of ITER in February 1993. In addition, 17 experienced JET staff have been transferred to the ITER teams since ITER was established.

JET is the major focus of fusion research in Europe. Its outstanding success so far and its reliable technical facilities represent a substantial capital investment and the JET Council is actively considering the case for prolonging the Project beyond 1996 so that critical scientific issues related to the ITER design can be addressed. This would contribute greatly to maintaining Europe's lead in world fusion research.

However, the year under review has not been without problems. The JET Council is concerned that a petition addressed to the European Parliament by the staff assigned to JET by the UK Atomic Energy Authority has not yet found a final settlement. A prolongation of the Project requires that social peace on the Project is maintained for the foreseeable future.

I should like to thank all my colleagues on the JET Council for their unfailing support since my election as Chairman in June 1993. I wish also pay tribute to Professor Paolo Fasella who, as Chairman for the previous three years, guided the JET Council and the Project with wisdom and foresight. On behalf of my colleagues on the JET Council, I wish to record our appreciation of the invaluable work and advice of the JET Scientific Council and the JET Executive Committee throughout the year. Our gratitude is also due to the Commission of the European Union, the UK Atomic Energy Authority and the Associations within the European Fusion Programme for their sustained support of the Project.

In conclusion, I congratulate Dr Martin Keilhacker (who was appointed Director of the Project in March) and his team on their substantial achievements in 1993. I have every confidence that they will meet the challenges ahead with equal enthusiasm and success.

H. von Bülow
Chairman of the JET Council
May 1994

Introduction, Summary and Background

Introduction

The Joint European Torus (JET) 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.

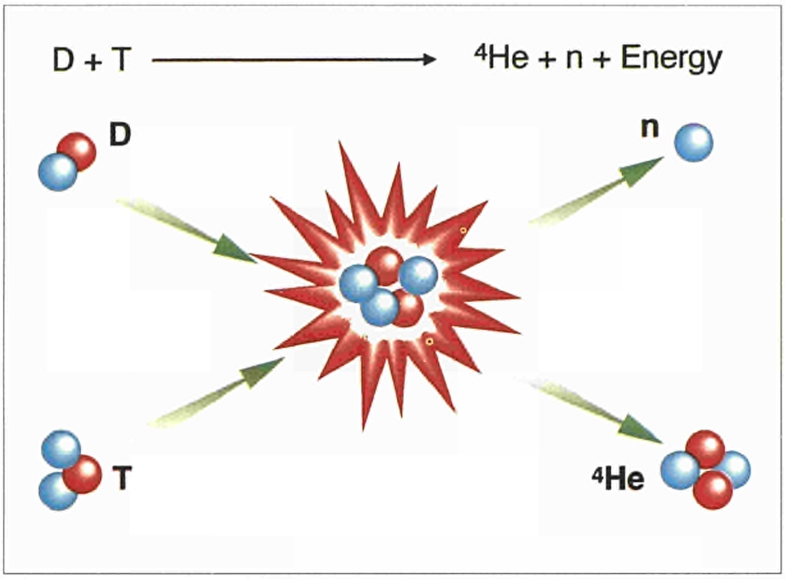
A more detailed and comprehensive description of the technical aspects of the JET Project can be found in the JET Progress Report.

Report Summary

The Report is essentially divided into two main parts:

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

The first part of the Report includes a brief introduction, provides an overview of the planning of the Report and sets the background



Nuclear Fusion

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

Most of the energy released in this reaction is carried away by a high speed neutron. The remaining energy goes to the alpha-particle (helium nucleus, ^{4}He) 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.

to the Project. This is followed by a description of JET and its experimental programme and explains its position in the overall Euratom and International Fusion Programmes. In addition, it relates and compares JET to other large fusion devices throughout the world and confirms its pre-eminent position in fusion research.

The following section reports the technical status of JET including: technical changes during the 1992/93 shutdown to prepare for the divertor phase of JET; and progress on systems for future operation. This is followed by a section on scientific achievements during 1993, and preparations during 1994/95 for the new phase. It sets out progress towards reactor conditions and compares the performance between JET and other tokamaks. It shows the substantial achievements made by JET since the start of operations in 1983. 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. It describes the administration of JET, in which it details the budget situation; contractual arrangements; and sets out staffing arrangements and complement.

Background

In the early 1970's, discussions were taking place within the European fusion research programme on a proposal to build a large tokamak fusion device to extend the plasma parameters closer to those required in a reactor. In 1973, an international design team started work in the

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.

UK, and by mid-1975, the team had completed its design for a very large tokamak device.

On 30th May 1978, the Council of Ministers of the European Communities decided to build the Joint European Torus (JET) as a Joint Undertaking of the European Fusion Programme. To implement the Project, the 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. Figure 1 shows the site of the JET Joint Undertaking at Culham, near Oxford in the United Kingdom.

The Members of the Joint Undertaking are Euratom, its Associated Partners in the framework of the Fusion Programme, including Sweden 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, UKAEA pays ten per cent, with the remainder shared between Members having Contracts of Association with Euratom in proportion to the Euratom financial participation in the total costs of the Associations.

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

In July 1988, the Council of Ministers agreed the prolongation of the JET Joint Undertaking to 31st December 1992. A further proposal to prolong JET to 31st December 1996 was approved by the Council of Ministers in December 1991. The extension will allow JET to implement the new Pumped Divertor Phase of operation, the objective of which is to establish the effective control of plasma impurities in operating conditions close to those of the Next Step. This programme of studies will be pursued before the final phase of full D-T operations.

Objectives of JET

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

Conditions for Fusion

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

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

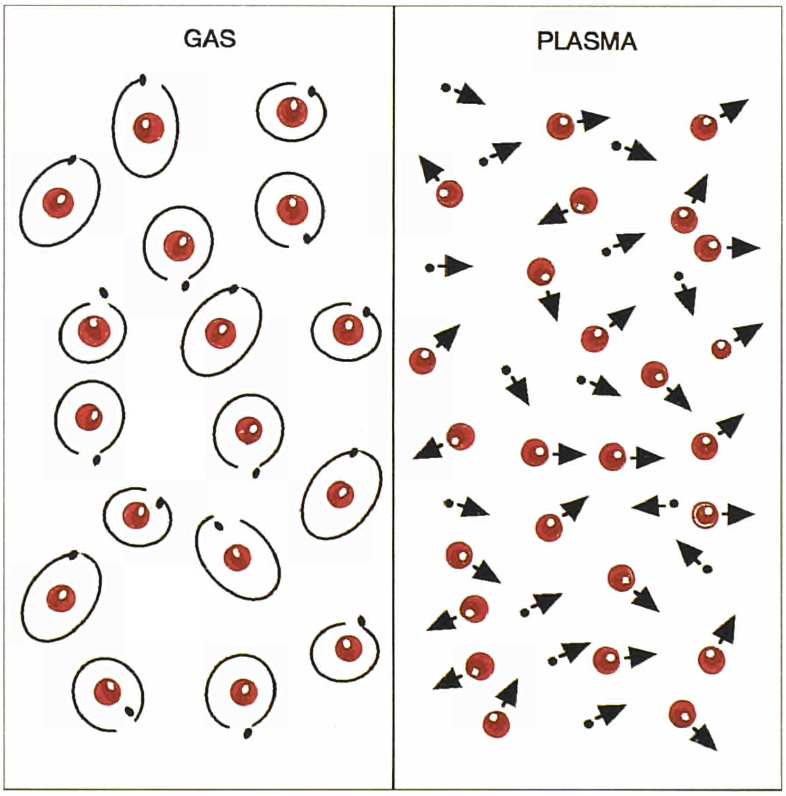
Power losses must also be kept to a minimum acceptable level by holding the hot gases in thermal isolation from their surroundings. The effectiveness of this isolation can be measured by the energy confinement time (τ_E) - the time taken for the system to cool down once all external forms of heating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

In a fusion reactor the values of temperature, density and energy confinement time must be such that their product ($n_i \tau_E T_i$), exceeds the figure of $5\times10^{21}m^{-3}$skeV. Typical values for the parameters that must be attained simultaneously for a reactor are:

Central ion temperature, T_i
10-20keV
Central ion density, n_i
$2.5\times10^{20}m^{-3}$
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).

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

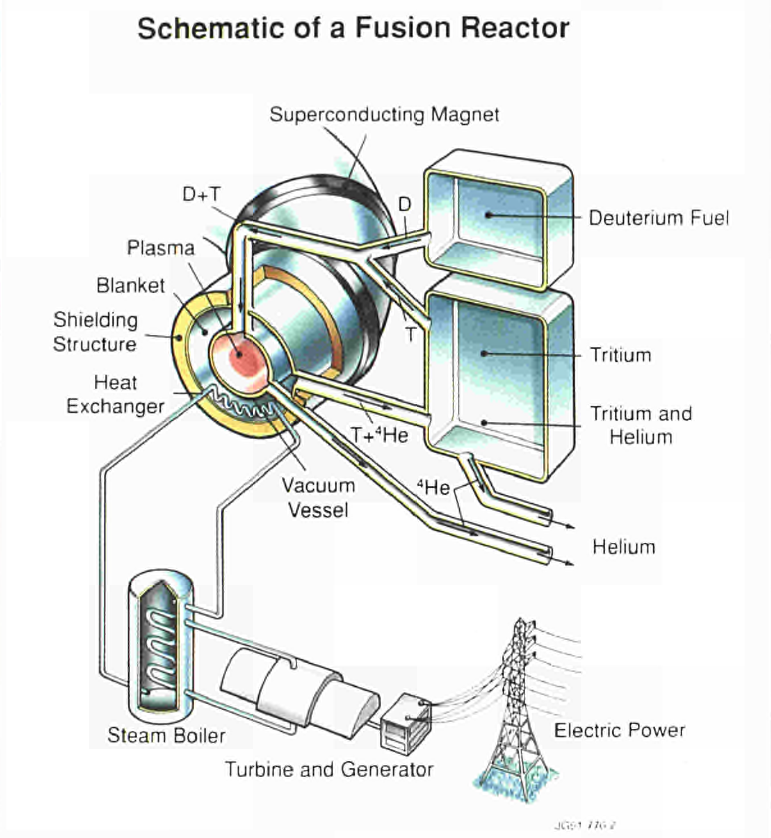


Plasma

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

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

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



Fusion Reactor

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

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

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

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

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

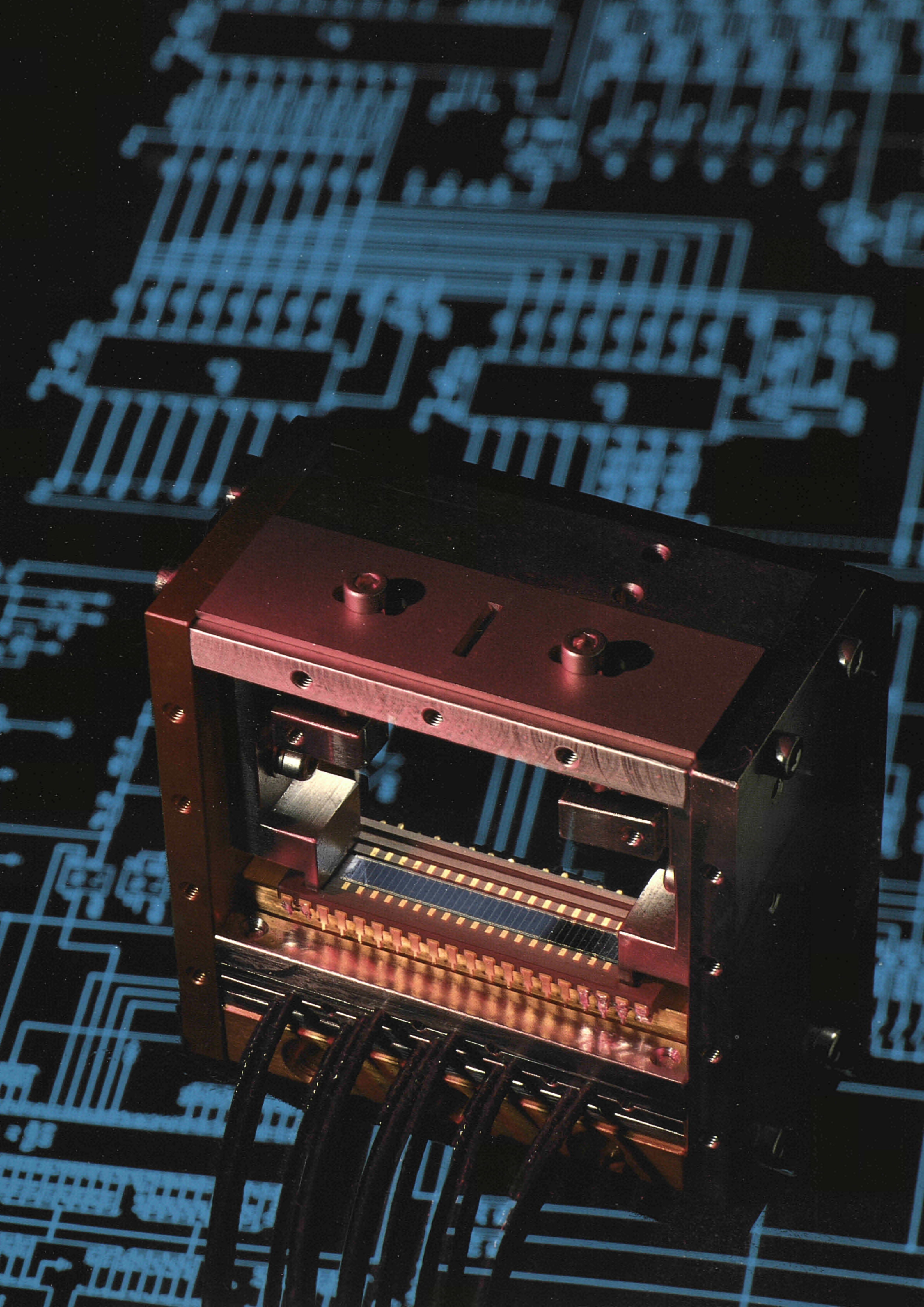
'... construct, operate and exploit as part of the Euratom fusion programme and for the benefit of its participants in this programme, a large torus facility of tokamak-type and its auxiliary facilities in order to extend the parameter range applicable to controlled thermonuclear fusion experiments up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

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

There are four main areas of work:

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

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



JET, Euratom and other Fusion Programmes

The Joint European Torus

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

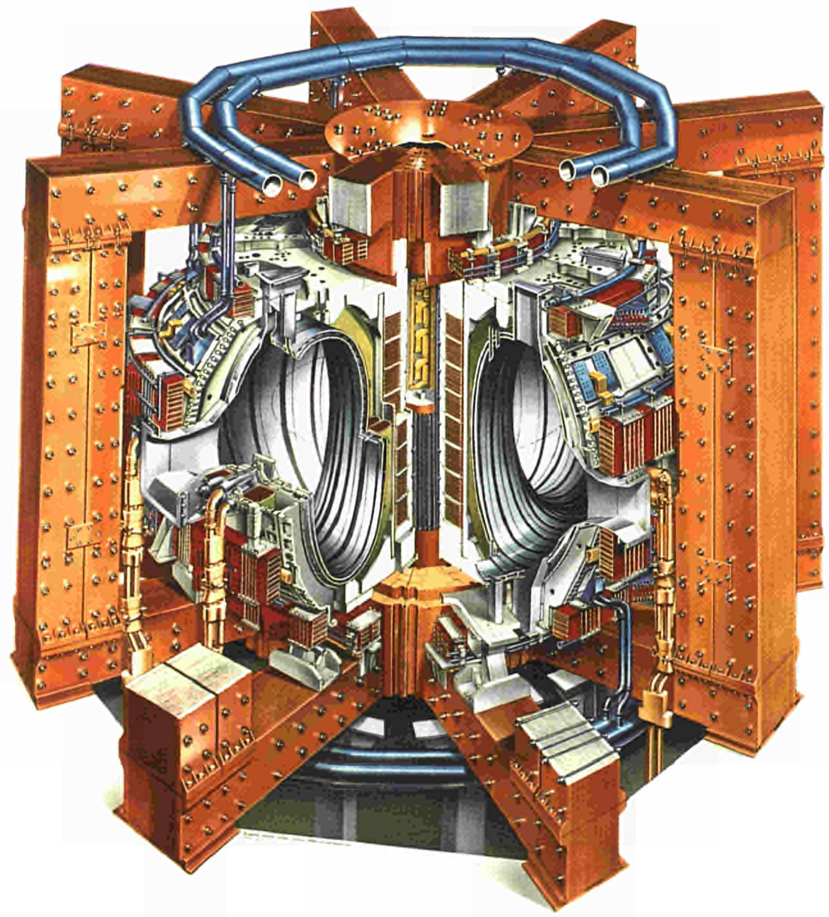
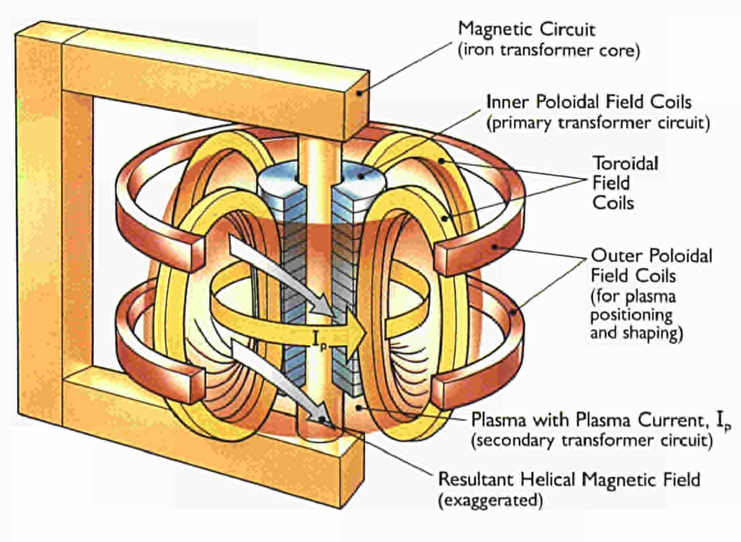


Fig.2: Illustration of the JET Apparatus

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

Table I: Original Design Parameters of JET

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



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.

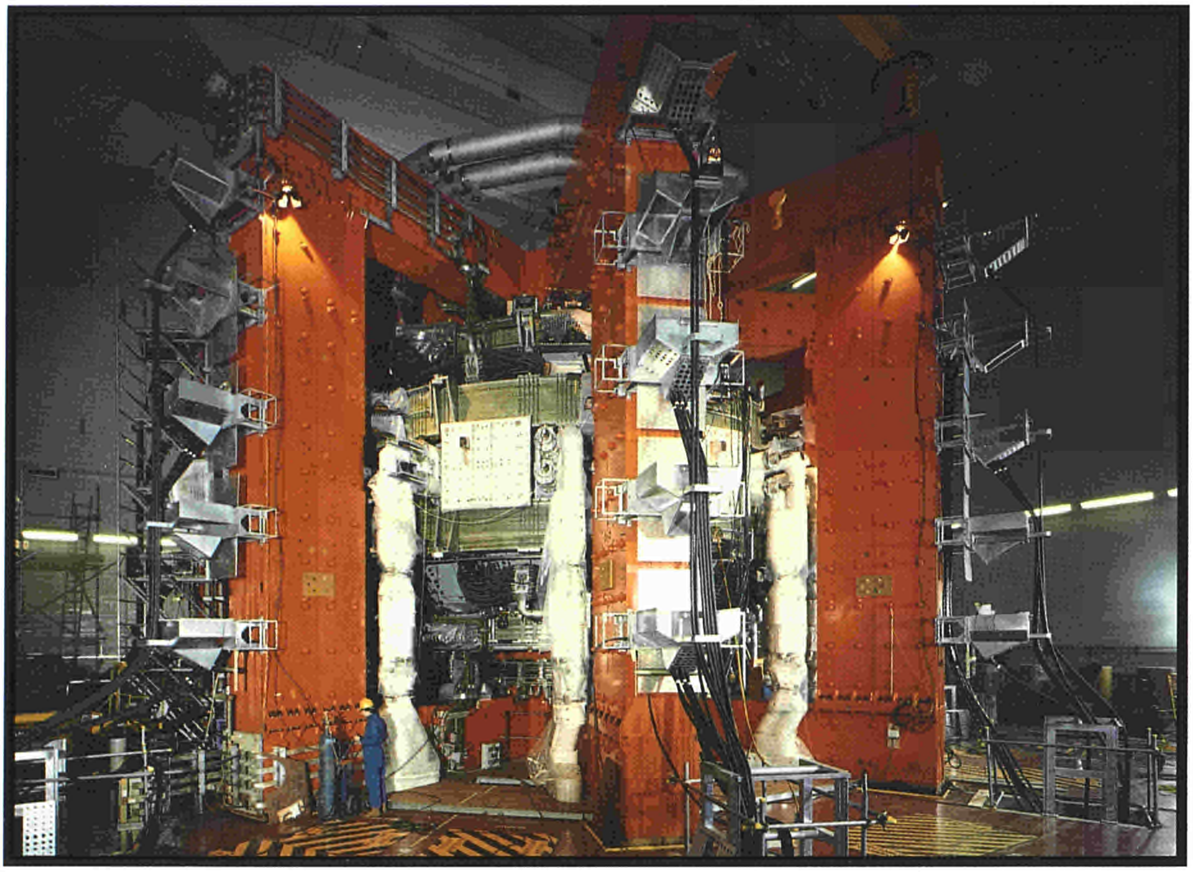


Fig.3: The JET experimental apparatus photographed in May 1983

positioning, shaping and stabilising the position of the plasma inside the vessel.

During operation large forces are produced due to interactions between the currents and magnetic fields. These forces are constrained by the mechanical structure which encloses the central components of the machine.

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

The construction phase of the Project, from 1978 to 1983, was completed successfully within the scheduled 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 1991 reached 22MW of power into the plasma. The neutral beam heating system was brought into operation in 1986, and exceeded its design capability in 1988, with 21.6MW of power injected into the torus.

Experiments have been carried out mainly using hydrogen or deuterium plasmas, although during 1991, experiments were performed in helium-3 and helium-4 and a preliminary experiment was performed using 10% tritium in deuterium. 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 produce significant heating of the plasma. During this phase, the machine structure will become radioactive to the extent that any repairs and maintenance would have to be carried out using remote handling systems.

The Community Fusion Research Programme

The long-term objective of the programme, embracing all activities undertaken in Member States (plus Sweden and Switzerland) in the field of controlled thermonuclear fusion by magnetic confinement, is "the joint creation of safe, environmentally sound prototype reactors". The long time span and the large human and financial efforts required before reaching this objective make necessary the total cohesion of the network of organisations associated in the Community action, as well as the full exploitation of co-operation with the large fusion programmes outside the Community.

A step-wise strategy towards the prototype commercial reactor is envisaged involving - after JET - a "Next Step", the first experimental reactor. The activities on the Next Step are concentrated on a tokamak, called ITER (International Thermonuclear Experimental Reactor). In July 1992, a quadripartite Agreement (involving Euratom

Heating

Initial production and heating of the plasma is produced by the large electric current flowing in the plasma itself (ohmic heating) used to generate the poloidal magnetic field.

The heating effect of this current is reduced as the plasma gets hotter as the electrical resistance of the plasma decreases with increasing temperature. Therefore, it is necessary to provide additional means of heating if the temperatures needed for a reactor are to be reached.

Two main additional heating methods are in general use:

(1) Neutral Beam Heating: In this method, a beam of charged hydrogen or deuterium ions is accelerated to high energies and directed towards the plasma. As charged particles cannot cross the magnetic field confining the plasma, the beam must be neutralised. The resulting neutral atoms cross the magnetic field and give up their energy through collisions to the plasma, thereby raising its temperature.

(2) Radio Frequency Heating: Energy can be absorbed by the plasma from high power radio-frequency waves. The frequency of operation is chosen to be close to that at which the ions or electrons orbit or gyrate in the magnetic field.

and the governments of Japan, the Russian Federation and the USA) "on co-operation in the Engineering Design Activities (EDA)" for ITER was concluded. The overall objective of ITER is "to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes". ITER would accomplish this objective by "demonstrating controlled ignition and extended burn of deuterium-tritium plasmas, with steady-state as an ultimate goal, by demonstrating technologies essential to a reactor in an integrated system, and by performing integrated testing of high heat-flux and nuclear components required to utilise fusion energy for practical purposes".

The Agreement further specifies that the ITER-EDA - to be conducted by the four ITER Parties under the auspices of the International Atomic Energy Agency (IAEA) and carried out by a Joint Central Team (JCT) located in three internationally staffed co-centres in San Diego (USA), Naka (Japan) and Garching (EU) and four Home Teams - should be implemented by two or more Protocols. Protocol 1 was defined to last 20 months at most after its signature (in 1992). To determine the best practicable way to achieve the overall programmatic objective of ITER, detailed technical objectives were established, from which followed by the end of 1993 the Outline Design of ITER. The ITER Council, in January 1994, considered the Outline Design report as "an acceptable basis for consideration by the Parties" to proceed towards the conclusion of Protocol 2: this Protocol, for one continuation of the ITER-EDA up to its end foreseen in 1998, is likely to be considered in March 1994. [Note: Protocol 2, covering the period up to completion of the ITER-EDA in July 1998, was signed on March 21st 1994]. The principal parameters of ITER are presently: I_p = 24MA, R = 7.7m, a = 3.0m, B_T = 6T and P_{fusion}= 1.5GW.

A staged approach to ITER operation is foreseen with:

- a basic operation phase for controlled ignited burn of D-T plasmas (1,000 seconds inductive pulse length, ITER design compatible with non-inductive current drive) and functional tests of blanket modules;
- an extended performance phase for tests with higher influence (target: $1MW/m^{-2}$) and the incorporation, if appropriate, of a breeding blanket.

The Next Step should provide an essential database for the design of a demonstration fusion reactor (DEMO) capable of producing

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.

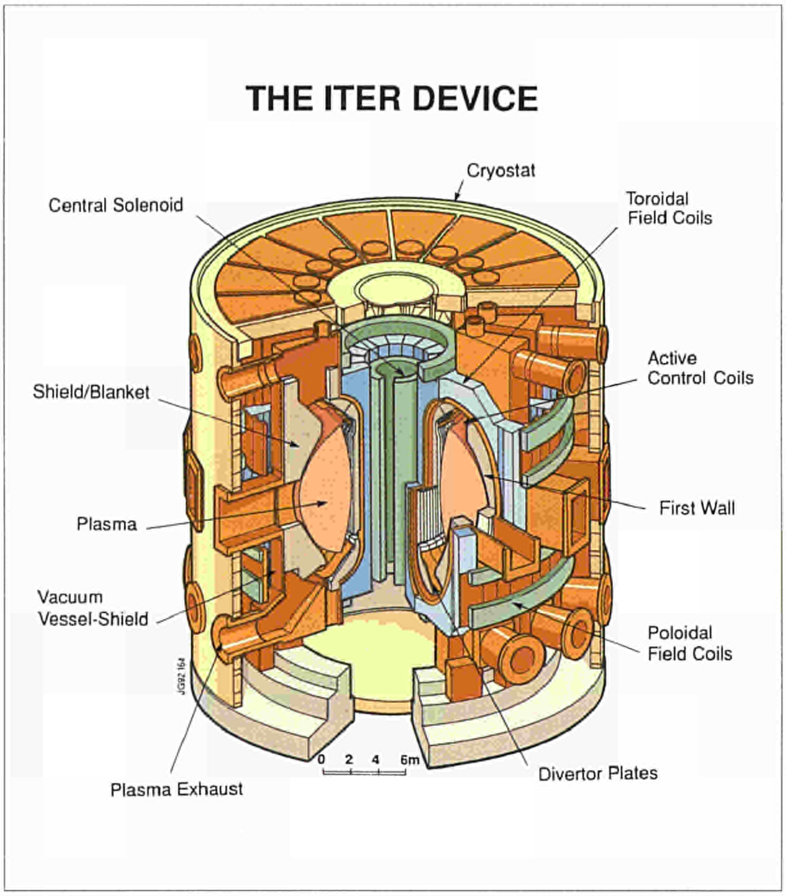
A measure of the overall impurity level is given by Z_{eff} which is defined as the ***average*** *charge carried by the nuclei in the plasma. A pure hydrogen plasma would have Z_{eff} =1 and any impurities in the plasma would cause this value to be increased. In JET, Z_{eff} is generally in the range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



Principal Parameters of ITER

Major Radius	*7.7m*
Minor Radius	*3.0m*
Elongation	*1.6*
Plasma Current	*24MA*
Toroidal Field	*6T*
Fusion Power	*1.5GW*
Burn Time	*1000s*

significant amounts of electricity while taking due account of environmental constraints.

In the frame of the current 1990 - 1994 Fusion Programme (Council Decision 91/678/Euratom of 19 December 1991, OJ No. L 375, 31-12 1991), the first priority objective is "to provide the scientific and technological base, to establish the environmental and safety criteria and to prepare industry for the construction of a Next Step device". For this purpose, a large fraction of the activities, including those on JET and within the Associated Laboratories, are in support of the Next Step. In particular the rationale behind the decision to prolong the JET Joint Undertaking until the end of 1996 was to establish in JET "reliable methods of plasma purity control in conditions relevant for the Next Step".

The scientific and technical achievements of the Community Fusion Programme place Europe in the forefront of world fusion research. Concentration on the most successful toroidal magnetic confinement line, the tokamak, and a few promising lines akin to it - while keeping a watching brief on inertial confinement fusion and on other approaches - continues to be fully justified by the results. The understanding of fusion physics has greatly improved, albeit a complete theoretical picture of important physical phenomena is still lacking. Systems were developed for heating plasmas to thermonuclear temperatures as well as for plasma fuelling and control; also powerful diagnostics for relevant plasma parameters were developed. Following a major shutdown for the installation of four divertor coils and the Mark I divertor structure, as well as the upgrading of the current drive and other systems, the commissioning of JET was amost completed by the end of 1993. The NET (Next European Torus) Team pursued its Next Step related activities, in particular in assisting the Euratom Home Team (HT) Leader in the performance of his duties and responsibilities in the ITER frame. In the Associated Laboratories, the specialised devices have made crucial contributions to the development of the physics base for ITER and DEMO. These explore, in support of the main objectives of the programme, the accessible parameter range and the possible modes of operations for the different confinement concepts and configurations. Furthermore these devices provide test beds for the development of new concepts and techniques for plasma engineering and wall technology. These also serve for fundamental fusion physics studies, for the development of diagnostics, for the preparation of collaboration on larger devices, for innovative studies and for the training of young professionals, and these are the links which allow the incorporation of university research into theoretical, numerical or diagnostic activities.

The European Commission, assisted by the Consultative Committee for the Fusion Programme (CCFP) composed of national representatives, is responsible for the implementation of the Fusion Programme. The Programme operates principally through: the JET Joint Undertaking; NET and the ITER-EDA Agreements covering the Next Step activities; Contracts of Association with organisations in, or with, Member States (plus Sweden and Switzerland); shared-cost contracts in countries having no Association, and in industry. The Joint Research Center (JRC), through its own programme, conducts research in specific areas of fusion technology in close collaboration with the Fusion Programme.

The Community approach has led to an extensive collaboration between the fusion laboratories. For example, most Associations undertake work for other Associations. The Associations are partners in JET, NET and ITER and carry out work for them through various contracts and agreements. The Programme has built across Europe a genuine scientific and technical community of large and small laboratories, readily able to welcome newcomers (as it will be the case with the enlargement of the European Union), and directed towards a common goal. Indeed, two non-Member States, Sweden and Switzerland, have been fully associated with the Programme since 1976 and 1979, respectively. The leading position of the Community Fusion programme has also made Europe an attractive partner for international collaboration. Apart from the most far-reaching collaboration illustrated by the ITER project, bilateral Framework Agreements have been concluded (with USA and Japan) and are in preparation (with Russian Federation). Also, a Memorandum of Understanding with the government of Canada for bilateral collaborations is being renewed; it covers, inter alia, the involvement of this country in the Euratom contribution to the ITER-EDA. Finally, there are eight Implementing Agreements in the frame of the IEA (International Energy Agency) and a ninth in preparation.

In March 1994, the CCFP concluded an assessment concerning the evolution of the Programme in the medium term. In particular, the CCFP was of the opinion that:

- The Community Fusion Programme should continue strongly to support ITER and prepare for its possible siting in Europe. For maintaining the ability to construct a Next Step in Europe and to increase industrial involvement, the Next Step related technology part of the Programme should be increased beyond the work needed directly for the European share of ITER;
- JET is expected to complete its present mission in 1996. However, there are substantial new scientific and technical arguments, in particular for the benefit of ITER, for a continuation of JET's operation beyond 1996;
- The strategical role of the stellarator project W 7-X (whose scientific and technical aspects had already been positively assessed by the CCFP) is now recognised, as W 7-X appears to be

Breakeven

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

Ignition

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

the right step to be taken for the evaluation of the potential of the stellarator line;

- Safety and environmental aspects of fusion remain the essential issues for orienting the long-term technology part of the Programme in order to make fusion socially acceptable.

Currently, Community funding of fusion research exceeds 200 MioECU per year. When funding by national administrations and/or bodies is taken into account, the expenditure on fusion from all sources in Europe amounts to ~450 MioECU per year. About 1,750 professional scientists and engineers are currently engaged in fusion research in Europe. In the frame of the 1994-1998 Euratom Framework programme for research and training. the envelope for fusion activities (JRC included) amount to 840 MioECU.

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 certain instabilities developing on specific magnetic surfaces.

Large International Tokamaks

Now that the ITER Engineering Design Activity (EDA) has started, achievements in tokamak research and, particularly, for the largest tokamaks (Fig.4), have become even more relevant. Table 2 sets out an overview of the large tokamaks, including their main parameters and starting dates. Considerable progress has been made by these tokamaks throughout the world, and these are detailed below.

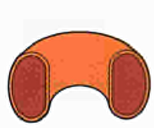
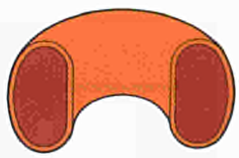
		TFTR	JET	ITER
				
MINOR RADIUS	a	0.85m	1.25m	3.0m
MAJOR RADIUS	R	2.5m	2.96m	7.7m
ELONGATION	κ	1.0	1.8	1.6
TOROIDAL FIELD	B	5.2T	3.45T	6.0T
INPUT POWER	P	32MW	36MW	30-200MW
FUSION FACTOR	Q_{DT}	0.3	1.1	30 - IGNITION
PLASMA CURRENT	I	3MA	7MA	24MA

Fig.4: Operating parameters of three large tokamak designs

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	1.25	1.8	2.96	7.0	3.5	36	1983
JT-60U	JAPAN	0.85	1.6	3.2	4.0	4.2	40	1991
TFTR	USA	0.85	1.0	2.50	3	5.2	32	1982
TORE-SUPRA	FRANCE	0.80	1.0	2.4	2.0	4.2	22	1988
T-15	CIS	0.70	1.0	2.4	2.0	4.0	-	1989
DIII-D	USA	0.67	2.5	1.67	3.0	2.1	22	1986
ASDEX-U	GERMANY	0.5	1.6	1.65	(1.6)	3.9	(15)	1991
FT-U	ITALY	0.31	1.0	0.92	1.2	7.5	-	1988

Table 2: Large Tokamaks operating around the World

Peak Performance

The highest peak performance, measured by the triple product of ion density, energy confinement time and central ion temperature ($n_D \cdot \tau_E T_i$) has been narrowly taken over by JT-60U, the large Japanese machine, in which a value of $11 \times 10^{20} m^{-3}$keVs was obtained. Peak values achieved are set out in Table 3 for the largest tokamaks.

The duration of the high performance phase in these different machines depends on various mechanisms. In JET and TFTR, the wall loading possibly together with certain instabilities related to the high plasma pressure limit the good confinement period. In JT-60U, the high performance appears to be limited by fast relaxations due to the

MACHINE	JET	JT-60U	TFTR	DIII-D
ELECTRON TEMPERATURE T_e(keV)	11	12	9	6
ION TEMPERATURE T_i(keV)	18	38	29	5.5
DURATION (s)	1.5	0.7	0.2	0.5
FUSION PRODUCT $n_i T_i \tau_E$ ($\times 10^{20} m^{-3}$keVs)	>9	11	4.6	5

Table 3: Fusion Products in Large Tokamaks

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.

high pressure only. However, wall loading is likely to become a major issue in the next generation of machines.

Advanced Divertor Concepts

It is now clear that a divertor is likely to provide a solution to the problem of impurity production and exhaust, on route to a tokamak reactor. The key concept of a divertor is to use magnetic fields to divert plasma particles along a channel towards target plates. The plasma flow will confine the impurities in front of the target plates. The result is a low temperature, high density plasma which will shield the target plates from the incident power and will eventually reduce the production of impurities.

A cryopump, installed close to the target plates, will help to remove impurities. The flow of plasma towards the target plates will be enhanced by refuelling by pellet injection in the so-called X-point region, where there is a null in the magnetic field.

If the target tiles in a divertor receive the full power of an ignited reactor, the power loading would exceed $40MWm^{-2}$, in excess of acceptable levels of $<10MWm^{-2}$. Several forms of advanced divertors are emerging, generally involving closed divertors with large active cooled areas. This allows for impurity retention as well as a high divertor density, so that most power entering the divertor can be radiated before it hits the target plates and so can be absorbed over a much larger area. In JET, future divertor plasmas heated with up to 22MW power could be thermally stable, maintained at high density with more than 90% of the power radiated.

Progress in Technology and Plasma Control

Reliable operation at high current without disruptions has made considerable progress. The highest plasma current of 7MA has been reached in JET with 28MW plasma heating for a duration of 8s. MHD activity is carefully avoided by programming the plasma cross-section during the current rise to avoid dangerous rational safety-factors at the plasma boundary. In several cases (TORE-SUPRA and JET), the plasma inductance has been controlled using Lower Hybrid Current Drive (LHCD). DIII-D(USA) has compensated errors in the magnetic fields to allow for low density operation.

Large machines, such as JT-60U(Japan) and JET, have developed disruption control tools which detect a disruption precursor and then act on plasma parameters to ameliorate further development of the instability.

TORE SUPRA (France) and Triam-IM (Japan) have both operated reliably at nominal performance with superconducting toroidal magnetic field coils and have made progress towards steady state operation.

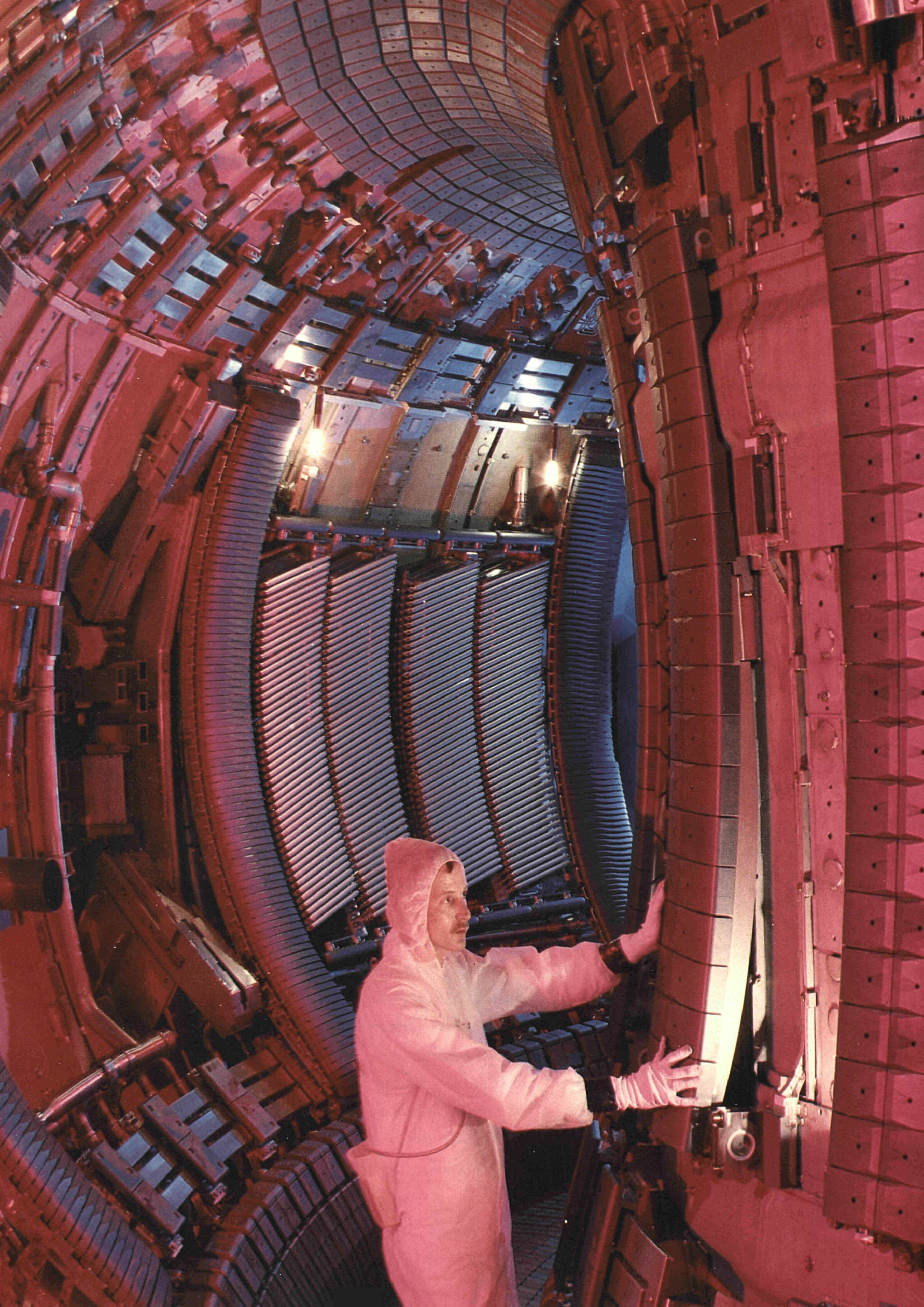
Tritium Experiments

The first successful tritium experiment was carried out in JET in 1991. Up to 10% tritium was used, which produced a peak fusion power of about 1.7MW in a pulse lasting for 2 seconds, giving a total energy release of about 2MJ. This was a major step forward in the development of fusion as a new energy source. The tritium concentration was limited to 10% to minimize the activation of the vessel. Tritium experiments were also carried out in TFTR during December 1993 and will be continued until September 1994. 50% tritium and 50% deuterium plasmas, in the so-called "super-shot" regime, at 2MA and 5T, were heated by 30MW of neutral beam power. By the end of 1993, TFTR had achieved fusion power of 6.4MW for a period of about one second. The aims of TFTR are to produce 5-10 MW of fusion power, and to investigate alpha-particle physics and detect initial evidence of subsequent heating. On completion, the TFTR machine will be closed and then decommissioned.

The JET programme includes up to one year's operation at full power with plasmas of 50% deuterium and 50% tritium in the new divertor configuration immediately prior to its closure at the end of December 1996. The programme will be directed at the physics of alpha-particle production, confinement and heating. Key additional information will be generated from experience of tritium operations on a reactor relevant scale - tritium retention, remote maintenance and plasma diagnostics with large neutron backgrounds. This experience of D-T operation in a reactor scale tokamak should provide information essential for ITER design and construction.

An Active Gas Handling System has been constructed to store and process tritium used in JET. The system will collect exhaust gases from the torus and fuel injectors using cryogenic pumps, which will permit the separation of unreactive hydrogen, deuterium and tritium from impurities by a cryo-distillation process. The deuterium and tritium will then be stored as metal hydrides ready for re-injection. JET has also developed a wide range of sophisticated remote handling systems to provide a complete maintenance, repair and modification facility of the activated machine.

The JET programme will therefore not only provide a sound scientific basis for the construction of the Next Step Experimental Reactor (e.g. ITER) but also give practical experience in the two key areas of tritium handling and remote handling technology.



Technical Status of JET

Introduction

At the beginning of 1993, JET was still in the midst of a major shutdown to undertake major modifications and changes for operation in the Pumped Divertor Phase of JET. This shutdown had started in February 1992 and is due for completion in January 1994. This is the largest and most complicated shutdown undertaken on JET.

The main objective of the major shutdown was to install an axisymmetric pumped divertor inside the vacuum vessel, together with all necessary auxiliary equipment. This facility will assist the aim of establishing in deuterium plasmas "reliable methods of plasma purity control under conditions relevant for the Next Step Tokamak". The main components of the divertor are, as follows:

- the four poloidal coils can create a variety of magnetic configurations, with the X-point far away from the target plates, and includes the capability of X-point sweeping to spread the thermal load. The coils are contained in a 1.2mm thick inconel casing, on which the rest of the divertor components are installed;
- the target plates, arranged in a U-shaped contour, collect the power released from the plasma. These consist of an inertially water-cooled structure, which support carbon fibre composite (CFC) tiles, accurately shaped to maximise the power wetted surface. The CFC tiles will be replaced later with beryllium tiles, for comparison of plasma performance;
- the toroidal cryopump should allow control of plasma density in the divertor region. It is anchored to the outer coil casing and its main components are a water-cooled baffle, a liquid nitrogen cooled

copper backed panel, a set of helium cooled pipes and a chevron structure.

The new plasma shapes of the divertor configuration has required a complete re-design of the vacuum vessel first wall to accommodate 'fat' plasmas, which maximise plasma cross-section and more elongated 'slim' plasmas, which allow configurations with enhanced connection length. Limiters are still required for plasma start-up and as protection for the ICRF antennae. The existing belt limiters were replaced with a new set of twelve discrete poloidal limiters on the outer wall and sixteen guard limiters on the inner wall, all covered with graphite tiles. The shutdown was undertaken in three major stages:

- Stage 1 involved the removal of components and preparation of the vacuum vessel for installation of the divertor coils (February - September 1992);
- Stage 2 involved assembly of the four divertor coils and casings inside the vacuum vessel (October 1992 - May 1993);
- Stage 3 involved installation of the Mark I inertially-cooled divertor, cryopump, RF antennae, limiters and saddle coils (May 1993 - December 1993).

Prior to commencing Stage 3, the inside of the vessel was thoroughly cleaned by blasting with frozen carbon dioxide pellets. Stage 3 of the shutdown then began in late May, with the installation of coil support structures. The coils were then set in their final position.

The shutdown was almost completed by the end of 1993. Upon completion, the inside of the JET vessel will have been almost completely rebuilt and JET will be effectively a new machine. JET will then be in a position to begin its programme of operations to demonstrate effective methods of power exhaust and impurity control in operational conditions close to those envisaged for ITER, before the final phase of full D-T operations.

The following sections detail the technical achievements made during 1993.

Technical Achievements

Installation of Divertor Coils

The purpose of the JET coil system is to establish, maintain and control the tokamak plasma configuration (Fig.5). It includes the toroidal coils, which establish the toroidal magnetic field, the poloidal

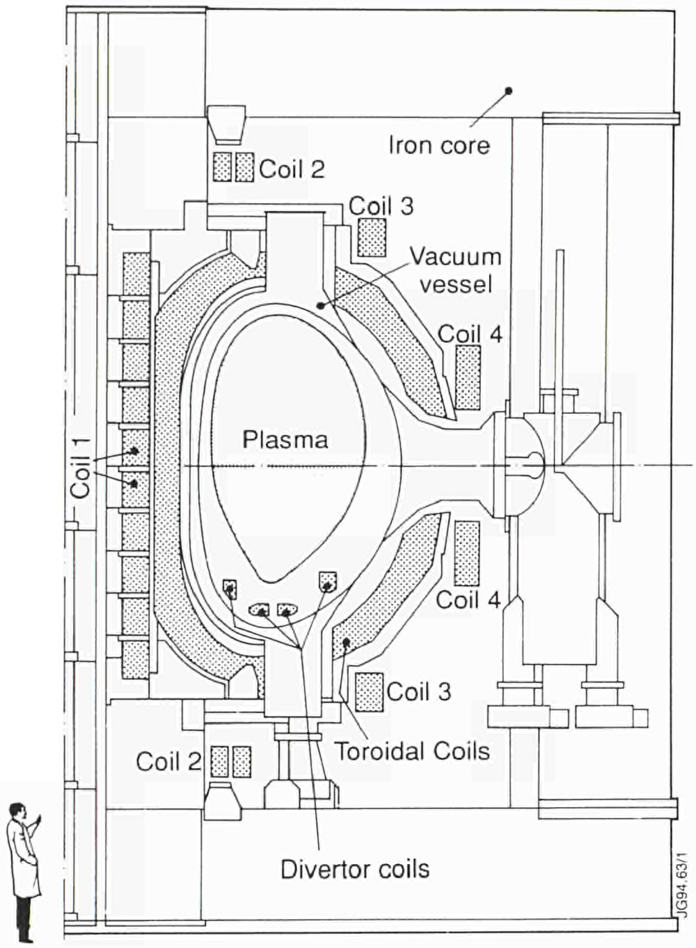


Fig.5: Cross-section of JET showing toroidal, poloidal and divertor coils

coils P1, acting as primary windings of the tokamak transformer, and coils P2, P3 and P4 to control plasma radial position, vertical position and shape. The main work for the shutdown was to install the divertor coils D1, D2, D3, D4 inside the vacuum vessel. These coils will now be an integral part of the poloidal system and, in conjunction with existing coils, will establish and control the new divertor magnetic configuration.

The four divertor coils were assembled, brazed and impregnated in the JET vacuum vessel (Fig. 6), a confined environment, where equipment and materials could only be introduced through narrow ports of about 0.5m^2. Difficulties caused by safety and prevention of contamination, both inward and outward, were successfully overcome.

Fabrication started at the end of October 1992 and was completed by mid-May 1993. The work comprised fabrication in-situ (using prefabricated sections) of divertor coil casing Nos:1, 2 and 4,

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 a JET pulse, the rotor windings are energised and the rotational energy of the flywheel is converted into electrical energy. On slowing down from the maximum speed of 225rpm to half speed, the generators can reach deliver 2.6GJ of energy with a peak power output of 400MW.

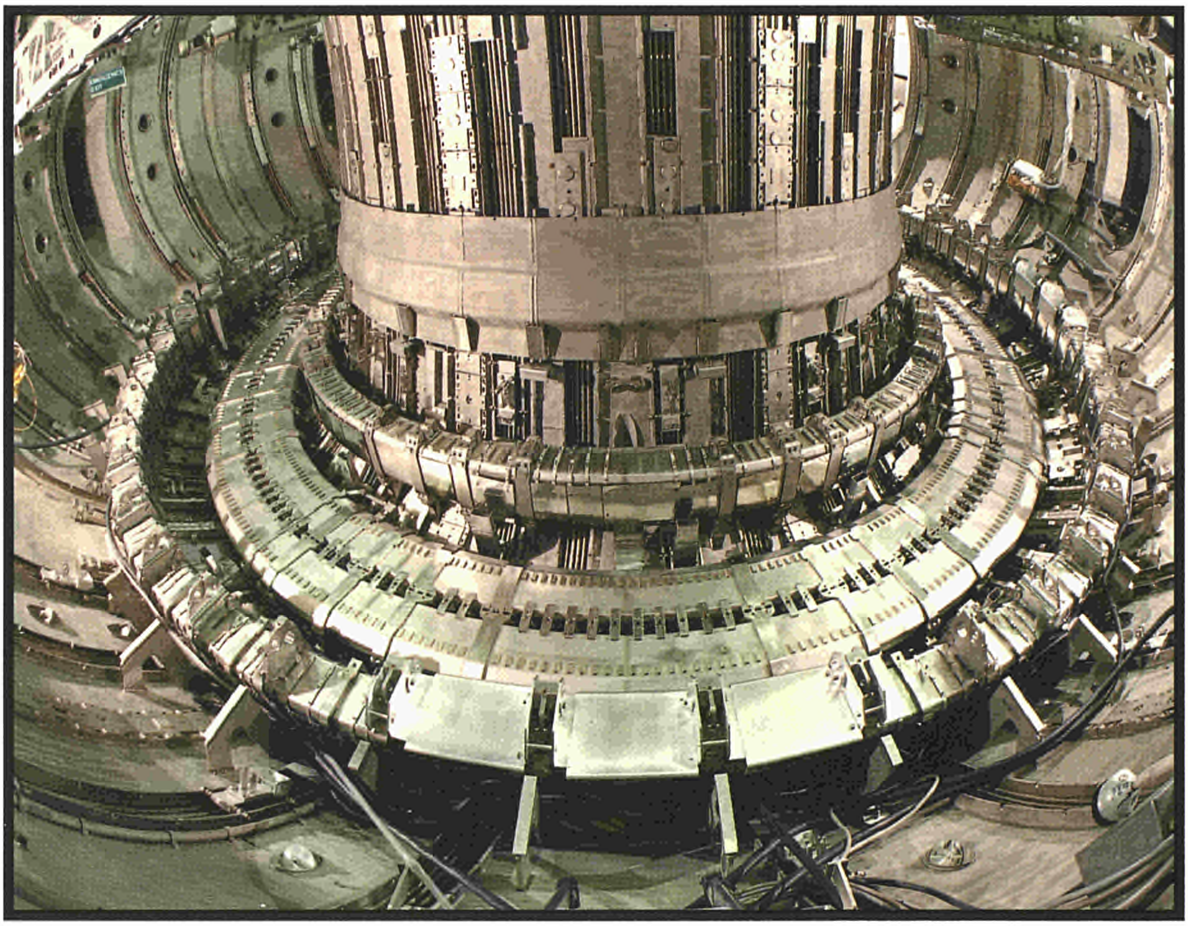


Fig. 6: Positioning of four divertor coils in the vessel

followed by storage of the lower part of the casings below floor level and the lids near the vessel ceiling. Fabrication and storage of Case No:3 at this stage would have limited the handling of prefabricated conductor bar sections to such an extent that sections would have had to be cut shorter and would have involved an increased number of brazed joints. Therefore, Case No:3 was fabricated after completion of brazing. After fabrication of the casings, the coils were formed by brazing prefabricated conductor bar sectors inside the vessel. This involved the making of about 200 brazed joints (Fig.7), which were checked by radiography. Following brazing, the coils were wrapped with insulation and then encased. The interspaces were filled with epoxy, and subsequently thermally cured. After completing Coil Nos: 1 and 4, Coil Nos: 2 and 3 were fabricated in parallel and Coil Case No:3 was built in the vessel following the encasing of Coil No:2.

The main differences in the divertor coil production compared with a conventional process in factory, besides the restricted space

Fig. 7: Brazing jig and brazing coil mounted on a joint

and the controlled environment, were: brazing of curved bar joints with jigs of minimal dimensions and weight assembled on each joint with required geometrical accuracy; tight pressure and X-ray tests of each joint; epoxy impregnation and curing inside the casing, which prevented observation of results; impregnation over-pressure limited to 300mbars (instead of 4-5 bars) due to the thin inconel casing; and the curing process by heating the coil conductors electrically.

Not surprisingly, some problems were encountered in these processes. During the fabrication of Coils No: D1 and D4, the rate of failure of the brazed joints (at 20%) was considerably higher than expected. The reason was the inconsistent pressure on the joints, due to unsatisfactory and degrading performance of the brazing jigs. Subsequently, these were modified and recalibrated and this led to a failure rate for Coils D2 and D3 of less than 5%. A second problem became apparent after completion. When removing the resin pipes, it was discovered that, in some areas, the resin between the coil and the casing was not fully cured. Since the coil-casing system had to be an accurate reference for the installation of the other divertor components, a re-curing cycle was devised. This process was completed successfully during Stage 3 of the shutdown.

The coil installation work was completed by May 1993, which was a major achievement. It is believed that this is the first time that full manufacture and assembly of coils had been undertaken in such a confined space, and the work was undertaken to demanding standards to ensure the highest reliability during subsequent operations.

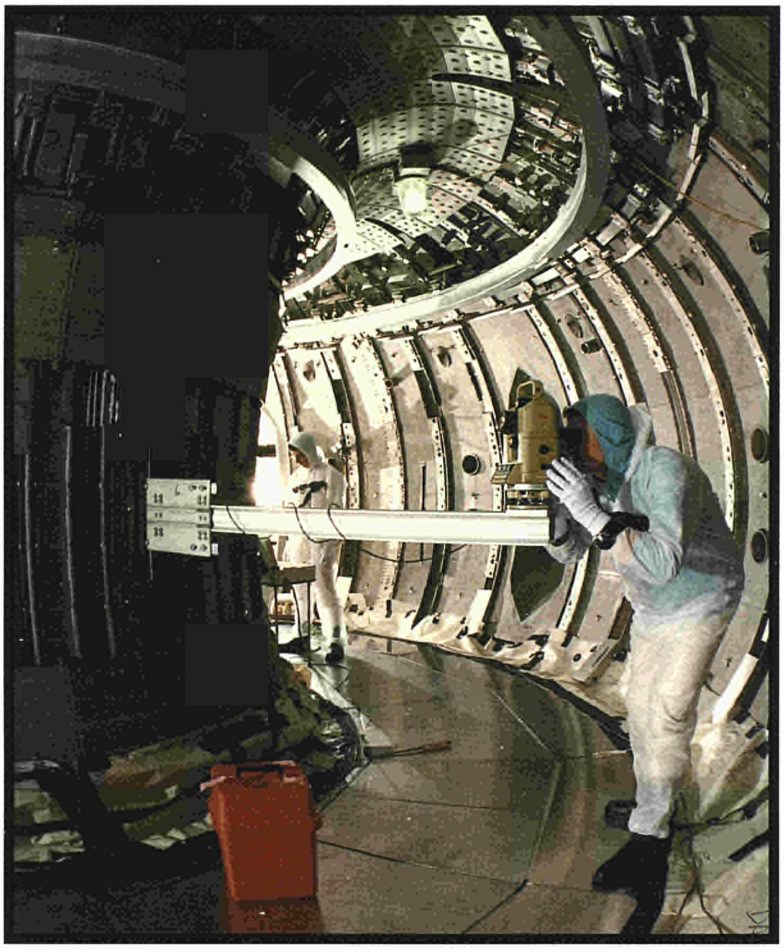


Fig. 8: Electron Coordinate Determination System (ECDS) in use

Installation of Divertor Components

The installation of new divertor components inside the vacuum vessel (Stage 3) was started in May 1993 and was virtually completed by the end of 1993. The first action was to clean the inside of the vessel, and the process selected consisted of blasting the vessel walls with a cold jet of carbon dioxide pellets. The mechanical and thermal shock of the blast embrittled and dislodged the contaminating film, which was then removed by vacuuming. Subsequent tests confirmed the effectiveness of the blasting process.

The next operation was the positioning of the four divertor coils within the torus (Fig. 6). Using datum references set inside the vessel with respect to the magnetic axis of the torus, it was possible to position the coils concentric to each other and at a pre-established radial and toroidal positions. Once in position, the coils were connected by clamps linked to supports welded on the vessel.

During the shutdown, it became clear that it would be impractical to set and align all components using jigs and fixtures due to the

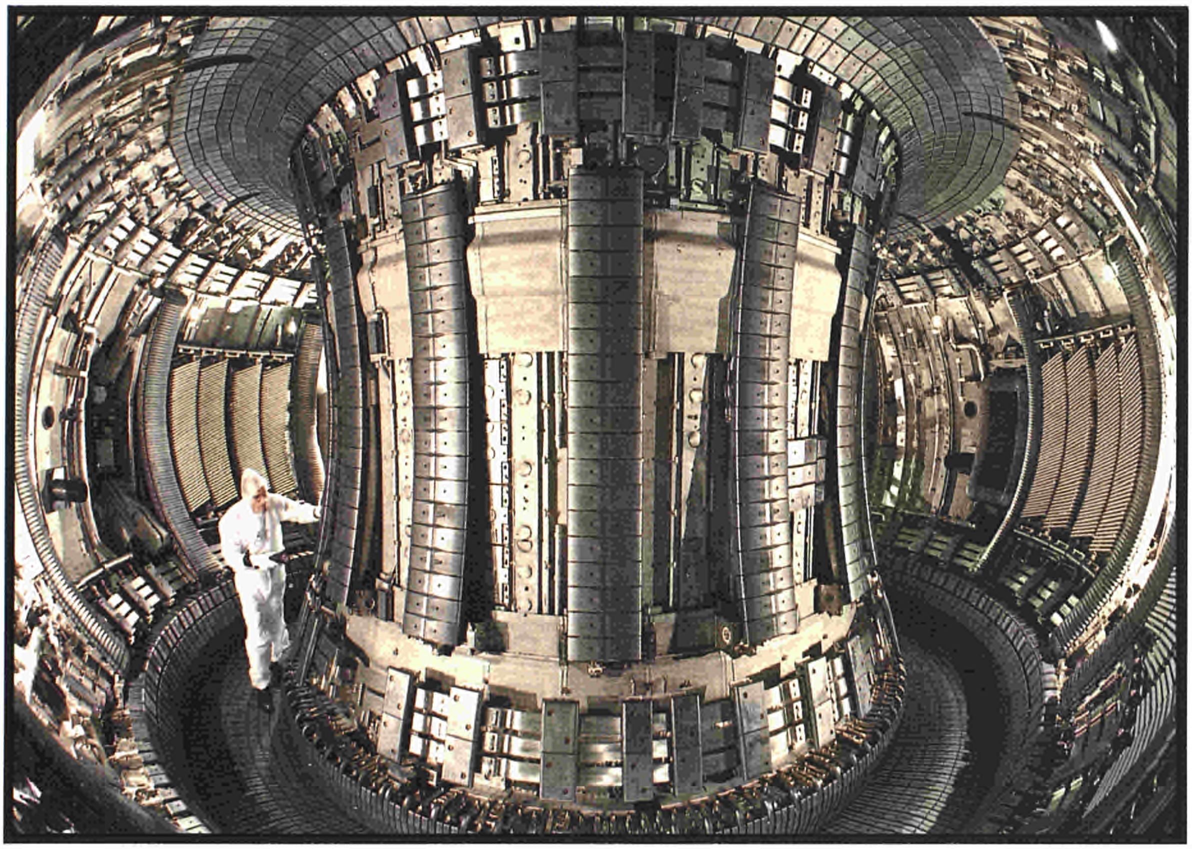


Fig. 9: Inside of vessel after completion of installation of components

long manufacturing time needed to produce very complicated and high precision jigs; and the long time required for the in-vessel surveys. Consequently, following a detailed study, an Electronic Co-ordinate Determination System (ECDS) was used. The ECDS system consists of two electronic theodolites linked to a computer, and can measure horizontal and vertical angles of targets. Software then solves resulting equations to find the 3-D coordinates of any given point to a precision of about ±0.3mm (Fig. 8). The system underwent an intensive period of trials to develop a method suitable for use in-vessel, and to prove its accuracy and reliability. It was then used successfully in the vacuum vessel for setting and measuring the major components - antennae, limiters, coils, and diagnostics. The positions of all major plasma facing components were measured to high precision and with the same reference.

Installation of the divertor target plate modules required extensive preparations due to the large number of surveys and associated machining of tailored parts. In fact, the installation of the modules represented the pinnacle of the entire shutdown, as it was then that the major components were linked together and the required very high accuracy had to be achieved. The 48 target plate modules were set on to inner and outer rails welded on to 640 pads and 32 clamps on the casings of Coils No. 2 and No. 3. Each of these parts were surveyed for height, tilt and toroidal position in order to machine each of the rails in such a way as to take into account any misalignment due to fabrication and installation errors of coils and casings. To connect the water manifolds to divertor modules, 192 automatic orbital pipe welds were performed and leak tested. The final survey of the assembled modules showed an average step between each horizontal beam of ~0.3mm, with the maximum step not exceeding 0.7mm.

Tile covered limiters are still required for plasma start-up and as protection for the ICRF antennae. The existing belt limiters were replaced with a new set of twelve discrete poloidal limiters on the outer wall and sixteen guard limiters on the inner wall, all covered with graphite tiles. The inside of the vessel on completion of the installation of in-vessel components is shown in Fig.9.

New Coil Protection System

Due to the complexity of the new magnetic coil system, a new Coil Protection System (CPS) has been designed, which will protect the coils against: electrical faults; and electrical, mechanical or thermal over-stressing due to operation outside safe limits.

Electrical faults are detected by comparing the actual electrical performance of the coils with a circuit model run in real time. Electrical, mechanical and thermal stresses are computed from the currents flowing and voltages applied to the coils. If acceptable values for any of these parameters are exceeded, the pulse will be terminated. The protection system is implemented fully digitally using a high performance digital signal processor.

The radial and vertical forces on the outer poloidal coils P2, P3 and P4 and the vertical forces on the divertor coils are computed using fluxes measured by coil mounted flux loops and measured ampere-turns. It was not possible to fit vertical flux loops on the divertor coils so that radial forces acting on these coils will be computed analytically. The tensile and shear stress of each coil is computed as a linear combination of vertical force, radial force and

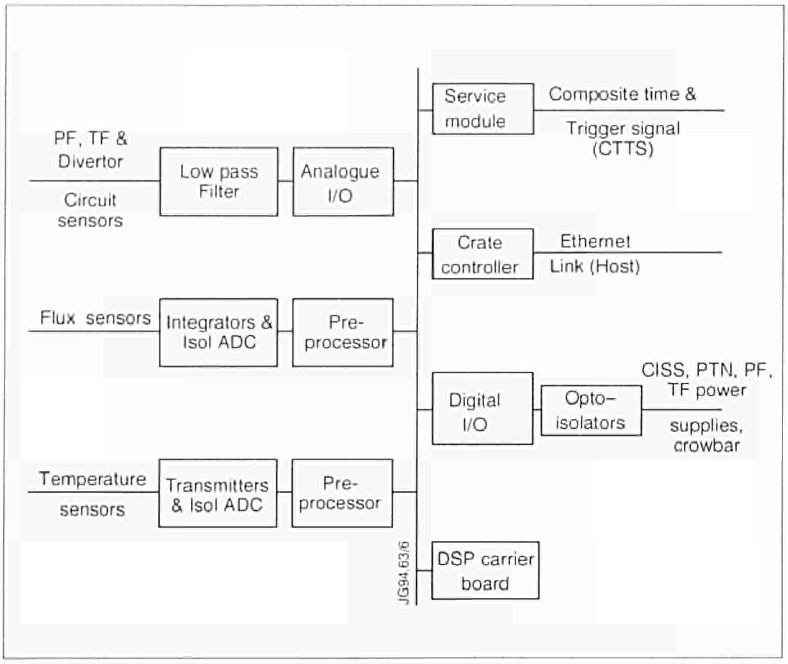


Fig. 10: Hardware configuration of the Coil Protection System

temperature. A simple model will be used to estimate the temperatures of the epoxy insulation and copper windings of the divertor coil. The inputs to the model are the vessel temperature, coil case temperature, coil currents, coolant flow and coolant inlet and outlet temperatures.

The object of the protection system is to keep the epoxy glass insulation in the main body of the coil below a safe temperature (60°C). To limit the thermal stresses between coolant inlet and outlet temperatures to 20°C, this temperature difference is monitored by the system. The system configuration is shown in Fig.10.

Measurements or computed quantities are compared with suitable thresholds. If a threshold is exceeded an alarm is generated and protective actions are taken. Detectable faults include: over-voltage, over-current, power too high, excessive shear or tensile stress, and temperature exceeded. Possible direct actions include Firing Pulses Block, Circuit Breaker Trip (CBT) and closing the crowbar. On a slower timescale, the direct actions are backed-up by the Pulse Termination Network and the Central Interlock and Safety System.

Plasma Control

Due to the enhanced asymmetry of the plasma in the new divertor configuration and to the strong coupling with the divertor coils,

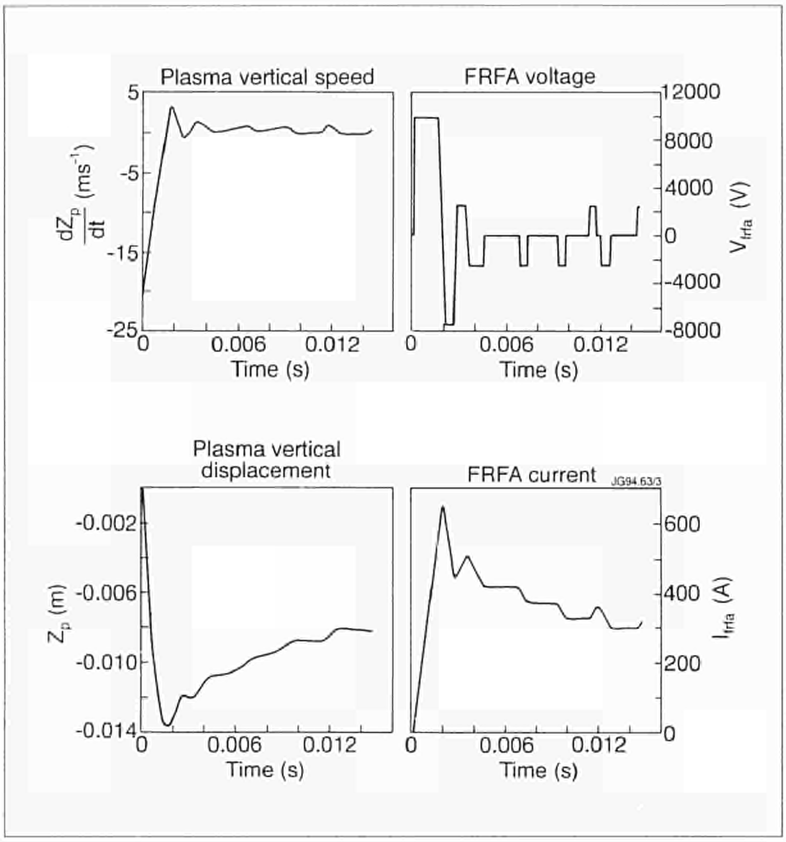


Fig. 11: Simulated response upon a force disturbance in a 6MA plasma

reconsideration of essential plasma and machine control and protection was necessary. Disruptive instabilities frequently lead to loss of vertical position and, consequently, to larger vertical plasma displacements (which can be up to 1m). The associated vertical force acting on the vessel is large at high plasma current and when large shaping currents are applied, such as in single or double-null configurations. The vertical instability produces potentially dangerous forces on in-vessel elements such as protection tiles. Consequently, a new Plasma Position and Current Control (PPCC) has been introduced which provides feedback control of the plasma current and of the position and shape of the detached divertor plasma, and stabilisation of the highly unstable vertical plasma position.

The vertical position of the divertor plasma is unstable, and simulations indicate that instability growth rates can be up to $10^3 s^{-1}$. The previous analogue stabilisation system had been replaced by one which employs a Fast Radial Field Amplifier (FRFA) and a fast digital signal processing and controller unit. Stabilisation is achieved by feedback of the vertical displacement speed of the current centroid, weighted with the plasma current. The plasma feedback signal is

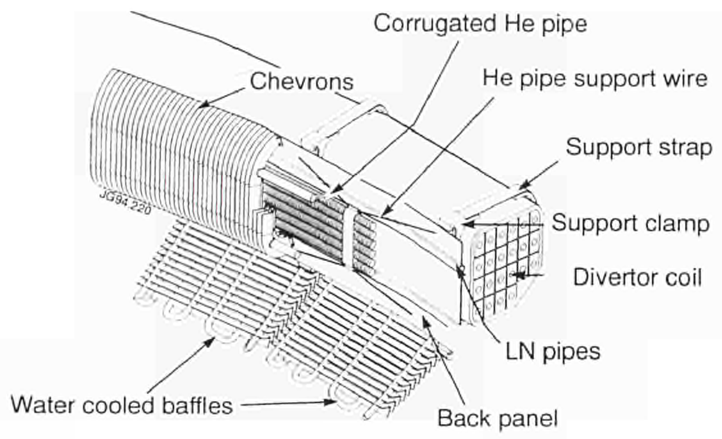


Fig.12: Divertor cryopump

derived from a non-integrated sub-set of the magnetic signals. A proportional/integral feedback of the FRFA current signal stabilises this current around zero at longer time scale. The vertical plasma position is defined by the shape control system.

The expected performance has been assessed on the basis of a simplified model of the plasma. One question of interest is the response to rapid displacement such as may occur in giant sawteeth and disruptions. Figure 11 shows an example of the simulated response upon an assumed rapid force perturbation in a 6MA plasma with open loop growth rate of $850s^{-1}$. The control system will be subject to early tests during operation in 1994.

Cryopumps and Cryoplant

An integral part of the divertor is a large cryocondensation pump shown schematically in Fig.12, which extends over the full toroidal length of the outermost divertor coil, and which also acts as the mechanical support. The tokamak environment is very hostile for a cryopump, not only in terms of electromagnetic forces, but also in relation to thermal stresses which can be generated during the normal high temperature operation of the vacuum vessel. In addition, various accident scenarios, such as uncontrolled loss of cryogens, loss of torus vacuum, and loss of water cooling could lead to large thermal stresses in the cryopump.

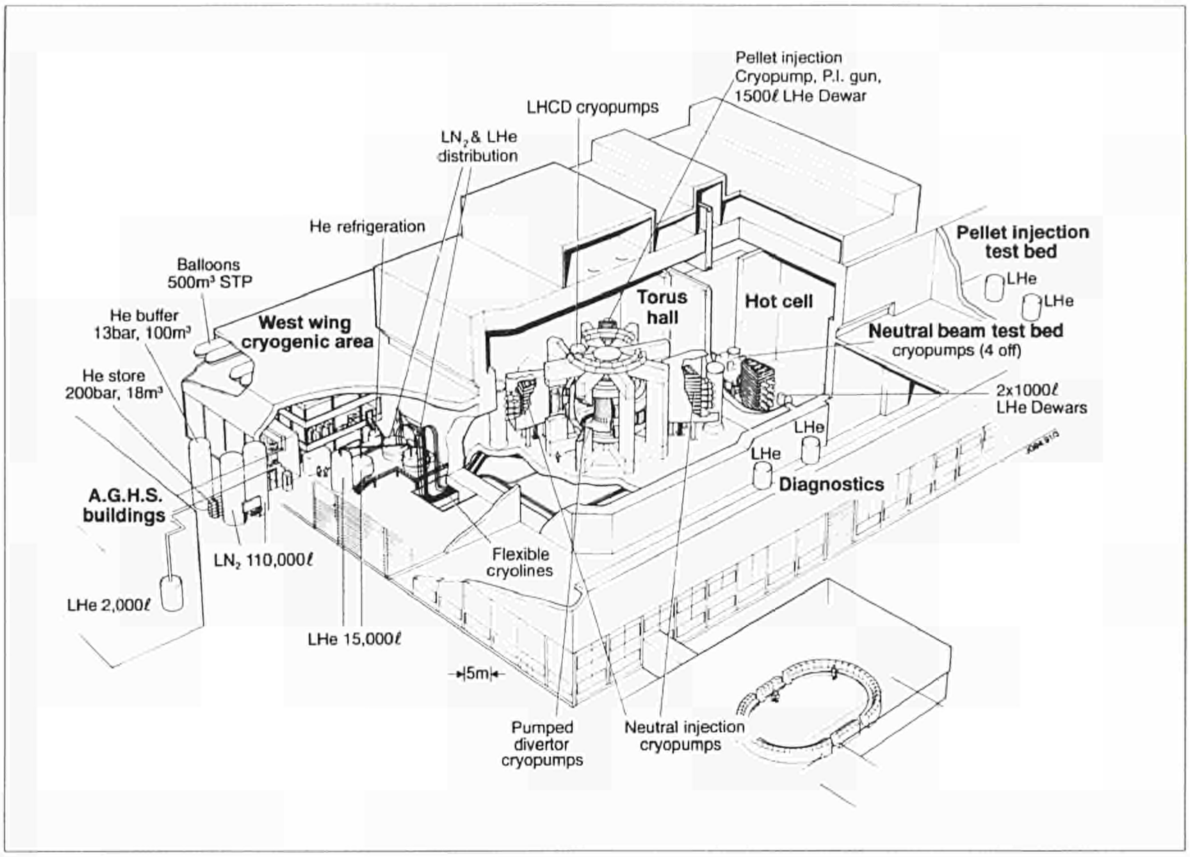


Fig.13: Overview of the upgraded Cryo-Plant

The design of the pump must also cope with uncontrolled cool down, baking and requires high reliability. It has a number of novel features which are of special interest, such as flexibility to cope with thermal stresses during accidents, support systems robust enough to deal with eddy current stresses and with the requirements to minimise consumption of cryogens. The eddy currents are directed towards preferred routes to minimise stresses, whilst the difficulties associated with sweeping the interaction zone of the plasma across the divertor target, a potential source of severe eddies from the current variation in the divertor coils, is not a problem in the toroidally discontinuous pump. Unstable flow regimes are avoided by use of supercritical liquid helium in a serial arrangement.

Manufacture and assembly presented a particular challenge. Special vacuum brazing techniques had to be developed. In vessel installation and welding were difficult in view of the relatively large tolerances of the complicated and restricted geometry which defined the environment of the pump. The very demanding task of installing these components inside the torus was carried out as planned within the two weeks of allocated time, due to very detailed preparation and planning of in-vessel procedures and activities.

In addition, the cryo-plant system has undergone an extensive upgrade of the nitrogen system and helium plant, due to an increase in the number of cryogen users by a factor of two. An additional new helium refrigerator was being commissioned prior to full integration into the existing plant. The original helium liquifier has been overhauled and is back in operation. Components for the extension to the liquid and gaseous nitrogen distribution system have also been integrated into the existing system. An overview of the cryoplant and its major users is shown in Fig.13.

Neutral Beam Heating

During the shutdown period, the neutral beam systems have been modified and upgraded. Some injectors have been converted to the new high current 80kV configuration originally developed for the Preliminary Tritium Experiment. Eight of these have been installed on the beam system at Octant No.4, which should now be capable of delivering in excess of 12MW of deuterons at 80kV. The Octant No.8 beam system will operate at 140kV.

The decision to revert to operating one injector at 80kV and one at 140kV, to increase both the injected power and overall flexibility for the next campaign, required an extensive programme of injector conditioning and qualification on the Testbed. Six injectors were modified from the 140kV three-grid configuration to the four-grid high current configuration. This differs from the original 80kV configuration previously installed by having reduced extraction and accelerator gap spacings to increase the extracted total beam power.

The beam system at Octant No.8 has been brought up to the specification of that at Octant No.4, with the installation of a central column equipped with improved full energy ion dumps. Both systems have been equipped with the extensive additional instrumentation necessary to allow safe operation with the beams re-steered to match the upwardly shifted plasma equilibria, which will be characteristic of the pumped divertor configuration. The range of movement for some beams is severely restricted by existing beam line components and only half of the eight beams (two per bank) can be re-steered by an appreciable amount. The difference within the

Neutral Beam Heating

The two JET neutral beam systems have been designed for long (~10s) beam pulses. They have the unique feature that each injector consists of eight beam sources in a single integrated beamline system connected to the torus. The first beam sources were designed to operate at accelerating voltages up to 80kV and in 1990 one system was substituted with units capable of operating up to 140kV. In addition, this box was also converted to operate with helium (^3He and ^4He) 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 12MW of power can be directed.

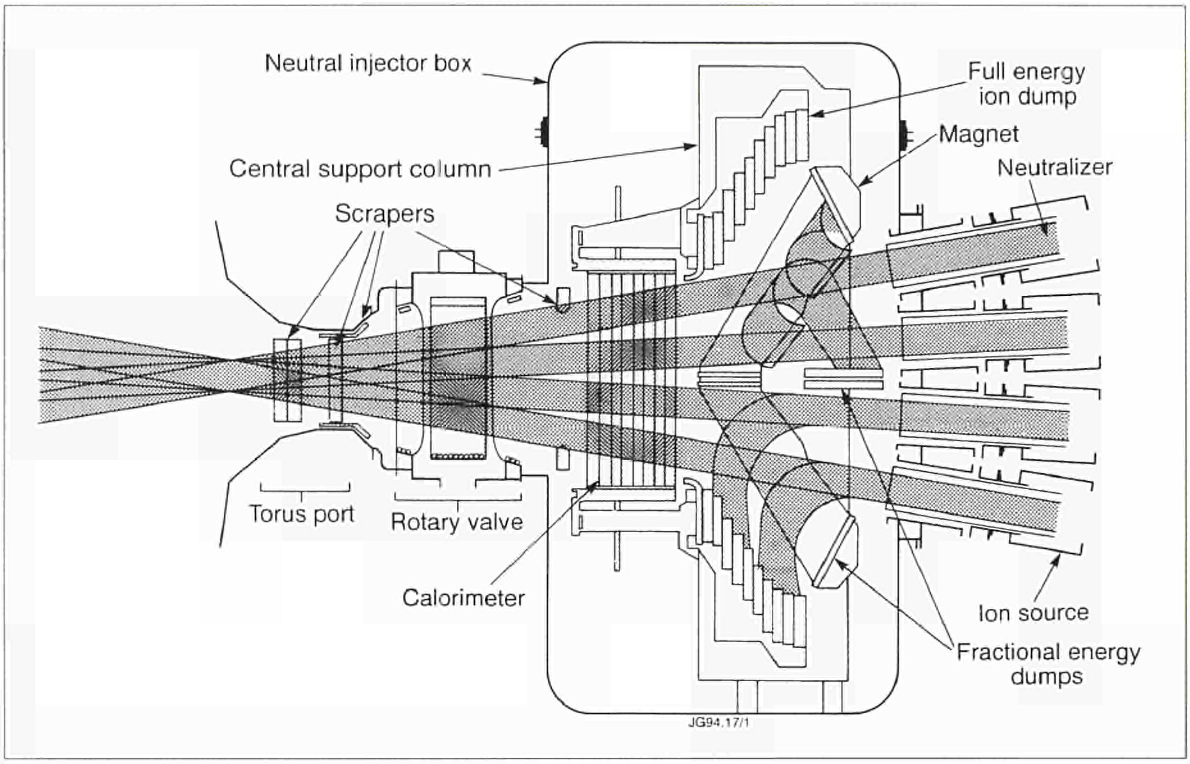


Fig. 14: Elevation of JET neutral injector showing re-steered beams

injector may appear negligible, as shown in Fig.14. However, there is a marked improvement in the power deposition on the axis of the displaced plasma equilibrium, since the axes of the re-steered beams pass close to the plasma centre. The re-steering is executed remotely using a motor drive on each individual injector steering flange. The box scrapers on both injectors have also been upgraded to make them compatible with the higher power beams of tritium (12MW per beam system) which will be used in the full D-T phase.

Radio Frequency Heating

The ion cyclotron resonance frequency (ICRF) heating system is used for high power centralised heating of the JET plasma, with an increased emphasis on Fast Wave Current Drive (FWCD) studies with the new antennae. The localisation depends mainly on the magnetic field and is insensitive to parameters such as density and temperature. Wide-band operation (23 - 57MHz) allows variation in both the choice of minority ion species heated (H or He^3 at present, D in the future D-T phase) and the localised position of the heating. With the previous antennae, up to 3.5MW on one antenna and 22.7MW total coupled power for 2s were achieved. Preliminary experiments on Fast Wave Ion Current Drive were successful showing

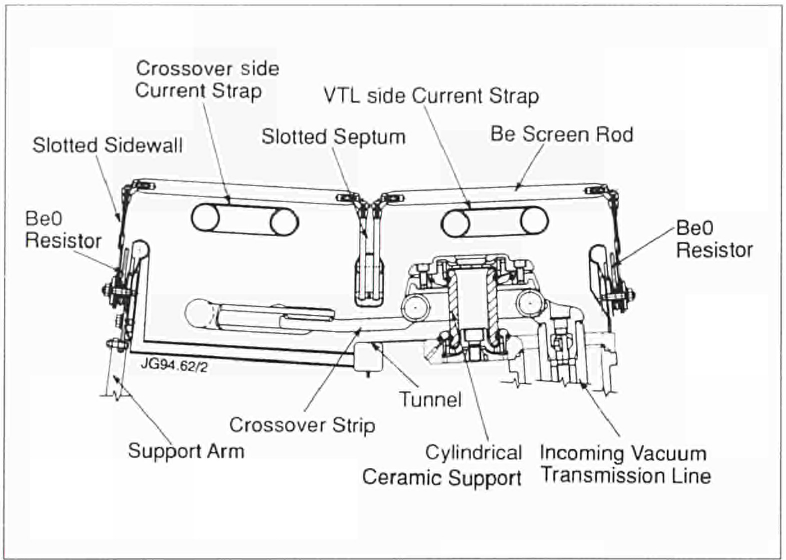


Fig.15: Sketch of new ICRF antenna

that the plasma current gradients near the q=1 surface were modified by changing the phase between straps of the antennae.

The manufacture and testing of the new ICRF antennae continued throughout 1993. The complex fabrication process of the new antennae as shown in Fig.15, had to be tightly controlled to achieve required tolerances. The conclusion of these programmes was the successful installation of the four arrays of antennae in the torus during a five day period in November. The new antennae have been optimised to the geometry of the divertor plasmas to maximise power coupling. Their location in the torus has been revised to give four arrays of two adjacent antennae (Fig.16). Each array has four RF radiating conductors, or straps, which provide an enhanced radiated spectrum optimised for current drive studies. Variation in the relative phase of the RF currents in the straps allow this spectrum to be varied for both heating and current drive experiments. The installation of the sixteen associated vacuum transmission lines and pumping systems was completed by the end of 1993. Running in parallel with these activities were extensive programmes covering upgrades to the RF power generation plant and modifications to the transmission systems to optimise performance. The maximum design power is 24MW coupled to the plasma.

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. The eight RF generators produce a maximum output power of 32MW. The net power coupled to the plasma has reached 22.7MW, compared with theoretical limit of 24MW.

Lower Hybrid Current Drive

The Lower Hybrid Current Drive (LHCD) system is capable of driving a significant fraction of the toroidal current in the plasma. This is

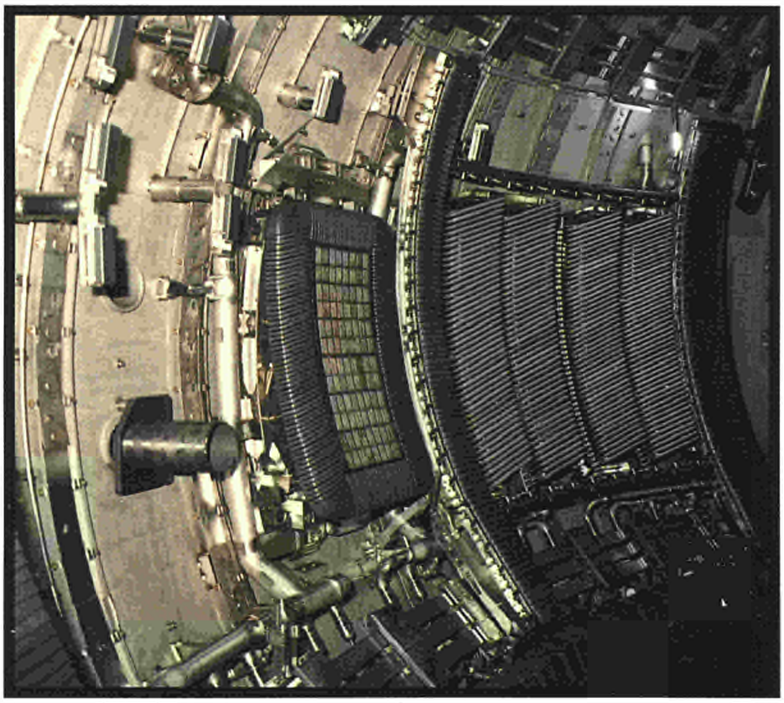


Fig.16: A new ICRF antenna in the torus, with LHCD launcher adjacent

achieved by launching an RF wave predominantly in one toroidal direction. This wave accelerates the high energy electrons in the plasma and so drives a current. It may be used to stabilise sawtooth oscillations, thereby increasing central electron temperatures. It is the system on JET for controlling the plasma current profile which is considered to be the main tool to stabilise high beta poloidal plasmas with a large proportion of bootstrap current (the so-called advanced tokamak scenarios). With a prototype launcher, up to 2.3MW of lower hybrid waves had been coupled to JET plasmas. Full current drive was demonstrated in 2MA low density plasmas. This prototype provided engineering, and operational experience of LHCD on JET in a variety of plasma configurations.

An upgraded launcher (Fig.17), was installed during the shutdown. Lower Hybrid waves at a frequency of 3.7GHz are radiated into the plasma from one single multi-waveguide antenna array in a horizontal main port of the vessel. The launcher is curved toroidally and poloidally to match the shape of the plasma surface. The plasma facing waveguide walls are protected against direct plasma contact by a surrounding frame of shaped carbon tiles. Lower Hybrid power is supplied through 40m long transmission lines from a generator plant of 24 klystrons. All installations inside the Torus Hall

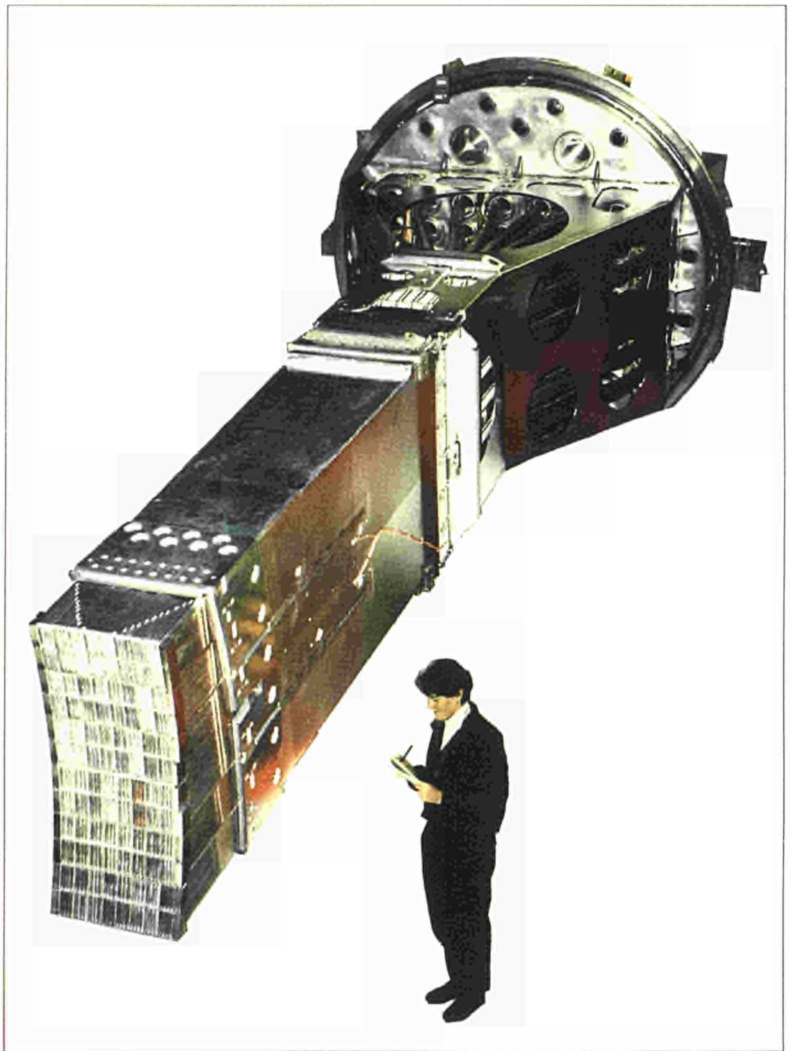


Fig.17: View of the LHCD launcher

are fully compatible with tritium operation. Double beryllium oxide windows separate the pressurised transmission lines from the launcher linked to the torus vacuum. The launcher is bakeable to 450°C for outgassing. Gas released from the inner walls of the waveguides during power transmission is removed by a large cryopump. The whole launching structure can be moved radially through positioning hydraulics. The maximum design launch power is 10MW with the intention of achieving full current drive for plasma currents up to 4MA and to control the current profile in high performance plasmas.

Diagnostics

The status of JET's existing diagnostic systems at the end of 1993 is summarised in Table 4 and their general layout in the machine is shown in Fig.18. The staged introduction of the diagnostic systems

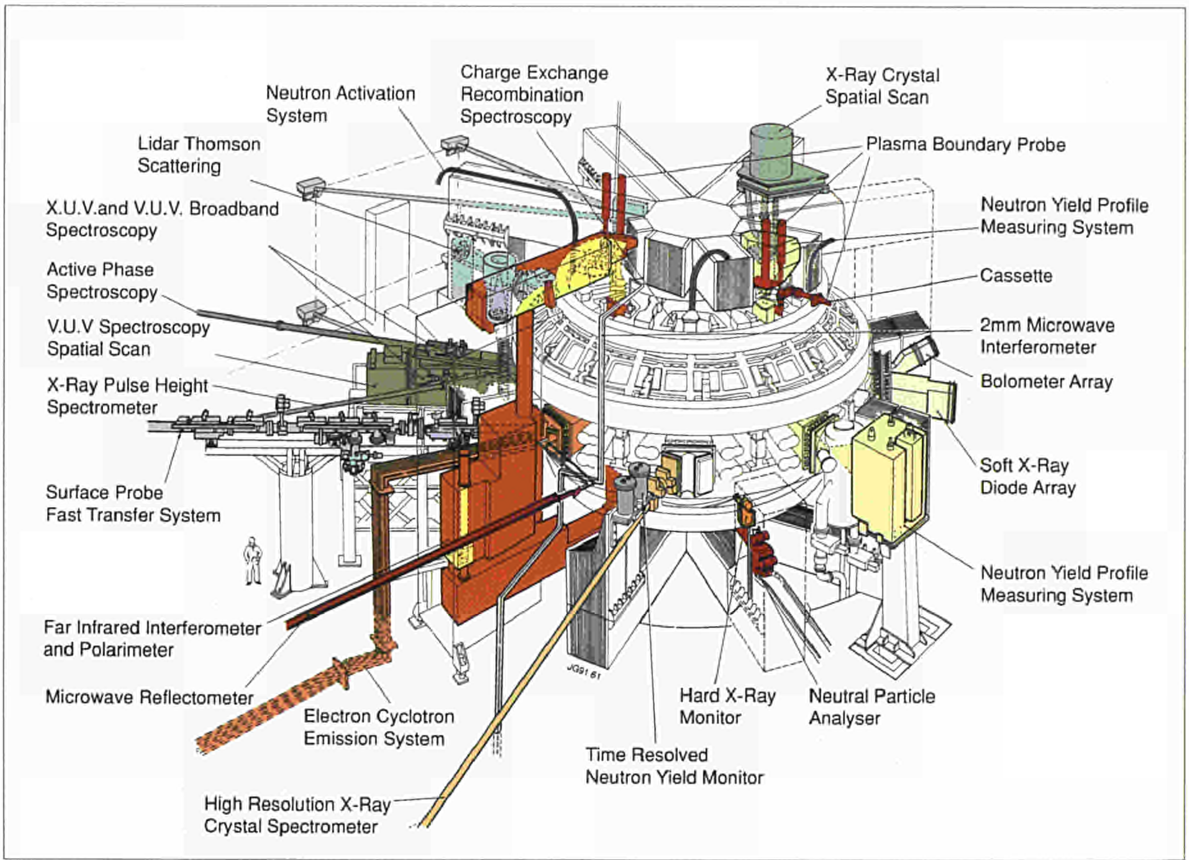


Fig.18: General layout of diagnostics in the machine

into JET has proceeded from the start of operation in 1983. The present status is that 36 systems are in existence. A further 22 systems are in preparation or in the design stage for operation in the new phase of JET or in the active D-T phase. Table 5 sets out the list of new diagnostics in the process of installation. Operational experience on the existing diagnostics has been good and most of the systems have operated automatically with minimal manual supervision. The resulting measurements have been of high quality in terms of accuracy and reliability. Further details on specific diagnostics systems are given below.

Temperature and Density Measurements

The construction of the in-vessel assembly of the Divertor LIDAR Thomson Scattering system was completed and was installed during the shutdown. This system should permit the measurement of electron density and temperature in the divertor region. A three-dimensional cutaway section of the system is shown in Fig.19. A separate laser has been built, which is based on the laser from the original single-point Thomson scattering system. The power supplies

No.	DIAGNOSTIC	PURPOSE	ASSOCIATION	STATUS
KB1	Bolometer array	Time and space resolved total radiated power	IPP Garching	Modified
KC1	Magnetic diagnostics	Plasma current, loop volts, plasma position, shape of flux surface, diamagnetic loop, fast MHD	JET	Upgraded
KE3	Lidar Thomson scattering	T_e and n_e profiles	JET and Stuttgart University	Upgraded
KF1	High energy neutral particle analyser	Ion energy distribution up to 3.5MeV	Purchased from Ioffe St Petersburg	Upgraded
KG1	Multichannel far infrared interferometer	$\int n_e ds$ on four vertical chords and four horizontal chords	CEA Fontenay-aux-Roses	Modified
KG3	Microwave reflectometer	n_e profiles and fluctuations	JET and FOM Rijnhuizen	Modified
KG4	Polarimeter	$\int n_e B_p ds$ on eight chords	JET and CEA Fontenay-aux-Roses	Upgraded
KH1	Hard X-ray monitors	Runaway electrons and disruptions	JET	
KH2	X-ray pulse height spectrometer	Monitor of T_e, impurities, LH fast electrons	JET	
KK1	Electron cyclotron emission spatial scan	$T_e(r,t)$ with scan time of a few milliseconds	NPL, UKAEA Culham and JET	Modified
KK2	Electron cyclotron emission fast system	$T_e(r,t)$ on microsecond time scale	FOM Rijnhuizen	
KK3	Electron cyclotron emission heterodyne	$T_e(r,t)$ with high spatial resolution	JET	Upgraded
KL1*	Limiter viewing	Monitor hot spots on limiter, walls, RF antennae, divertor target tiles	JET	Upgraded
KL3	Surface temperature	Surface temperature of target tiles	JET	Upgraded
KM1	2.4MeV neutron spectrometer	Neutron spectra in D-D discharges, ion temperatures and energy distributions	UKAEA Harwell	
KM3	2.4MeV time-of-flight neutron spectrometer		NFR Studsvik	Modified
KM7	Time-resolved neutron yield monitor	Triton burnup studies	JET and UKAEA Harwell	
KN1	Time-resolved neutron yield monitor	Time resolved neutron flux	UKAEA Harwell	
KN2	Neutron activation	Absolute fluxes of neutrons	UKAEA Harwell	Modified
KN3*	Neutron yield profile measuring system	Space and time resolved profile of neutron flux	UKAEA Harwell	Upgraded
KN4	Delayed neutron activation	Absolute fluxes of neutrons	Mol	
KR2	Active phase neutral particle analyser	Ion distribution function, $T_i(r)$	ENEA Frascati	
KS1	Active phase spectroscopy	Impurity behaviour in active conditions	IPP Garching	
KS3	H-alpha and visible light monitors	Ionisation rate, Z_{eff}, impurity fluxes from wall and limiter	JET	Upgraded
KS4	Charge exchange recombination spectroscopy (using heating beam)	Fully ionized light impurity concentration, $T_i(r)$, rotation velocities	JET	Modified
KS5	Active Balmer α spectroscopy	T_D, N_D and $Z_{eff}(r)$	JET	Modified
KS6*	Bragg rotor X-ray spectrometer	Monitor of low and medium Z impurity radiation	UKAEA Culham	Upgraded
KS7*	Poloidal rotation	Multichannel spectroscopic measurement of poloidal rotation	UKAEA Culham	Modified
KT2*	VUV broadband spectroscopy	Impurity survey	UKAEA Culham	Upgraded
KT3	Active phase CX spectroscopy	Full ionized light impurity concentration, $T_i(r)$, rotation velocities	JET	Modified
KT4*	Grazing incidence+visible spectroscopy	Impurity survey	UKAEA Culham	Upgraded
KX1	High resolution X-ray crystal spectroscopy	Central ion temperature, rotation and Ni concentration	ENEA Frascati	
KY3*	Plasma boundary probes	Vertical probe drives for reciprocating Langmuir and surface collector probes	JET, UKAEA Culham and IPP Garching	Modified
KY4	Fixed Langmuir probes (X-point belt limiter)	Edge parameters	JET	Modified
KZ3*	Laser injected trace elements	Particle transport, T_i, impurity behaviour	JET	Upgraded
Kγ1	Gamma rays	Fast ion distribution	JET	Modified

* Not compatible with tritium

Table 4: Status of JET Diagnostic Systems, December 1993 - Existing Diagnostics

No.	DIAGNOSTIC	PURPOSE	ASSOCIATION	STATUS
KB3D	Bolometry of divertor region	Power balance of divertor plasma	JET	In installation.
KB4	In-vessel bolometer array	Time and space resolved radiated power	JET	In installation.
KC1D	Magnetic pickup coils	Plasma geometry in divertor region	JET	In installation.
KD1D	Calorimetry of Mark I divertor targets	Power balance of divertor plasma	JET	Waiting for installation.
KE4	Fast ion and alpha-particle diagnostic	Space and time resolved velocity distribution	JET	In installation.
KE9D	Lidar Thomson scattering	T_e and n_e profiles in divertor plasma	JET	Undefined.
KG6D	Microwave interferometer	$\int n_e dl$ along many chords in divertor plasma	JET	In installation.
KG7D	Microwave reflectometer	Peak n_e along many chords in divertor plasma	JET	Procurement of source, detection and data acquisition systems in progress
KG8	E-mode reflectometer	Measurement of density profiles in edge and SOL	JET and CFN/IST Lisbon	Procurement of in-vessel systems in progress
KJ3	Compact soft X-ray cameras	MHD instabilities, plasma shape	JET	Waiting for installation.
KJ4	Compact soft X-ray camera	Toroidal mode number determination	JET	Waiting for installation.
KK4D	Electron cyclotron absorption	$n_e T_e$ profile along many chords in divertor plasma	JET	In final stage of construction.
KM2	14MeV neutron spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distributions	UKAEA Harwell	In installation
KM5	14MeV time-of-flight neutron spectrometer		NFR Gothenberg	In installation.
KT1D	VUV spatial scan of divertor	Time and space resolved impurity densities	JET	In installation.
KT5D	Toroidal view visible spectroscopy of divertor plasma from Octant No: 7 mid-plane	T_z and V_z, ion temperature and toroidal velocity of impurities	JET	Waiting for installation.
KT6D	Poloidal view visible spectroscopy of divertor plasma using a periscope	Impurity influx, 2-D emissivity profile of lines	JET	In installation.
KT7D	VUV and XUV spectroscopy of divertor plasma	Impurity influx, ionization dynamics	JET	Waiting for installation.
KY4D	Langmuir probes in divertor target tiles	n_e and T_e in the divertor plasma	JET	Installed.
KY5D	Fast pressure gauges	Neutral flow in divertor region	JET	Installed.
KY6	50kV lithium atom beam	Parameters of the scrape-off-layer plasma	JET	Waiting for installation.
KY7D	Thermal helium beams	n_e and T_e in the divertor plasma	JET	Installed.

Table 5: Status of JET Diagnostic Systems, December 1993 - New Diagnostics

were upgraded and the laser now operates at 4Hz with 300ps pulses of about 1J energy. Rayleigh scattering measurements have confirmed the expected transmission of the optical system. Raman scattering signals were observed and these indicate that it should be possible to make measurements close to the divertor target plates.

The multichannel reflectometer probes the plasma along a radius in the mid-plane with e-m radiation propagating in the ordinary mode through the plasma. It measures the edge electron density profile and density transients and fluctuations. During 1993, the 12-channel O-mode reflectometer was modified to be compatible with the new divertor plasma configuration. The in-vessel antennae were extended and raised 300mm to be in line with the new plasma centre. For fluctuation measurements, the data acquisition system has been extended so that measurements can be made for 3s with a 100kHz bandwidth.

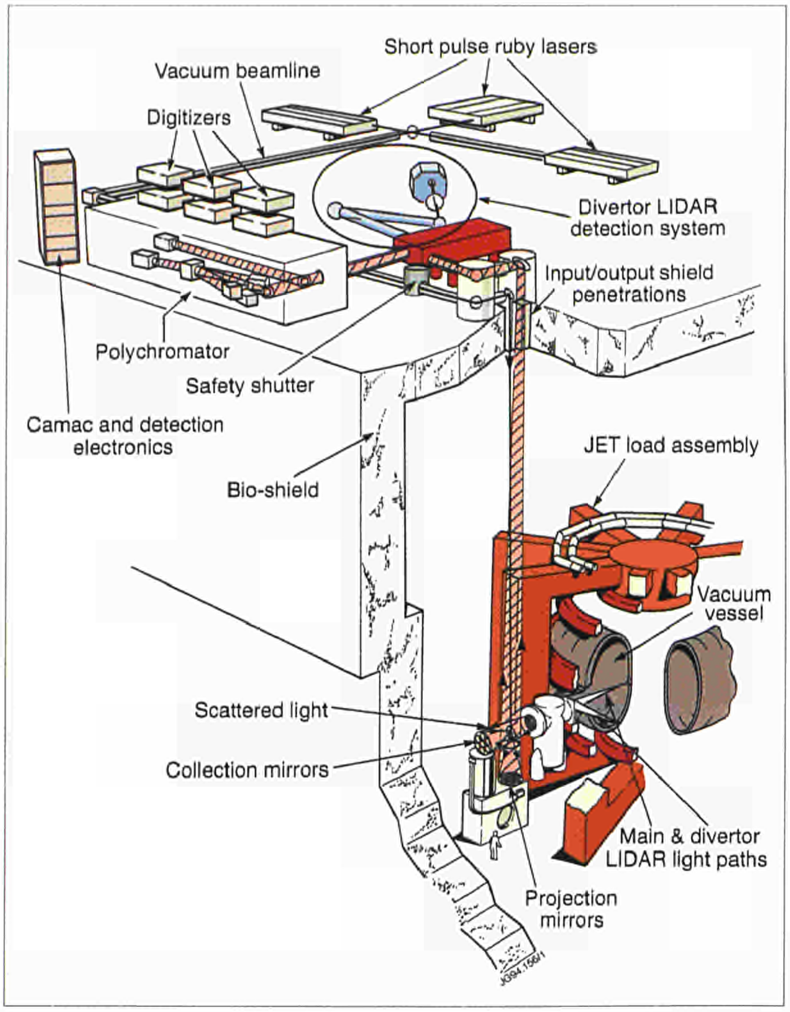


Fig.19: Cutaway section of the LIDAR Thomson Scattering System

The construction of a broad-band swept extraordinary mode system for measuring density in the scrape-off layer and plasma edge was started during 1993. The system will use new antennae and waveguides and operate in the range 50-100GHz. Previous experiments on correlation reflectometry have shown that it is necessary to measure both phase and the amplitude to deduce the density fluctuation level. In addition, resolving the propagation behaviour of the fluctuations unambiguously requires measurements in the toroidal, poloidal and radial direction. A new E-mode correlation reflectometer was designed, which uses a four-antenna array and operates at 80 (or 105) GHz. It can be configured for measurements in either the toroidal or poloidal directions. In addition, a two channel radial correlation reflectometer operating in the range 92-96GHz will share the same antenna system.

The new E-mode and the existing 12-channel O-mode systems will provide complementary information. In particular, the E-mode

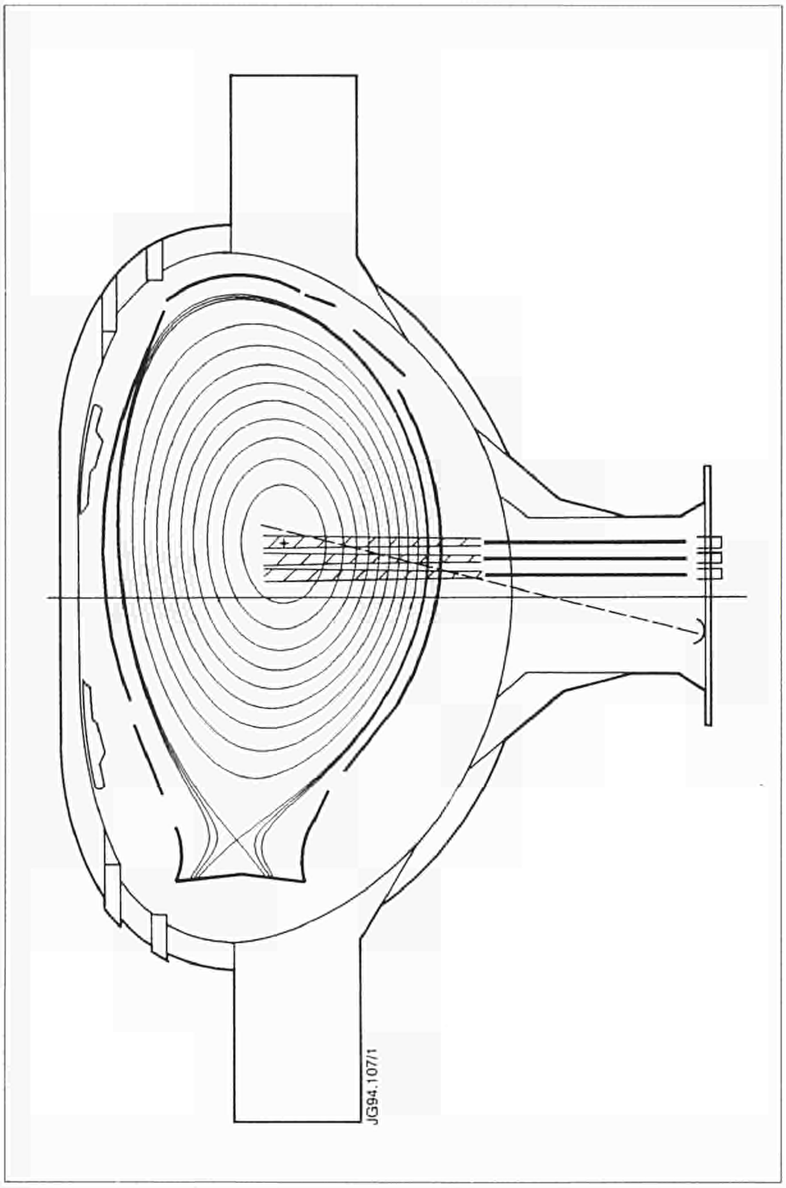


Fig.20: Poloidal cross-section showing location of the four horizontally viewing ECE antennae, and the new Gaussian beam collection system for the ECE heterodyne radiometer

system can provide measurements near the plasma centre when the O-mode system is frequently confined to the edge of the profile.

Major modifications to the electron cyclotron emission (ECE) system have been made during the shutdown to adapt the diagnostics to the new configuration and to further enhance the measurement capability. In the 1994/95 campaign, the three different instruments in the ECE system (Michelson interferometers, the grating polychromator and the heterodyne radiometer) will again provide electron temperature data on most pulses. The in-vessel ECE antennae have been modified to provide more sightlines viewing the plasma through the new centre, ~0.3m above the vessel mid-plane. A new array has been installed, with three horizontally viewing antennae at the height of the new mid-plane plus a fourth oblique antenna aimed at the new plasma centre. The original array of four horizontally viewing antennae has been retained since the uppermost provides another view near the new mid-plane, plus some sightlines off the mid-plane. Figure 20 shows the location of the horizontal sightlines and the Gaussian beam sightline.

The Michelson interferometer was previously used for electron temperature, T_e, profile measurements with moderate spatial and temporal resolution. The availability of more sightlines near the plasma centre will enable higher resolution. Once the performance and reliability of the higher resolution Michelson is demonstrated, it will become the standard source of T_e profile data in JET databases.

Measurement of electron temperature in the divertor plasma by electron cyclotron emission will not be possible, since the plasma will not be optically thick to this radiation. Therefore, the plasma will not radiate as a black-body (the emission intensity will depend on both electron density and temperature) and, more importantly, a measurement of the divertor plasma ECE would be swamped by the much more intense emission from the plasma core. For these reasons, an electron cyclotron absorption (ECA) diagnostic is being constructed to measure the optical depth of the divertor plasma directly. From this measurement, the electron density-temperature product (the electron pressure) will be determined. The diagnostic will measure the attenuation by the divertor plasma of radiation from frequency-swept microwave sources. Ultimately, the diagnostic should measure the spatial profile of the n_eT_e product in the range 25-2500x$10^{19}m^{-3}$keV at most values of toroidal field, with an accuracy of about ±10%.

Boundary Measurements

During the shutdown, new Langmuir probes have been installed in the pumped divertor targets to provide localised measurements of electron temperature, electron density and ion flux. Probe tips protrude from the toroidal gaps between successive rows of tiles. Of the 149 probes installed in the divertor, two poloidal arrays of 16 single probes approximately match the positions of the diagnostic

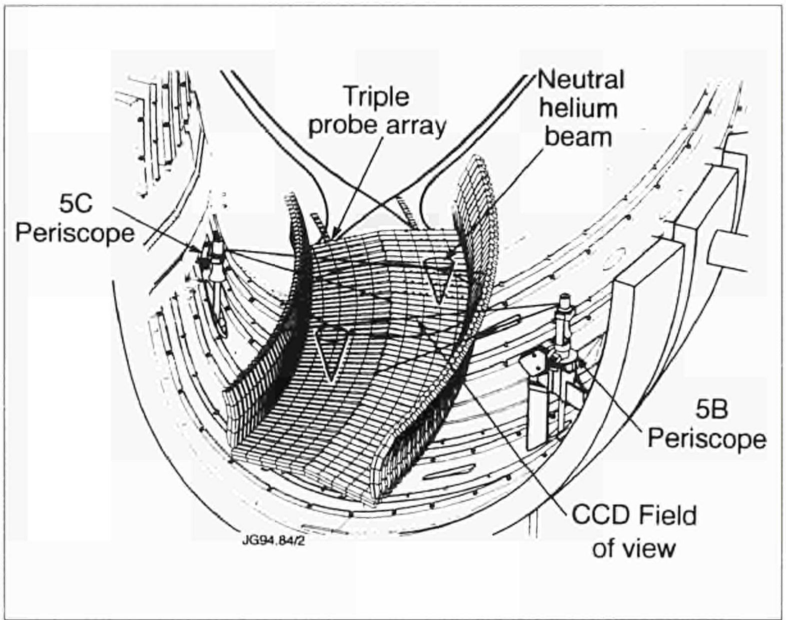


Fig.21: Layout of helium beam diagnostic, triple Langmuir probe and CCD camera field of view (Octant No. 5)

magnetic coils. The remainder are configured as an array of 39 triple probes (Fig.21), with the distribution chosen to have the highest density at the probable strike point locations. Triple probes have the advantage of allowing continuous observation of the plasma parameters. In addition, for measurements during plasma start-up and limiter discharges, 22 single Langmuir probes have been installed in the inner and outer limiters.

Since the probes protrude from the divertor target and intercept the plasma at a steeper surface angle, the incident heat flux is much greater than on the tiles. Consequently, the material and design of the probe tip had to be carefully chosen to ensure that the thermal performance of the probe was significantly better than that of the tiles. Studies indicated that two materials, a 3D carbon fibre composite (CFC) and pyrolytic graphite, would provide the desired thermal properties. Experiments simulated conditions expected at the divertor target. No fracturing occurred but scanning electron microscopy revealed significant surface cracking in the CFC material. Therefore, pyrolytic graphite was used for the majority of probe tips.

The magnetics diagnostic is used to reconstruct a picture of the magnetic flux surfaces of the configuration and has been upgraded for the new divertor configuration. Since the plasma will be further from the outer vessel wall, the accuracy of the plasma boundary reconstruction with the original set of sensors would have been reduced. Therefore, a set of magnetic coils has been added on the poloidal limiters. In addition, several coils and flux loops have been added under the divertor target, on the inner wall and at the top of the machine for refinement of the equilibrium reconstruction, adding to a total of 93 new magnetic sensors. Simulations show that the plasma boundary should now be constructed with an accuracy of ~1cm. The digitised data will be sent to the plasma position and current control system (PPCC), where the XLOC plasma boundary code is solved in real-time for feedback control of the plasma. For transient events in the plasma, the full set of signals for equilibrium reconstruction can be triggered to record at 10kHz sampling rates for post-pulse analysis of rapidly evolving plasmas.

Infra-red camera systems are used to measure the evolution of surface temperature of the divertor target surfaces. From the time history of the temperature, the power distribution at the divertor targets can be computed. The camera system is being implemented in two phases. The first will be available at the start of 1994: it will have spectral sensitivity in the range 800-1650mm and will have time resolution of 1.6ms and spatial resolution of 3mm. The second will be available later with a sensitivity in the range 3000-5000nm, time resolution of ~0.5ms and spatial resolution of 3mm.

A thermal helium beam has been introduced to measure the electron density and temperature at the edge of the plasma. The intensity ratio of two visible helium lines 728nm:706nm is most sensitive to electron temperature, while the ratio 728nm:668nm is most sensitive to electron density. Such a system has been implemented using the divertor periscopes for observation and nozzles located in the inner and outer divertor targets to provide beams of neutral helium (Fig. 21). This diagnostic will provide measurements of electron density and temperature in the divertor with a 2cm spatial resolution. Diagnostic simulations are being conducted using an impurity transport code to explore the effects of beam divergence on the interpretation of results.

Neutron Measurements

At the start of the 1994 campaign, the set of neutron diagnostics will be substantially the same as in previous years, although many changes have been made to accommodate the new divertor

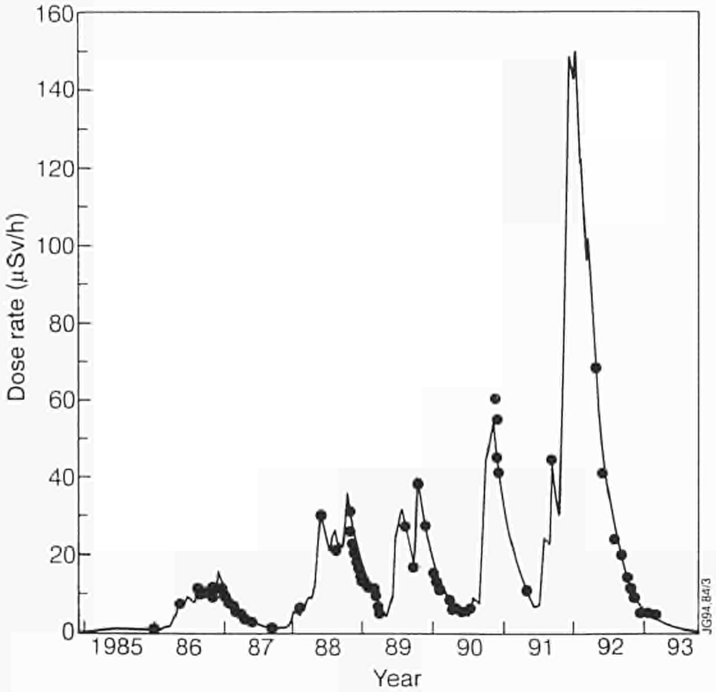


Fig.22: Gamma-dose rate in vessel, recorded between operational periods. The solid line is the prediction obtained from measured neutron yield, summed over each week of operation. The vessel activation is dominated by a single long-lived radio-isotope, ^{58}Co. The data-points are in-vessel measurements obtained with a Health Physics Dosimeter

arrangement. The additions and upgrades specific to tritium plasmas will not be introduced until later in 1994.

The fission chambers used for monitoring the instantaneous neutron emission strength have performed reliably since their installation. The absolute calibration of these chambers is a difficult task, achieved either through in-vessel calibrations using portable neutron sources or through activation measurements. A useful check on the reliability of these calibrations is obtained by comparing the estimates of gamma-radiation dose rate inside the vessel obtained from predictive calculations with those measured with Health Physics instrumentation during shutdown periods. Figure 22 shows this comparison from 1985 until the present. Agreement between prediction and measurement is well within the expected accuracy, which provides convincing confirmation of the reliability of the fission chamber calibrations.

The 2.5MeV neutron spectrometer, comprising a massive radiation shield and associated adjustable collimator, located in the

Torus Hall, has been raised 25cm so that it will have a line-of-sight passing horizontally through the new plasma centre, up to 30cm above the median plane of the vacuum vessel.

According to the original programme schedule the 2.5MeV neutron time-of-flight spectrometer, in the Roof Laboratory above Octant No.8, should have been replaced by the new 14MeV associated-particle time-of-flight neutron spectrometer in preparation for the tritium phase of operations. Now that JET has embarked on the divertor programme, this planned replacement has become inappropriate and both instruments will be operated simultaneously. Accordingly, the neutron time-of-flight spectrometer has been moved from its position above Octant No.8 to a new position above Octant No.5 and the particle spectrometer has been installed in the Octant No.8 position. The neutron collimators for both spectrometers have been carefully aligned. An upgrade for the present neutron profile monitor is currently under construction. The new profile monitor will be provided with separate detectors for bremsstrahlung radiation, 2.5 MeV neutrons and 14 MeV neutrons. This diagnostic will be installed by Summer 1994, and the existing profile monitor will be used until then.

Fast Particle and Alpha-Particle Studies

A new high energy neutral particle analyser for use during D-T experiments, was installed during 1993. This instrument will measure MeV energy D-T and D-D fusion products and ICRF driven minority ions. The low energy neutral particle analyser has been refurbished, and a new Water-Extended-Polyethylene and lead shield against neutrons and γ-rays has been procured. This analyser is suitable for operation during D-T experiments.

Work continued during 1993 on a system to measure the velocity and spatial distributions of fast ions, including α-particles in the D-T phase. The system is based on collective scattering of radiation at a frequency of 140GHz generated by a powerful gyrotron source. After experiencing technical difficulties, the high power gyrotron source was rebuilt by the manufacturer during the year. A prototype gyrotron, loaned as part of a collaborative agreement with US DoE, is suitable for initial diagnostic measurements. Although this gyrotron developed a leak to a water cooling channel, it was repaired and, after a long period of cathode cleaning, the gyrotron was brought into operation on a dummy load in December. Conditioning of the gyrotron is continuing, to recover from contamination.

A large diameter water-free fused silica single disk has now been selected for the high power torus window. This should transmit a full 5s pulse, with mainly radiative cooling between pulses. The change in reflection coefficient with temperature is substantially reduced compared with the original sapphire window. When tritium is used, double inter-pumped windows will be used on the vacuum vessel. Methods for reducing the frequency dependence of the transmission of double windows for millimetre wavelengths were investigated. Suitable crystal quartz double windows have been designed, based on refractive index data measured at elevated temperatures.

Impurities

XUV and VUV spectroscopy will be used to observe line radiation of the main plasma impurities emitted from the divertor region. There are three spectrometers, a double-SPRED (Survey, Poor Resolution, Extended Domain) combining two VUV spectrometers in one instrument, and a SOXMOS (Soft X-ray Multi-channel Spectrometer). These cover a range from 15 to 1500Å. The region between 100 and 1500Å is detected simultaneously, whilst data is collected for two smaller regions in the 15-1500Å range. The three vertical lines-of-sight focus onto the divertor region and, by oscillating the whole spectrometer assembly at a frequency of 1Hz, radial emission profiles covering the total divertor cross-section can be recorded every 500ms. The main improvements are a stainless steel shielding against γ and X-rays, new detector systems with more channels and a higher time resolution.

The pulse height analysis system is essentially unchanged. The diagnostic uses Si (Li) and Ge detectors to measure the thermal or non-thermal parts of the soft X-ray spectra. The thermal spectra may be used to determine T_e, Z_{eff} and impurity concentrations, whereas the non-thermal spectra are of interest principally to study fast electron distributions produced by lower hybrid heating.

Remote Handling

Remote handling equipment is being prepared to permit maintenance and repair of the tokamak and systems within the Torus Hall during the D-T phase of operation. Since man access to the Torus

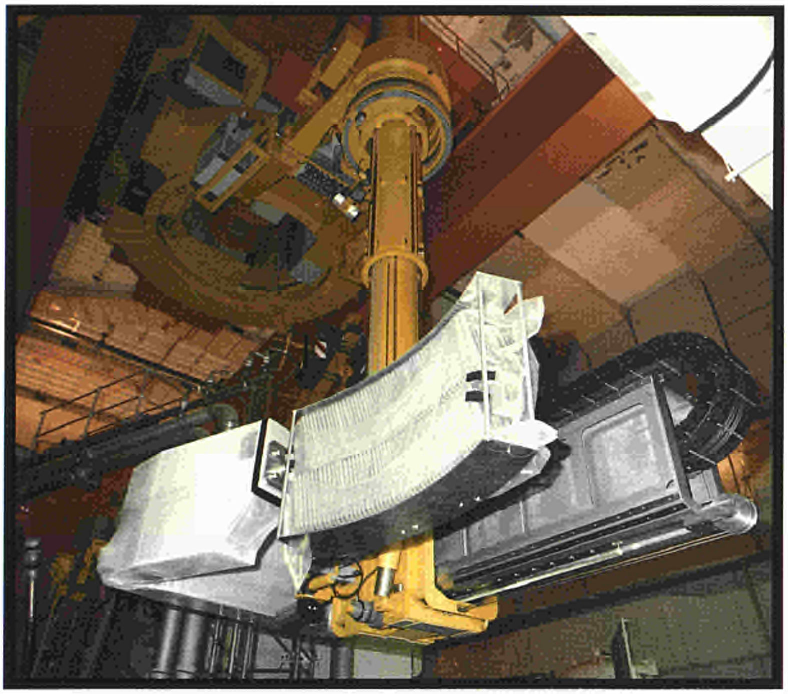


Fig.23: The telescopic articulated remote mast (TARM) positioning a new RF antenna

Hall will be effectively prohibited due to radiation from neutron activation, remote handling equipment will be operated from a Control Room outside the biological shield. Much of this equipment has been deployed during the shutdown under local operation. As well as proving its operation for the D-T phase, it has assisted in difficult mechanical handling tasks and has permitted a number of installation operations to be carried out semi-automatically.

In particular, the Boom has been used to install the saddle coil elements, upper dump plates, inner wall guard limiters, poloidal limiters, divertor target plate modules, LHCD in-vessel components and the poloidal limiter straight sections. The telescopic articulated remote mast (TARM) has been used to insert the new antennae through the port at Octant No.3 into the torus, where these were transferred to the in-vessel crane and installed on the torus wall (Fig. 23). Gaps were about 10mm and tracking repeatability was 1-2mm. Installation time was approximately five minutes. Special remote handling tools have been used in-vessel to install the divertor cooling water pipe systems, to connect them to the 48 divertor target plate modules and to install and weld ~20 circular port feedthroughs. Outside the vessel, special tools have been used to install components or flanges on over 25 vessel port lip joints and about 50 circular port windows of various sizes.

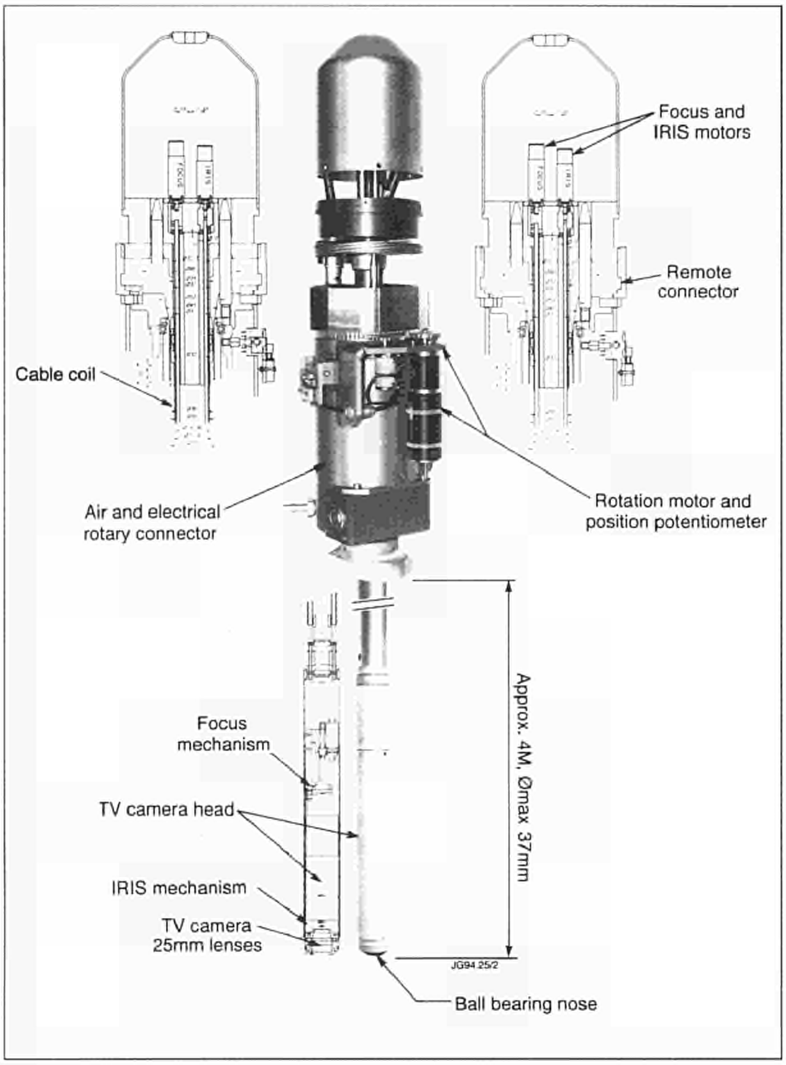


Fig.24: The new In-Vessel Inspection System (IVIS) TV camera probe

An enhanced version of the In-Vessel Inspection System (IVIS) has been developed which should obtain higher quality pictures and better views of the divertor tiles (Fig. 24). The work has presented difficult problems of miniaturisation and high vacuum compatibility. In addition, neutron and radiation resistance tests have been carried out in the Petten test reactor on sapphire, natural and synthetic silica, cameras, light-guides, lighting components and d.c., universal and a.c. motors. The software of the man-machine interface system was reviewed, improved (using high level languages), tested and documented. Automatic scanning techniques and "mosaic" reconstruction can be used to minimise the time the inspection probes have to be within the vessel and so that analysis can be done after the probes have been removed. All visual information can also be transmitted to the main control room.

Fig.25: Carbon dioxide pellet blasting in the vessel

Waste Management

The responsibilities of the Waste Management Group include the provision of the infrastructure in JET for waste handling (radwastes and beryllium-contaminated wastes) and the provision and maintenance of respiratory protection and equipment. Five controlled area facilities, which are all equipped to handle components and materials activated and contaminated with tritium and beryllium, have been operated in support of the shutdown. Wastes generated in these areas are disposed of either as beryllium or low level radioactive waste. Considerable reductions in volume of waste produced, compared with that originally estimated, were achieved through better control, segregation and compaction procedures.

The Torus Access Cabin (TAC) was installed on the machine at the start of the shutdown, in an extended configuration with an enlarged operations box and improved facilities for the transfer of components in ISO-freight containers. Support of the in-vessel programme for 24 hours per day on a 6-7 days per week basis meant that the TAC was manned and operated almost continuously.The main TAC activity during the first half of the year, was the construction of the pumped divertor system inside the torus. No respiratory protection was necessary during this period. For two weeks in May, the TAC was then used to support the full-suit operations during cleaning of the vacuum vessel, when frozen carbon dioxide pellet blasting was carried out (Fig 25). A full report on the experience gained at JET in the use of pressurised suits during both this phase and in earlier shutdowns was completed.

Both Beryllium Handling Facilities were operated throughout the year in support of the shutdown. Decontamination of materials and equipment and preparation of components for installation on the machine were the principal tasks. Access control to the facilities for both personnel and materials was improved with the connection to the Alnor system. Other facility enhancements have included a new improved removable roof and a complete refurbishment of the interior of one of the facilities. As a result of modifications, the usable space for controlled area operations has been increased significantly.

Although the suit cleaning facility in the Waste Management area was only used for a brief period during the carbon dioxide pellet cleaning exercise in the torus, the PVC fabrication workshop was in continuous operation throught the year producing isolators, tents and other enclosures required for contamination control during the shutdown. Modifications carried out during the year included an extension to the storage areas for suits and protective equipment, the commissioning of a new respirator maintenance area and a light fabrication facility.

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 for detailed analysis. A summary of information from the JET pulses is held in the JET Survey Data Bank.

Control and Data Management

The JET Control and Data Acquisition System, (CODAS), is based on a network of minicomputers. It provides centralised control, monitoring and data acquisition on JET. The various components of JET are logically grouped into subsystems such as Vacuum, Toroidal Field, Lower Hybrid heating, etc. Each subsystem is controlled and monitored by one dedicated computer interfaced to the machine and its diagnostics through distributed front end instrumentation. Signal conditioning and some data conversion use EUROCARD. The rest of the instrumentation is based on CAMAC and VME standards. Embedded front-end intelligence is implemented through microprocessors which are also used for real-time applications. The actions of the various computers are co-ordinated by a supervisory software running on the Machine Console computer. During 1993, main efforts have been devoted to completion of the move of CODAS to a UNIX environment and the deployment of new front end intelligence based on the VME standard connected by a dedicated network.

The Computing Service has operated since June 1987 and the central computer was upgraded in 1990 from an IBM 3090/200E to an IBM 3090/300J, with three processors, two vector facilities and 384 MBytes of memory (128MB central and 256MB expanded), almost doubling the processing capacity. In 1992, a Memorex-Telex automated cartridge tape library (ATL) with a capacity of about 1000GBytes was installed. The ATL not only provides storage for all the raw JET data (JPFs) and archived processed JET data (PPFs), but also provides storage for backup and dump tapes, that were previously handled using manually operated cartridge tape drives. This together with the introduction of automated operations has eliminated requirements for operator cover. In 1993, the eight tape drives of the ATL were upgraded doubling the data recording density, hence doubling the capacity of the ATL.

The JET IBM Computer Centre was originally established at the UKAEA Harwell Laboratory but was relocated to Building J2 at JET in July 1992. The service has run very successfully from the new location, providing the expected improvement in communications, integration with the UNIX systems, and a reduction in staff. In general, the service has been most reliable.

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 shutdown periods. Reference should be made to the section on the Future Programme of JET to relate these technical developments to the overall JET Programme.

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

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.

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}. Further work is underway on two systems: a high-speed pellet launcher and a pellet centrifuge for shallow deposition.

The high-speed launcher is designed to accelerate sabot supported 6mm deuterium pellets to speeds up to 4kms^{-1} by using two-stage light gas gun driver technology for deep central plasma fuelling purposes. Sabots are small plastic pistons, set behind the deuterium pellets to protect them from the hot driving gas. These sabots, needed for pellet velocities in excess of about 3kms^{-1} and being accelerated with the pellet, are made from two halves of equal mass, which split after leaving the barrel due to aerodynamic forces and can be eliminated from the pellet path by a shear cone.

The two-stage gun has performed well with few problems. The main effort has been devoted to pellet formation, and a number of difficulties have been overcome. Eventually, good pellets were obtained and shot in subsequent trials with non-split sabots in a large number of shots with speeds of 2.5-2.8 kms^{-1}. This success as well as pellet transfer studies - moving the pellets from a cryo-condensation/storage place to the breech and waiting for it to dissolve without firing - established that the pellet was not in danger of being lost during transport. Even when closing the breech, it took more than one minute to lose the pellet by a thawing or an expulsion process due to pressure build-up from gasification. The commissioning programme will now progress to the firing of pellets with split sabots and to the upgrading of the gun parameters to achieve the higher pellet speeds. It is expected to install the injector at Octant No. 2 on JET during 1994.

The pellet centrifuge is to provide a source of deuterium particles at varying depths beyond the recycling layer and with it a minimum recycling flow into the divertor. The injection parameters chosen are pellet sizes of 1.5-3mm with repetition frequencies up to 40s^{-1} at speeds of 50-60ms^{-1} for long pulses approaching one minute. A schematic of the pellet centrifuge unit is shown in Fig.26. It accelerates pellets mechanically from the hub to the tip of a rotor

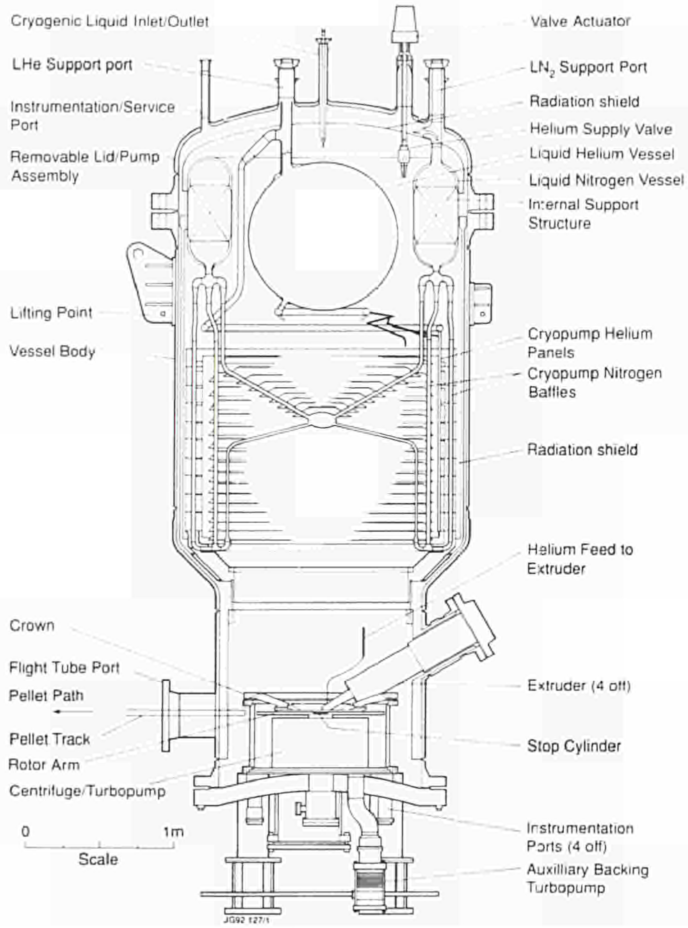


Fig.26: Schematic of the Pellet Centrifuge Unit

arm, where these leave at about 1.4 times the rotor tip speed. Each size of deuterium ice pellet will be launched from one of up to four possible individual extruder units into the central part of the centrifuge rotor hub, into which reaches the stationary stop cylinder featuring a hole to ensure the proper starting conditions for the pellet on the rotor arm. The design of centrifuge rotor and stop cylinder follows very closely that of the centrifuge developed for ASDEX Upgrade by IPP, Garching, Germany, who also advise JET under contract. The extruder is of a new design by JET to provide a much larger number of pellets per tokamak pulse. A large liquid helium cryopump will cope with the gas losses from pellet acceleration and guidance. The centriguge is expected to be installed on JET at Octant No. 2 during 1994.

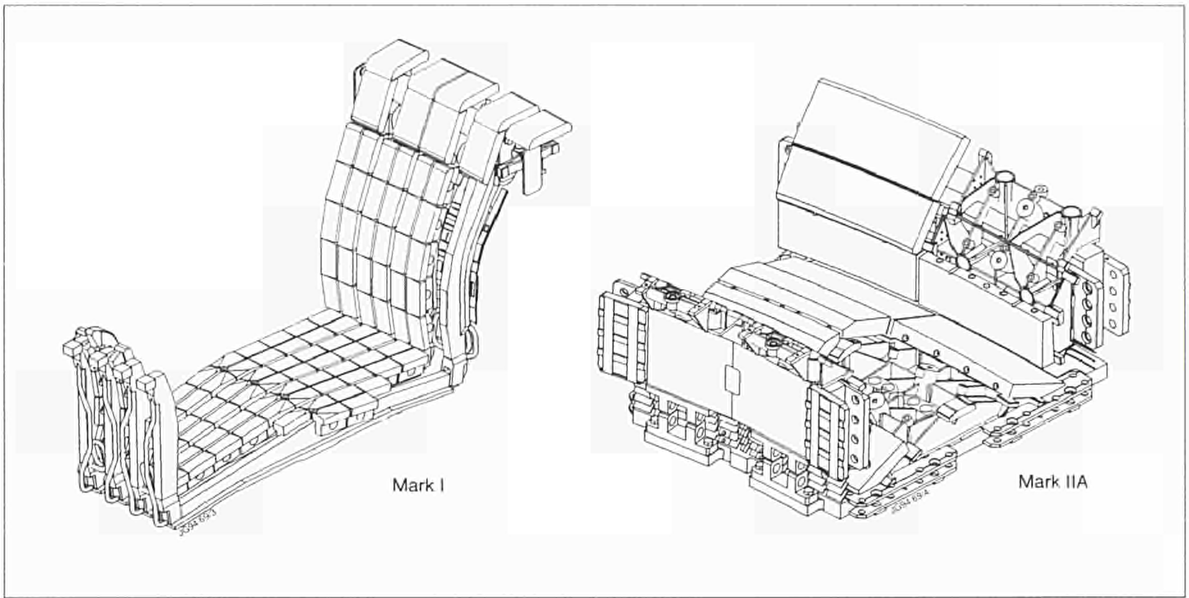


Fig.27: Isometric views of Divertor modules: (a) Mark I; and (b) Mark IIA

Design of Mark II Divertor

The Mark I divertor has always been considered an interim solution, due to its limited power handling capability and open structure. Therefore, in parallel with shutdown work, a Mark II divertor has been designed and its major components are under procurement. Mark II will have a closed divertor structure, leading to increased impurities and neutral retention, increased radiation and reduced conducted power to the target plates. Moreover, a 'continuous target design', still inertially cooled, will further increase the power handling capability, and will not require X-point sweeping. Approval for the installation of Mark II divertor in 1995 is likely to be considered by the JET Council in 1994. Mark II would also permit easy changes of graphite (or beryllium) tiles to follow ITER divertor design development.

Components for the new divertor were designed during 1993 as shown in Fig.27. The principle behind the design is to fit a relatively rigid U-shaped channel in the divertor region and to use it as a support structure for mounting a range of carrier designs with plasma facing tiles to define the divertor shape. The design started at the beginning of the year, and the contracts for the main support structure, the material for the main support structure, the tile carriers, and for the CFC material for the divertor tiles were all placed before the end of the year. The only large contract still to be placed is for the machining of the CFC tiles, for which the tender is

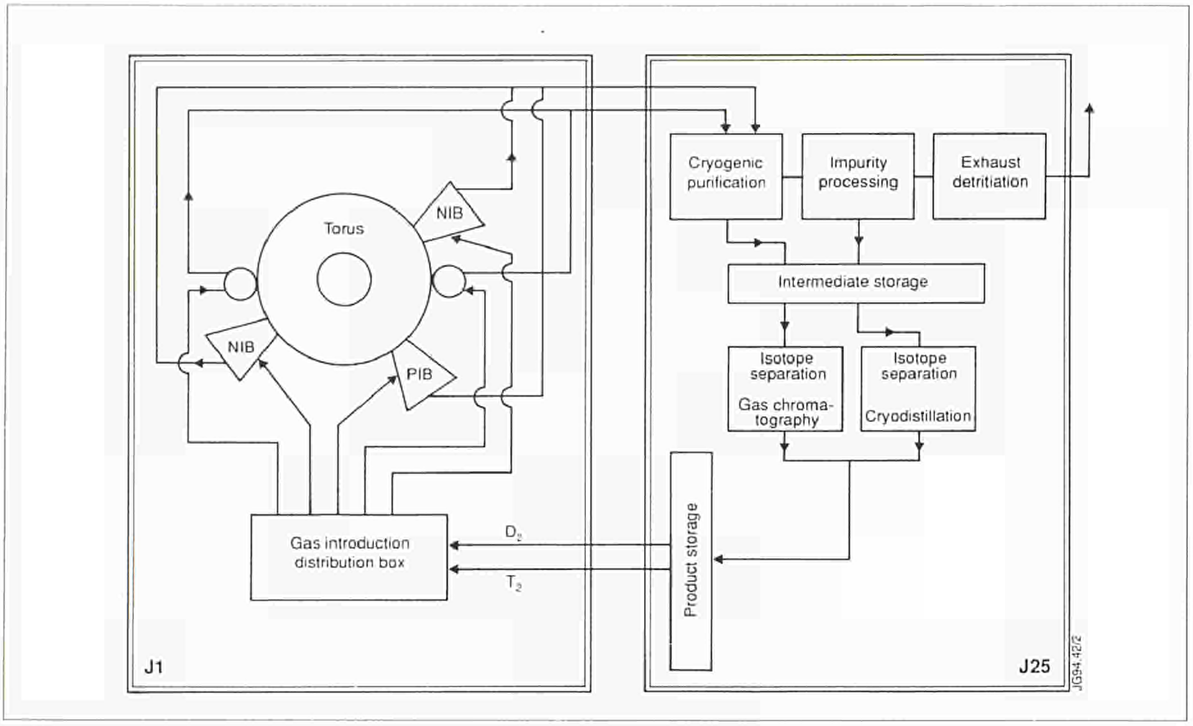


Fig.28: Block diagram of the functions of the Active Gas Handling System

planned for early 1994. The manufacturing programme is on schedule and within the budget proposed.

The choice of the particular carbon fibre composite (CFC) tile material was made after an extensive theoretical and experimental study of the consequences of the expected heat load on the materials proposed, given their specified properties. Ten different materials from four major European CFC suppliers were tested in the JET High Heat Flux Test Facility. The measurements included the bowing of the tiles, their thermal conductivity, and their mechanical integrity, under heat load. Tests were also performed to determine which tile surface treatment and surface conditions were required to minimise the problem of hot spots caused by small particles on the surfaces, which are not well connected thermally to the body of the material. The diagnostic systems and the gas introduction system have been integrated into the Mark II structures. The tile carriers and all diagnostic systems are attached to the structure which can be exchanged by remote handling tools.

Tritium Handling

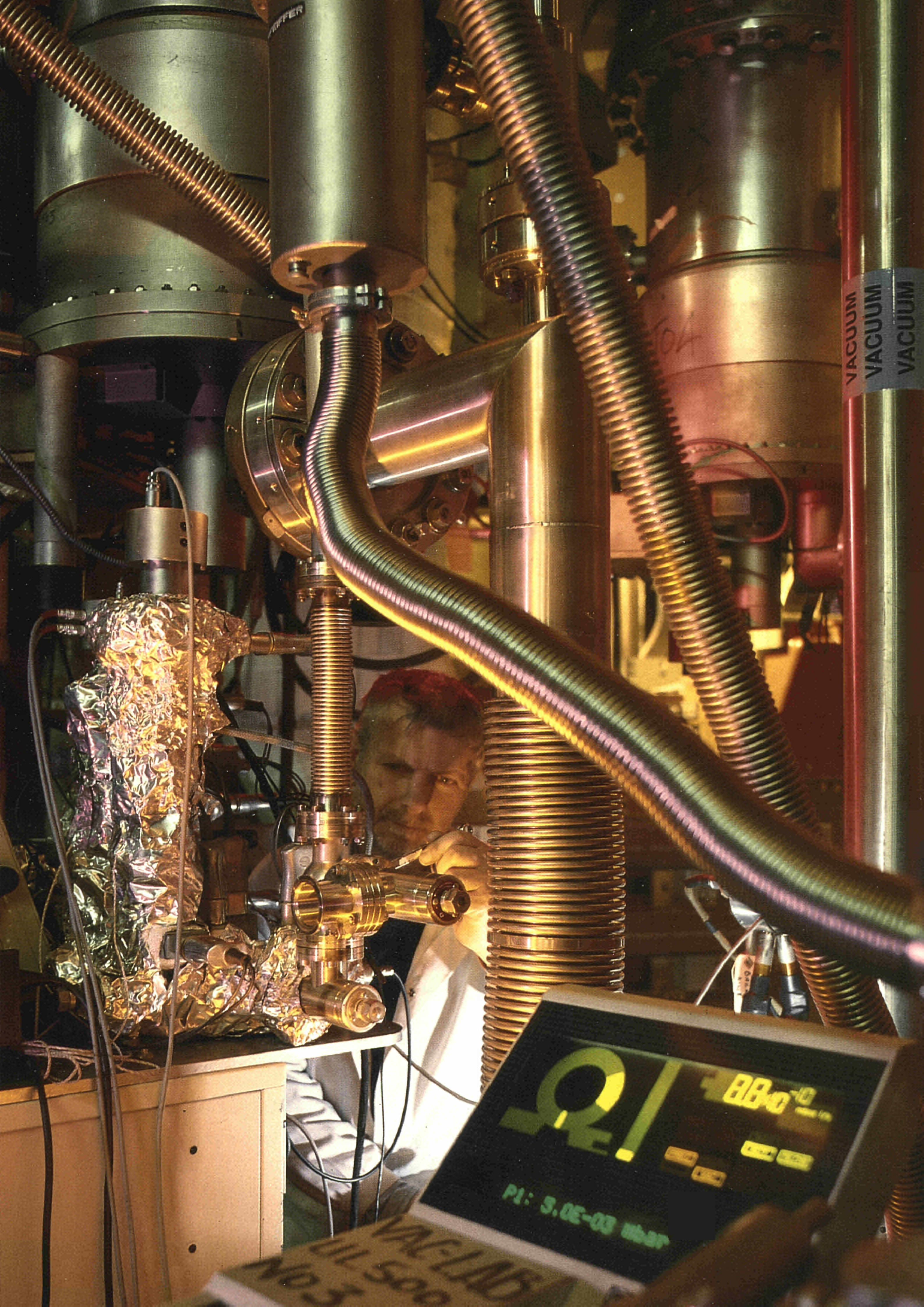
Within the Project Development Plan to the end of 1996, the Active Gas Handling System (AGHS) will be required to be fully operational before the start of the full D-T phase of JET scheduled for 1996. The function of these systems is to collect gases from the torus, to remove impurities and to separate pure deuterium and tritium for storage or re-injection through neutral beam, pellet or torus gas introduction, as required. The functions of the Active Gas Handling System are shown in Fig.28. The main aim of these operations is to minimise the release of tritium to the environment and to avoid production of tritiated waste, as far as practicable.

Installation of the process systems within the AGHS Building was essentially completed at the beginning of 1993 and effort during the year has concentrated on inactive commissioning and interfacing with the torus systems. The torus vacuum lines have been connected to the AGHS in such a way that either the conventional rotary pumpset or the AGHS can be used to back the torus turbomolecular pumps. This will enable active commissioning to proceed relatively independently of torus operations. The connection to the existing systems were made in accordance with the strict "quality assurance" standards required for tritium operation. End-to-end commissioning of signal and control loops connected to the distributed control system have been completed and the majority of the control sequences have been tested.

As the Active Gas Handling System (AGHS) handles pure tritium, it has been designed and built to extremely high standards. To meet the approval requirements of the UKAEA's Safety and Reliability Directorate (SRD), it is required to be certificated by a so-called "third party" Inspector. This necessitates an extremely rigorous quality assurance system to ensure that procurement, fabrication and modification documentation is complete and acceptable. A milestone was achieved when the complete certification for the gas chromotography system, which involved several external manufacturers and on-site fabrication, was received. Good progress is being made on the other systems.

The final safety case document from the AGHS required before tritium can be introduced into the plant, under the new UKAEA system is the "Pre-Commissioning Safety Report (PCMSR)". This has been prepared and SRD comments are being implemented. It is evident that the overall risk from the AGHS meets current UKAEA standards.

Torus safety documentation is being prepared consistent with the timescale of a further preliminary tritium experiment (PTE-2) in the second half of 1994 and full D-T operation in 1996. A Hazard and Operability Study (HAZOPS) and associated limiting dose assessments have been carried out to identify those systems which require detailed safety analysis. This was necessary to fulfil SRD requirements for a systematic method of hazard indentification, particularly as JET is a novel form of radioactive plant. A Preliminary Safety Report (PSR) has been prepared and SRD comments on this are being reviewed.


VACUUM
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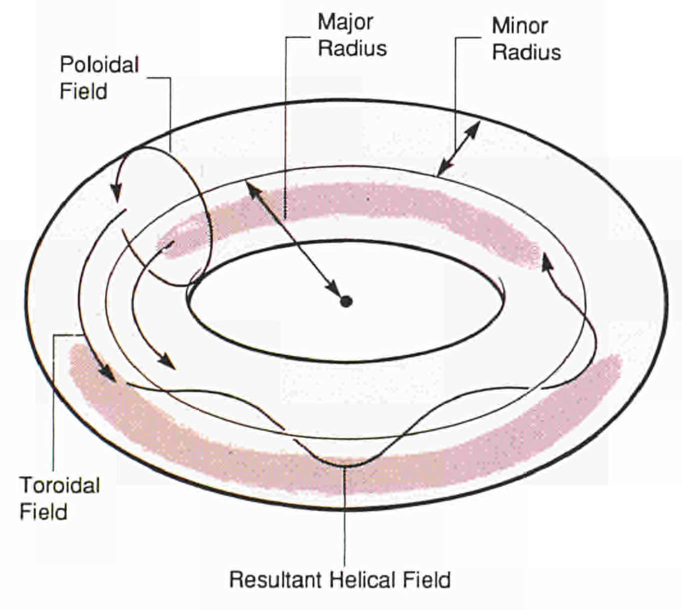
P1: 3.0E-03 mbar

Scientific Advances During 1993

Introduction

The overall objective of the Project is to study plasma in conditions and with dimensions close to those needed in a fusion reactor. The central values of temperature, density and energy confinement time required for a reactor operating with deuterium and tritium are such that the fusion triple product, ($n_i \tau_E T_i$), must exceed the value of $5 \times 10^{21} m^{-3}$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, temperatures of 3keV and 4keV for the ions and electrons, respectively, densities of $4 \times 10^{19} m^{-3}$ and energy confinement times of 1s are the limits that have been achieved. These parameters were obtained simultaneously during one discharge and resulted in a fusion product of $1.2 \times 10^{20} m^{-3}$keVs.



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.

TABLE 6: REACTOR PARAMETERS

CENTRAL ION DENSITY, n_i	$2.5\times10^{20}m^{-3}$
GLOBAL ENERGY CONFINEMENT TIME, τ_E	1-2s
CENTRAL ION TEMPERATURE, T_i	10-20keV

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.

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

Higher values of temperature, density and energy confinement have been obtained individually in separate experiments, but not simultaneously during one discharge. These include peak ion temperature up to 30keV, energy confinement times up to 1.8s and central densities up to 4x$10^{20}m^{-3}$.

Ignition

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

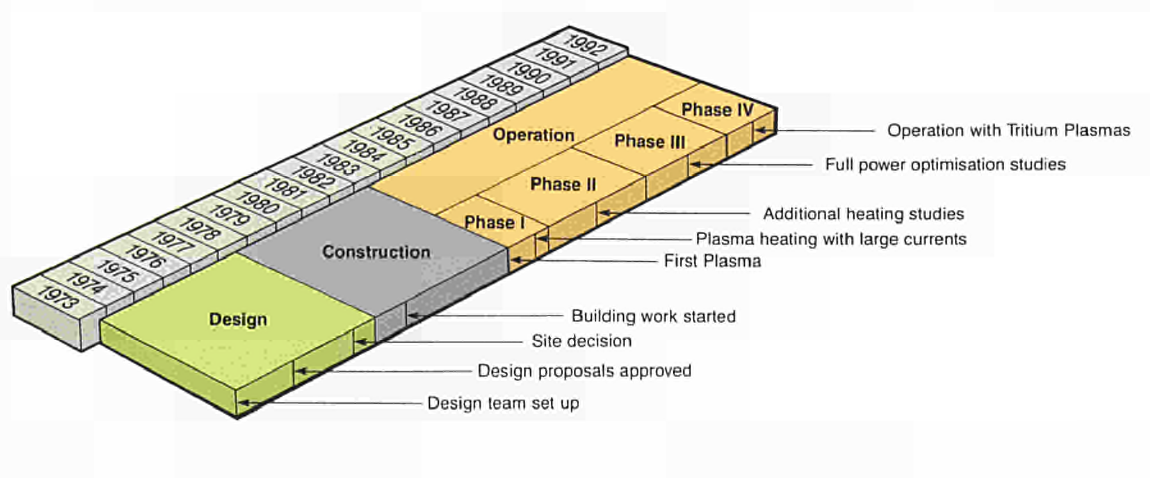


Fig.29: The original overall JET programme

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 acceptable 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.29. The Ohmic Heating, Phase 1, was completed in September 1984 and Phase II - Additional Heating Studies - started early in 1985. By December 1986, the first part, Phase IIA, had been completed. The machine then entered a planned shutdown for extensive modifications and enhancements before the second part of the Additional Heating Studies, Phase IIB, which started in June 1987. The objective of this phase, from mid-1987 until late-1988, was to explore the most promising regimes for energy confinement and high fusion yield and to optimise conditions with full additional heating in the plasma. Experiments were carried out with plasma currents up to 7MA in the material limiter mode and up to 5MA in the magnetic limiter (X-point) mode and with increased radio frequency heating power up to 18MW and neutral beam heating power exceeding 20MW at 80kV. The ultimate objective was to achieve full performance with all systems operating simultaneously. Phase III of the programme on Full Power Optimisation Studies started in 1989 and was completed in early 1992. In 1991, JET's lifetime was prolonged by four years until the end of

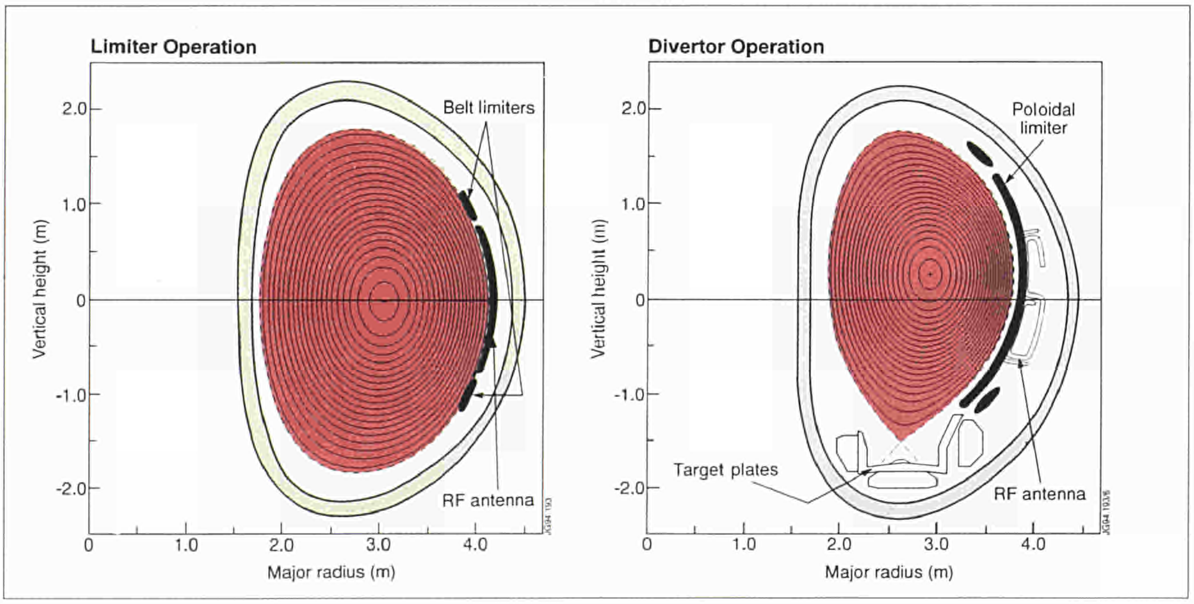
Operating Modes

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.



1996. The extension was approved to allow JET to implement the new Pumped Divertor Phase of operation, the objective of which is to establish effective control of plasma impurities in operating conditions close to those of the Next Step. This programme of studies would be pursued before the final phase of full D-T operations in JET.

The 1991/92 experimental period concentrated on: optimisation of plasma performance; advancing understanding in certain key areas of tokamak physics, (such as: physics of the H-mode; energy transport and confinement; and transport of particles and impurities); and establishing the basis for pumped divertor and Next Step physics (including a Preliminary Tritium Experiment).

The machine entered a major shutdown in early 1992, which lasted throughout 1992 and 1993, to prepare the machine for the divertor phase of operation.

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.

Main Scientific Results

Throughout 1993, JET was in the course of a major shutdown to prepare for the pumped divertor phase of JET. Consequently, no further scientific results were available from the machine. Scientific effort during this period was shared among the areas of:

- Further analysis of previous results;
- Further analysis of Preliminary Tritium Experiments;
- Preparation for 1994/95 operation;
- Studies of advanced divertor operation;
- Studies of advanced tokamak scenarios;
- Consideration of ITER-related issues.

The following sections describe significant advances in these areas.

Further Analysis of Previous Results

Pellet Enhanced Performance (PEP) H-modes

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 (PEP) mode. PEP H-modes have been developed using up to 28MW of heating power, but the highest fusion performance (~2×10^{16} neutrons s^{-1}) was obtained using about 11MW of neutral beam heating with a small amount of ICRF heating.

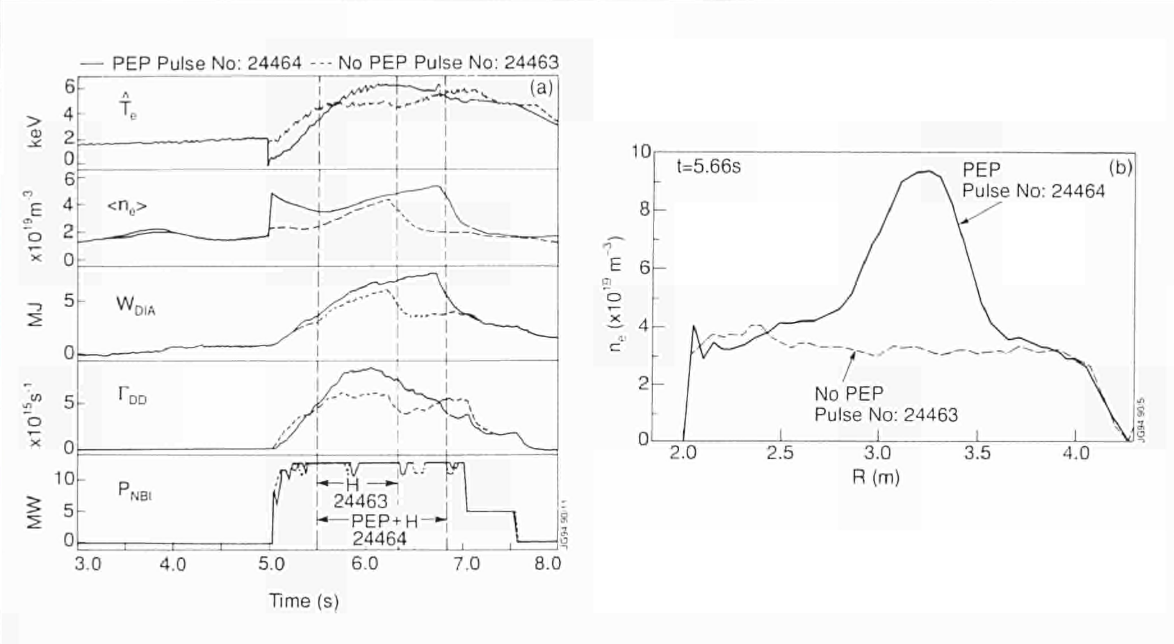


Fig.30: Comparison of (a) time evolution of the central electron temperature, plasma energy, total neutron rate and neutral beam power of an H-mode with (Pulse No.24464) and without (Pulse No.24463) the PEP density enhancement; (b) Plasma electron density profile measured at t=5.66s for the two pulses in (a)

The central power deposition of the ICRF heating was essential to achieve highest performance. Some of these discharges had global confinement enhancement relative to L-mode of factors up to ~3.

The PEP confinement properties can be seen by comparing an H-mode alone with a PEP H-mode under similar conditions. Figure 30(a) shows the time evolution of two almost identical neutral beam heated discharges, one with a 4mm pellet injected at 5s and the other without. In the case with the pellet, higher values are obtained for the plasma stored energy and neutron yield. In Fig.30(b), the effect of the PEP is evident by a significantly higher central electron density.

Figure 31 shows the non-inductive current density profiles calculated for these two pulses. In the PEP discharge, the bootstrap current dominated due to the steep pressure gradient near the plasma centre. In the case without the PEP, the beam driven current dominates due to lower central density and results in a centrally peaked non-inductive current profile. The effect of pellet injection combined with the off-axis bootstrap current produced a region of negative shear in the plasma core, which may play a role in the enhancement of local confinement. However, the region of improved confinement is somewhat larger than the negative shear region. The particle diffusion in the core of the PEP H-mode also appeared to be reduced below normal L-mode values.

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.

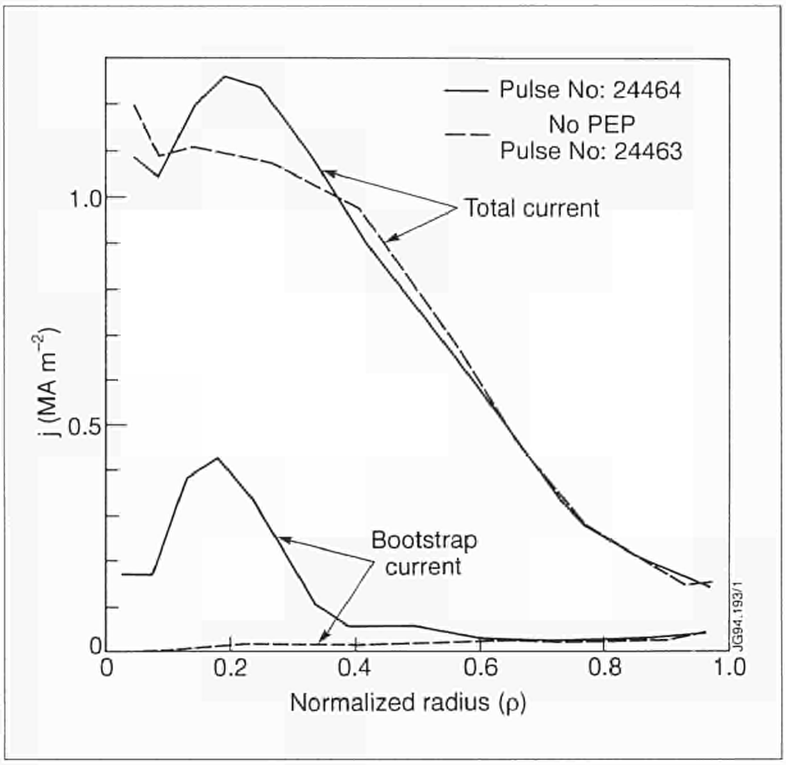


Fig.31: Total current and bootstrap current profiles versus normalised radius, for the pulses shown in the previous figure

Central heating, by the deposition of RF power within the central region leads to an improvement in the central electron and ion temperatures of the discharge and also in the fusion performance. At the central densities achieved in the best PEPs (>8x10^{19}m^{-3}), equipartition ensured that the electron and ion temperatures were nearly equal. The highest ion temperatures (~14.5keV) achieved on JET with ICRF heating were measured, in these cases.

Synergy between Lower Hybrid and RF Heating

The first evidence of the interaction of lower hybrid waves with ICRF minority ions with an energy of a few MeV was detected in JET. These synergistic effects have been found in combined operation of lower hybrid and ICRF heating, in deuterium and helium plasmas. When lower hybrid waves were launched into the plasma in conjunction with ICRF waves, increases in the γ-ray emission and neutron emission rate were observed. The increase of the neutron rate was associated with an increase of the deuteron energy, either due to direct coupling of the lower hybrid waves to deuterons or due to deuteron heating through bulk electron-ion coupling. The energy content of the fast ions increased during combined operation of

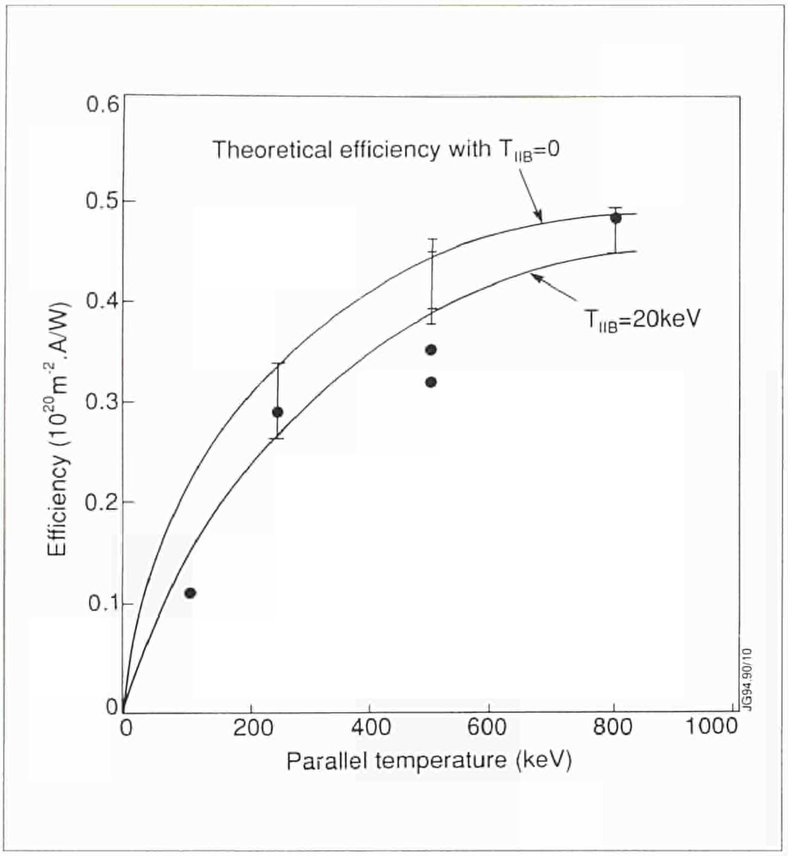


Fig.32: Current drive efficiency with combined lower hybrid and ICRF heating compared with theory

lower hybrid and ICRF heating. A transfer of up to 20% of the injected lower hybrid power to the fast ions much be assumed to reproduce these measurements.

The global current drive efficiency, with the total RF power input, reached values of 0.4. The increase of the current drive efficiency with the parallel tail temperature is in good agreement with theory, as shown in Fig.32. Therefore, combined operation of lower hybrid and ICRF power provides a way to reach values of non-inductive current drive efficiency required in a reactor at potentially higher densities than could be achieved with LHCD alone.

These experiments confirm the model calculations for the interaction of LH waves with α-particles in reactor grade plasmas. At sufficiently high frequency (>5GHz in ITER), the damping of lower hybrid waves can be concentrated onto electrons.

Further Analysis of Preliminary Tritium Experiments

Following the Preliminary Tritium Experiments (PTE) in November 1991, a thorough analysis followed throughout 1992 and was carried over

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.

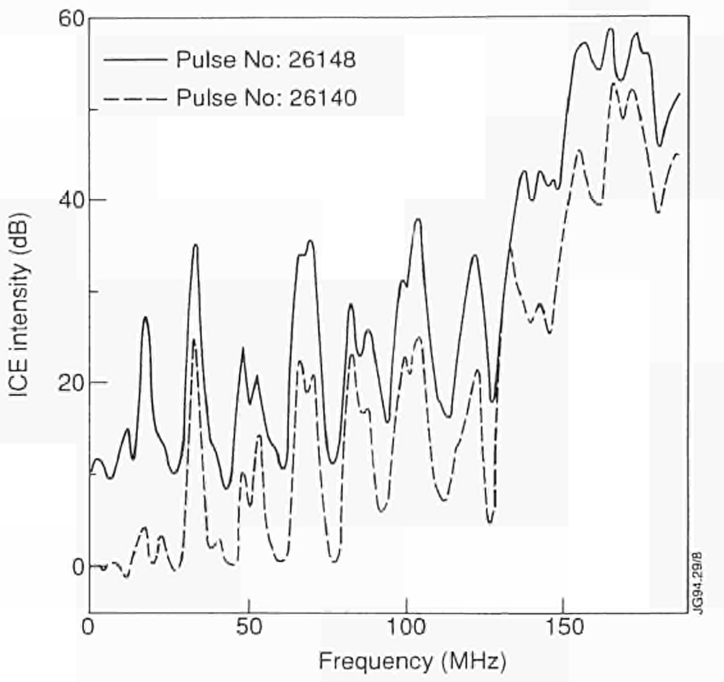


Fig.33: Two ICE spectra in comparable plasmas (Solid curve: mixed D-T plasma; dashed curve: pure deuterium). Although the D-T spectrum is more intense, both spectra have similar forms

into 1993. This has led to a series of publications in the Nuclear Fusion journal in 1993, which covered the following subjects:

- Neutron emission profile measurements during the tritium experiments;
- Release of tritium from the first wall;
- Particle and energy transport during the PTE;
- Ion cyclotron emission measurements during the deuterium-tritium (D-T) experiments;
- Discharge termination of high-performance discharges.

Substantial further analysis has been carried out during 1993, in the following areas;

- Ion cyclotron measurements;
- Discharge termination.

Ion Cyclotron Emission in D-T Experiments

In 1993, progress has been made in developing a theoretical interpretation of the superthermal ion cyclotron emission (ICE) during the preliminary tritium experiment and with pure deuterium. The

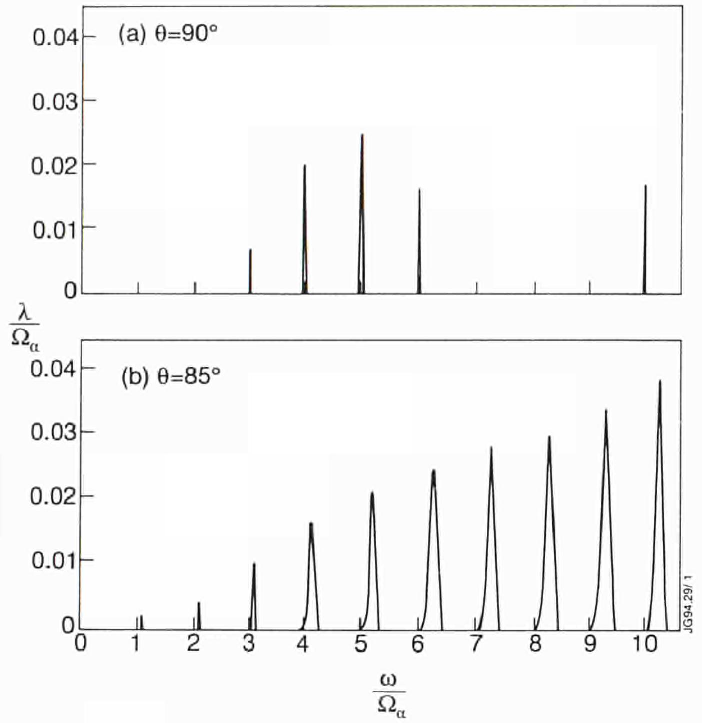


Fig.34: Linear growth rate of the cyclotron instability as a function of frequency: (a) propagation angle is 90°; (b) propagation angle is 85°

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)).

radiation intensity is proportional to the total fusion reactivity of the plasma over a range of six decades of signal intensity. This evidence connects the superthermal ICE with the birth of charged fusion products and shows that a fraction of their free energy is transformed into wave energy. There is no threshold in fusion reactivity below which ICE is not excited in the plasma. Within a single discharge, correlations have been observed between the time evolution of the ICE signal and the neutron flux. The ICE spectra (Fig.33) contain superthermal, narrow, equally spaced emission lines which match successive cyclotron harmonics of deuterons or fusion alpha-particles at the outer mid-plane of the plasma. All harmonic numbers, up to at least ten, are present in the spectrum.

Previous work on the mechanism for this emission has focussed on determining the linear stability of ion cyclotron frequency modes excited in a plasma by a diffuse population of energetic fusion ions. This early theoretical treatment involved coupling of fast Alfven waves with certain ion waves and included only waves which propagated normal to the magnetic field. In this model, an instability threshold was evident. As a result, the simple model predicted a threshold concentration of energetic particles below which it would not be possible to excite certain harmonics. However, experimentally, there was no threshold concentration. Given typical parameters appropriate to JET plasmas, this theory predicted instability for some, but not all, of the alpha-particle ion cyclotron harmonics observed (Fig.34(a)).

However, during 1993, the theory has been extended to include waves which propagate obliquely across the magnetic field. In this picture, the thermal deuterons support propagation of Alfven waves, which are perturbed by alpha-particles, and the radiation excited by the fast ions is decoupled from the background deuterons. For typical JET parameters, oblique propagation excites all harmonic numbers from one to ten, as observed experimentally (Fig.34(b)). The growth rate of each of the cyclotron harmonics is proportional to the concentration of the energetic ions. A finite concentration threshold is still predicted with the revised theory. However, the magnitude of the threshold is very much smaller than in the earlier model. In addition, the low predicted threshold suggests that the odd deuteron harmonics observed in pure deuterium ohmically heated discharges could possibly be explained in terms of emission from the secondary alpha-particles, which are produced when the primary fusion tritons fuse with the bulk deuterium.

MARFE

A MARFE (Multifaceted Asymmetric Radiation From the Edge) is a toroidally symmetric band of cold, highly radiating plasma which normally 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.

Termination of Hot-ion H-mode Discharges

The hot-ion H-mode discharges developed for the preliminary tritium experiment usually suffered a dramatic termination of their high performance phase. At the termination, the neutron rate declined sharply caused by the central ion temerperature falling (from a value of about twice the central electron temperature to a value of about equal to the central electron temperature). The central electron temperature remained relatively unchanged. In good temporal correlation with the termination, a reduction of the electron temperature occurred over large parts of the outer plasma cross-section without reduction of plasma heating. This electron temperature behaviour was also found with the ion temperature in the outer plasma cross-section and marked a dramatic loss of confinement.

The termination was sometimes precipitated by large MHD instability events, like sawteeth, coupling to giant edge localised modes (ELMs) or by giant ELMs on their own. More regularly observed was that, during the degradation of the edge electron

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.

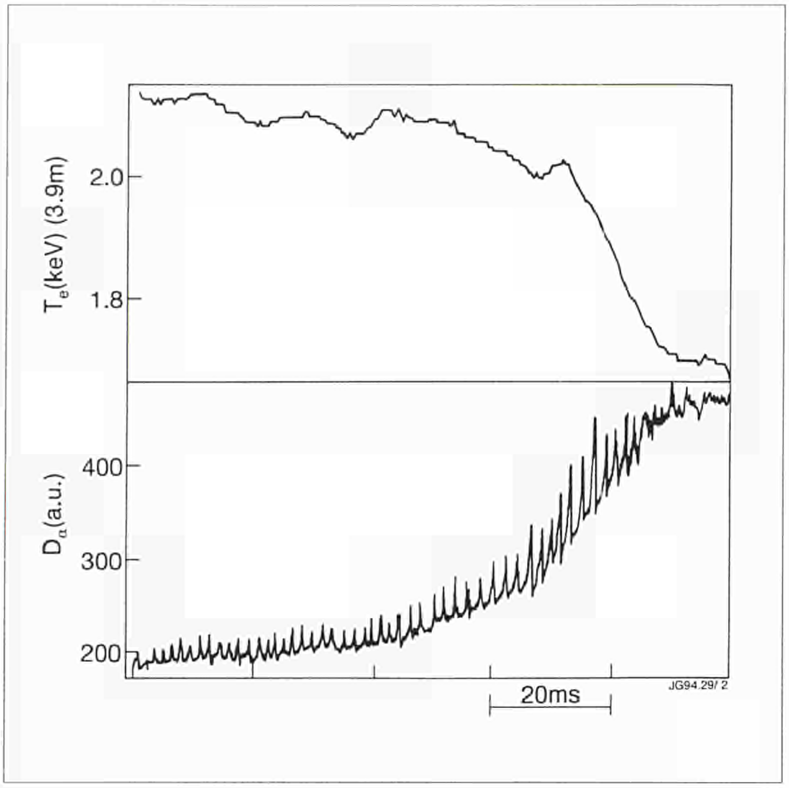


Fig.35: Reduction of electron temperature at the edge of the plasma and bursts of D_α emission

temperature, bursts of emission of D_α radiation at low repetition frequency grew in amplitude (Fig.35).

At the termination, both the heat transport and the particle transport increased. At present, it can not be excluded that the termination is ultimately caused by effects at the plasma centre. However, it can be stated positively that the termination always coincided with a sudden loss of edge confinement, which affected, in a global way, large parts of the outer plasma cross-section. The increased particle transport in the outer plasma region, in the presence of hollow impurity profiles at the termination, in conjunction with the carbon bloom due to the increased outflow of heat, make the termination irreversible.

Preparation for 1994/95 Operation

Real Time Plasma Boundary Determination

The equilibrium reconstruction provides essential input for many diagnostic systems at JET. The pumped divertor phase requires accurate determination of the magnetic field configuration, especially of the plasma boundary. For this purpose, the existing equilibrium codes have been modified to include the four divertor coils as well as upgraded magnetic diagnostics.

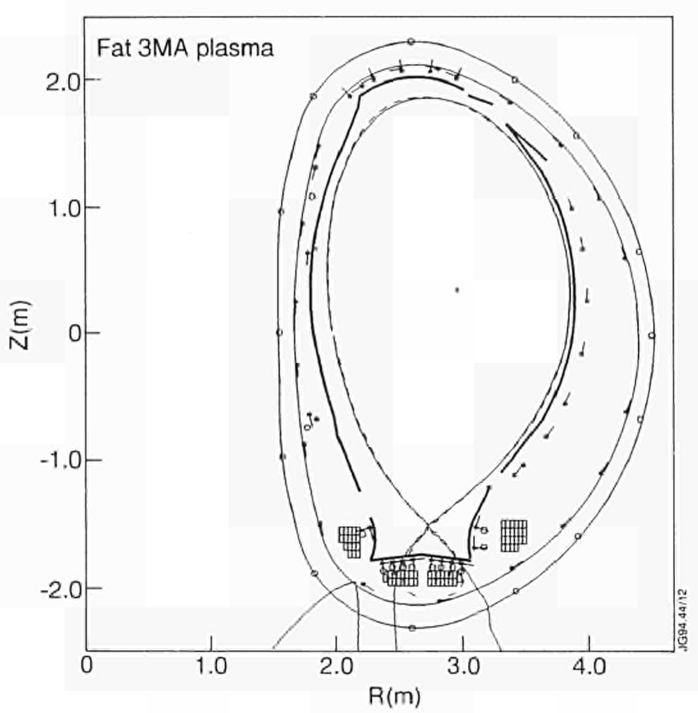


Fig.36: Reconstruction of a pumped divertor 3MA FAT plasma using the XLOC code. The dashed line is the PROTEUS code, and the solid line is the XLOC reconstruction

Three computer programs have been used in studies of X-point plasma geometries: the predictive code PROTEUS has been employed to generate "data" for the full equilibrium identification code EFITJ and the plasma boundary identification code XLOC. Both identification codes reproduce the plasma boundary calculated by PROTEUS.

A transputer based system has been developed capable of performing real time determination of the plasma boundary. This system has been used successfully to produce, for the first time, an animated display of the plasma boundary cross-section. To provide a real time, on-line calculation of the plasma boundary, the transputer based system takes its input directly from the magnetic pickup coils and performs the calculation in less than 2ms. The system provides a real time on-line display and play-back facility. The boundary data is also suitable for use in plasma shape control, which plays an important role in optimising plasma performance, necessary for long pulse operation in future reactors. The plasma boundary determination is based on a local

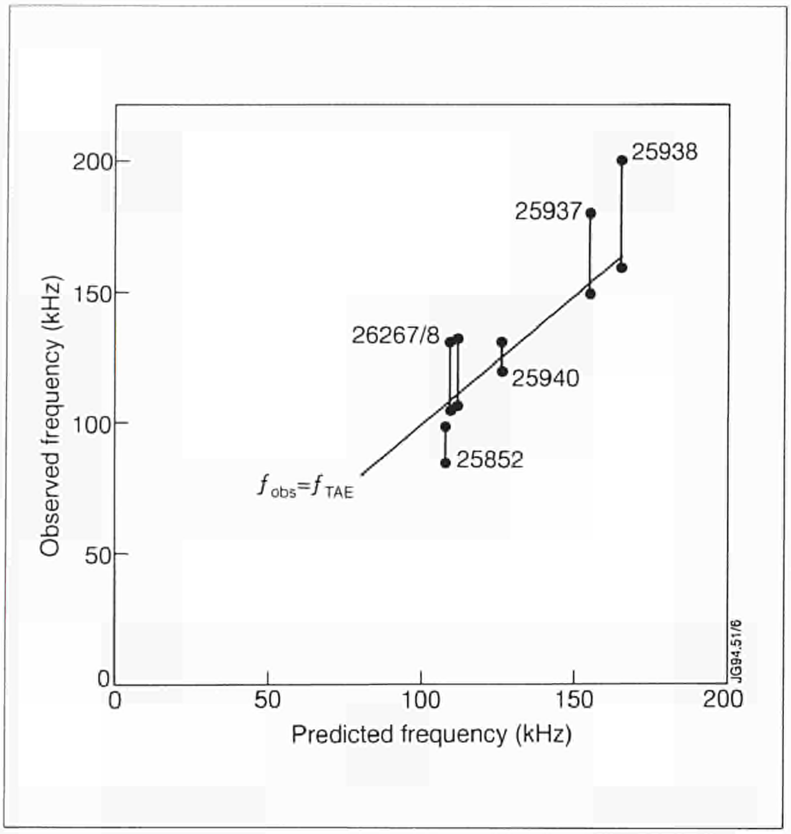


Fig.37: Comparison of observed and predicted TAE mode frequencies

expansion technique that was originally introduced at JET to have a fast and accurate determination of the plasma boundary in the X-point region. A reconstruction of a fat 3MA pumped-divertor type configuration using this code is shown in Fig.36.

TAE Modes

Toroidicity-induced Alfven Eigenmodes (TAEs) can be driven unstable by fast particles originating from neutral beam injection, ICRF heating or fusion reactions. Destabilisation of such modes in reactors is a subject of concern as they may lead to anomalouly rapid losses of energetic alpha-particles, reducing alpha heating efficiency and potentially damaging the first wall. These modes are characterised by high frequency (typically 100-200kHz in JET) which depends on the Alfven speed. Theory predicts several TAEs can be simultaneously unstable. Recent analysis has revealed the presence of modes in JET showing these features. A comparison of observed frequency with the predicted frequency is given in Fig.37 for several pulses. The frequency spectra show that the structure contains several discrete modes, with typical toroidal mode numbers in the range n=1-6. No reduction in neutron rate, correlated with these modes, has been observed, although, in ICRF heated plasmas, a correlation between low level fast particle loss and the mode amplitude is suggested. Detailed analysis of these modes will be possible with improved spatial and temporal resolution of diagnostics in future experiments.

In view of their potential importance in a reactor, a system is being prepared, which will excite Alfven eigenmodes in the plasma. The chosen approach is based on the use of the large inductance saddle coils to generate a perturbation in the tokamak magnetic field which affects most of the plasma volume and oscillates at the typical Alfven eigenmodes frequencies. When the excited perturbation matches the natural Alfven eigenmode frequencies (both in terms of real frequency and wave number spectrum), a resonant response, i.e. a peak in the magnetic activity detected by poloidal pick-up coils and the saddle coils themselves, is expected.

Initially, a study of driven spectra without fast particles will provide a full description of the Alfven eigenmodes complex dispersion relation and specifically of the different mode damping mechanisms for different wave number spectra and plasma configurations. Subsequently, experiments associated with the creation of fast particles with additional plasma heating methods such as ICRF and/or neutral beam injection should enable a quantification of the fast particle driving term in the different scenarios, corresponding to different fast particle contents, and to infer the marginal stability limit for these modes in reactor relevant plasma conditions.

Advanced Divertor Studies

The Mark I divertor has always been considered an interim solution to the impurity problem, due to its limited power handling capability and open structure. Studies were started in 1992 to define a new divertor (Mark II) to follow Mark I. This work resulted in a concept for an inertially cooled divertor based on a toroidally continuous rigid "substructure", onto which tile/tile carrier modules are mounted. It is possible to change the divertor geometry relatively quickly and inexpensively by exchanging one set of tile/tile carriers for another. Furthermore, Mark II has been designed so that the exchange can be carried out by remote handling, permitting installation of a new divertor even after an extended phase of D-T operation.

Divertor

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

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

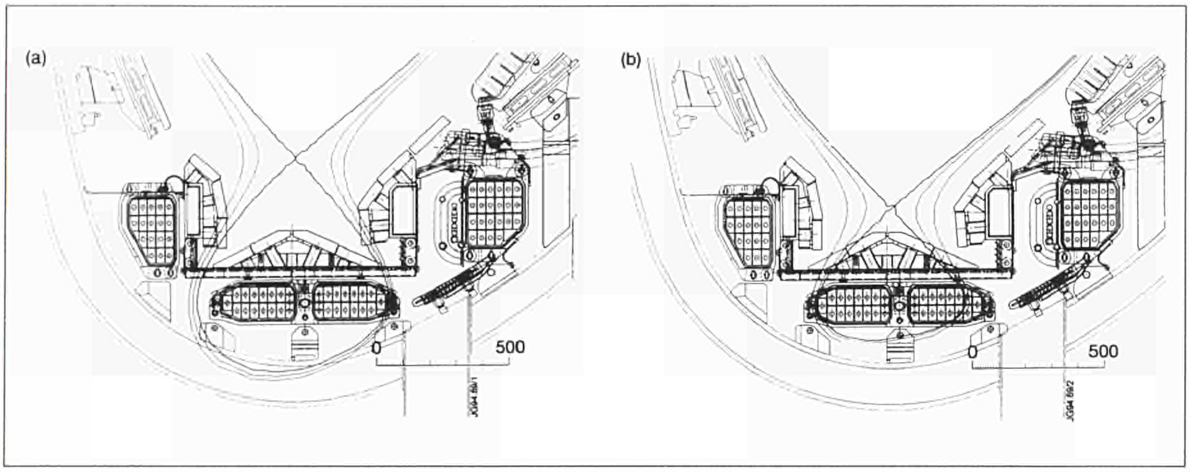


Fig.38: View through Mark IIA divertor: (a) with strike points on side plates; (b) with strike points on dome.

In early 1993, the construction of a Mark II divertor was proposed. The JET Council authorised construction of Mark IIA in June 1993. In October, the JET Director presented a proposal to the European Joint Working Group for an extension of JET operation until mid-1999, during which time a second version of Mark II would be tested.

The two stage Mark II divertor programme is designed to fulfil the divertor requirements of the high performance programme, while also providing important information for the development of an ITER divertor by systematically investigating a range of suggestions put forward for solving the ITER divertor problem. These include gas box divertors, slot divertors with high neutral pressure, divertors with glancing incidence target, and others. Although a great deal of progress has been made recently in modelling divertors under the high power, high density conditions expected in ITER, none of the models has been validated. Therefore, it is necessary to test experimentally as many aspects of high power/high performance divertor physics as practical, on a timescale rapid enough to impact on the ITER design. This is the aim of the proposed JET divertor programme. JET has proposed two tile/tile carrier geometries for the Mark II base structure as part of an integrated divertor test programme, as set out below.

The Mark IIA Divertor

Mark IIA is a moderate slot or V-type divertor, which is flexible enough to accept a wide range of JET equilibria; its principal purpose is to explore geometric effects by exploiting both "vertical" and "horizontal" (dome) target plates for a wide range of conditions. The Mark IIA geometry, shown in poloidal cross-section in Fig.38, was chosen to accommodate JET discharges over a wide range of operating conditions:

- it accepts a large variety of equilibria, allowing extensive variation of X-point height, connection length and flux expansion, with plasma currents up to 6MA;
- operation at field line angles of incidence as low as 0.5° is possible, allowing tests of "glancing incidence" concepts;
- it was designed specifically to accommodate "high performance" equilibria.

In addition, the Mark IIA design retains all the technical features inherent in the basic Mark II concept; the use of large tiles precisely aligned on a rigid base structure to provide a high toroidal wetted length. Mark II also features a flexible gas introduction system with a high degree of toroidal symmetry and the ability to independently supply gas at four poloidal locations in the divertor chamber. It can also incorporate beryllium tiles, if required.

The experimental programme will cover many of the issues initially investigated in Mark I, but with the significant advantages of no sweeping required, the ability to operate with high power and plasma current on the vertical target plates, and in a more closed geometry. Highlights of the programme will include:

- investigation of "attached plasma" operation on both vertical and dome target plates for a wide range of power and plasma density, with examination of power handling, impurity retention, and pumping/puffing scenarios;
- dedicated scans of the magnetic configuration (X-point location, connection length, flux expansion);
- investigation of "detachment" in divertor plasmas;
- studies of "glancing incidence" geometries;
- helium exhaust studies;
- studies of long pulse H-modes and ELMs.

Mark II-GB (Gas-Box) Divertor

Mark II-GB is a "gas box" divertor, described generically as an arrangement with a fairly narrow opening near the X-point (the "entrance baffle"), below which there is a large, relatively open divertor volume in which neutrals can recirculate freely, entering the plasma fan laterally and removing energy by radiation and charge-exchange

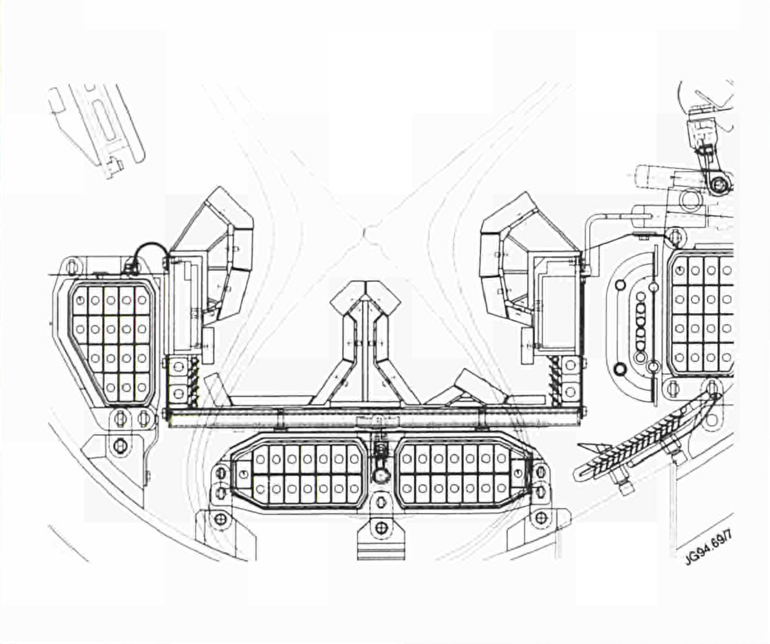


Fig.39: Preliminary design of Mark II-GB. (Targets are indicative only)

processes. While a preliminary design for Mark II-GB exists and modelling has begun, the design need not be finalised until early 1995, allowing input from the Mark I experiment, and continued modelling.

The primary intended advantage of a gas box design is that it spreads the power more uniformly over the divertor walls, thus minimising the peak power loading. However, there are some clearly recognisable problems. The existence of an appreciable neutral density near the base of the baffle cools the outer layers of the divertor plasma, tending to make the elimination of backstreaming neutrals more difficult than in a design (such as Mark IIA) which tapers the distribution of neutrals in the vertical direction. In addition, the same high neutral density can cause severe erosion problems at the baffle, introducing impurities in the neighbourhood of the X-point. Nevertheless, the gas box concept has much promise, and is currently the favoured ITER choice. JET is therefore presently planning its Mark II programme to include a test of this concept. Figure 39 shows an outline sketch of a preliminary Gas Box design based on the Mark II structure, a preliminary mechanical/thermal analysis of the design is currently underway. At the same time, modelling is continuing to optimise the baffle shape and define the target shapes and the need for side fins. During early 1994, a strong input of experimental data is expected from operation of Mark I to help guide the design. This should result in finalisation of the shape

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.

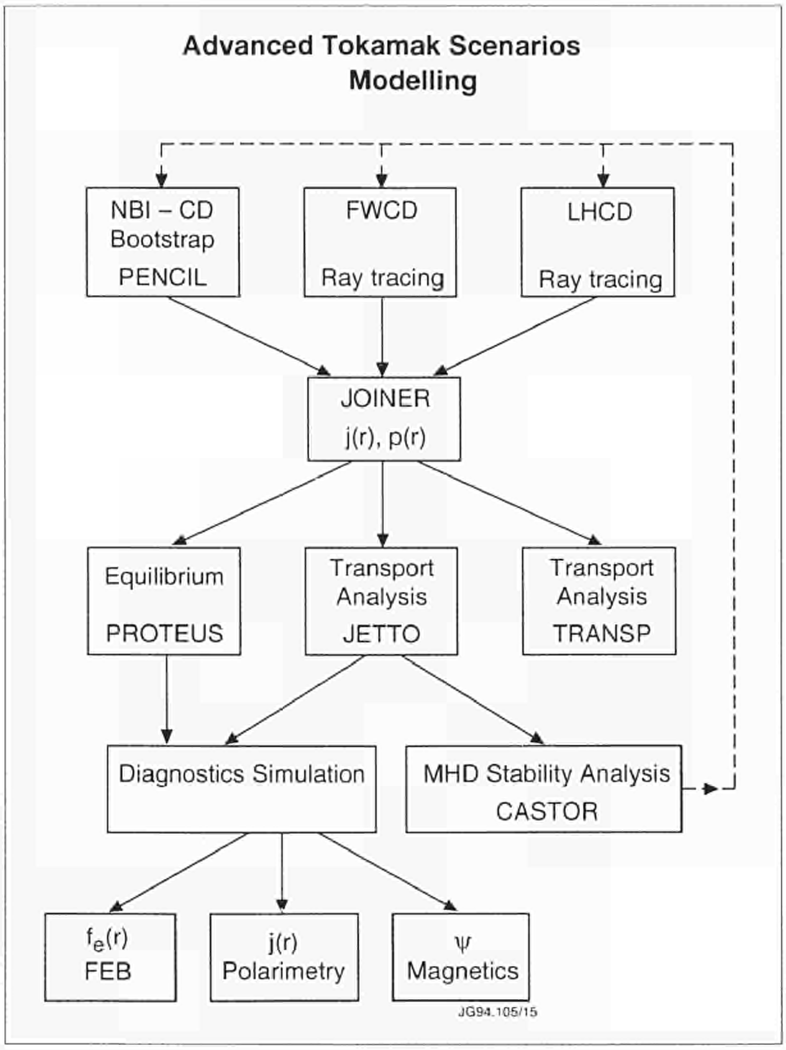


Fig.40: Flow chart of the code calculations for profile control scenarios

of Mark II-GB by early 1995, in time to ensure operation in early 1997.

It should be stressed that both Mark IIA and Mark IIGB are ITER-relevant. Each tests aspects of divertor physics which are essential to building the database necessary to define the divertor which will ultimately be built for ITER. The proposed JET programme provides for introduction of Mark IIA in 1995, followed by operation of Mark II-GB beginning early in 1997, thus providing the information soon enough for the EDA phase of ITER.

Advanced Tokamak Scenarios

The proposal for a further JET extension to 1999 included the proposition to investigate coherent steady-state tokamak concepts (the so-called advanced tokamak scenarios) for ITER and DEMO. Advanced Tokamak scenarios for steady-state operation require a high bootstrap current fraction (>70%), high beta and good H-mode energy

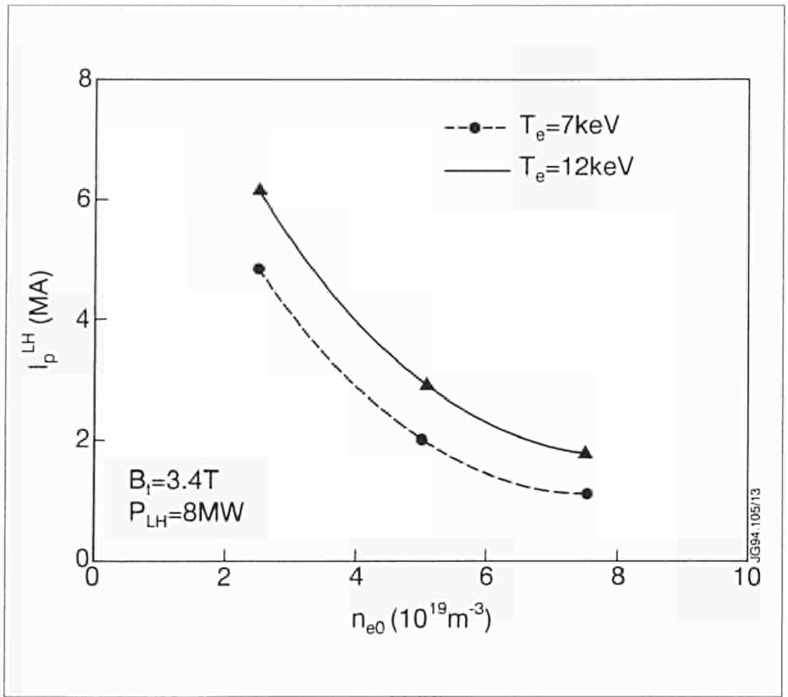


Fig.41: Current drive capability of the LHCD system on JET

confinement. The broad current density profiles typical for high bootstrap current operation are prone to MHD instabilities. Active profile control is therefore required. Complex model calculations have been performed in preparation for specific experiments. Code calculations have been validated against existing data from previous experiments on JET with high bootstrap current and with LHCD. The flow chart for the model calculations is shown in Fig.40. Modules for the bootstrap current, for neutral beam current drive and LHCD have been validated and implemented. Self-consistent transport code calculations with all current drive and heating methods have now started.

Three high power noninductive current drive systems are available now on JET, with lower hybrid current drive (LHCD), fast wave current drive (FWCD), and high energy neutral beam current drive (NBCD). Current drive experiments have been extensively prepared for the new experimental campaign, in the divertor configuration. The work has concentrated on code development and modelling of complete scenarios involving all three current drive and heating systems. Codes were developed for the calculation of power and current deposition profiles and for predictive transport calculations. Scenarios of potential steady-state tokamak operation with high bootstrap current and residual non-inductive current drive were studied, using these codes.

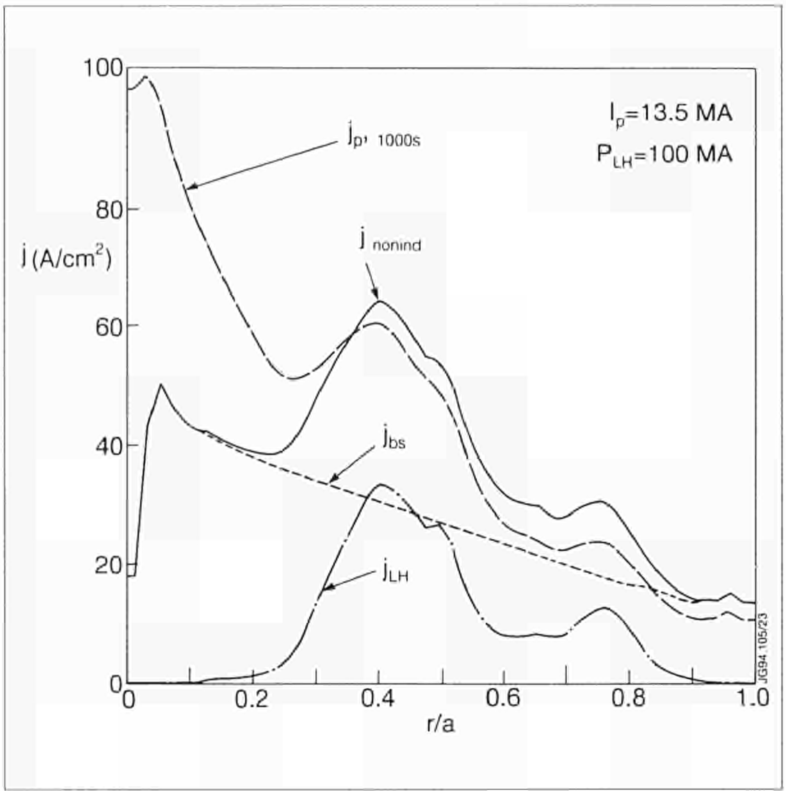


Fig.42: Radial profiles of LH driven current (j_{LH}), the bootstrap current (j_{bs}), the total non-inductive current (j_{nonind}) and plasma current at 1000s into the discharge ($j_{p,1000s}$) for the ITER steady-state case.

Profile control schemes were developed to provide stable operation at high poloidal beta values with non-monatomic q profiles.

Modelling calculations were carried out for the prospective operational range of lower hybrid current drive experiments on JET. Penetration of lower hybrid waves into the plasma centre is obtained up to a central density of $3x10^{19}m^{-3}$ at 3.4T magnetic field. At this field, the full plasma current of 4.5MA can be driven by LHCD up to this central density. The current drive capability of the LHCD system is shown in Fig.41. A maximum net current drive input power of 8MW can be expected from this system. The results of extensive calculations for this LHCD power launched into plasmas are shown in Fig.41 for two different central electron temperatures (7keV, 12keV). Significant contributions from LHCD to the total plasma current are still obtained at a central density of $7.5x10^{19}m^{-3}$.

The tools developed for profile control experiments on JET were also used to model possible scenarios of steady-state operation in the presently proposed ITER device. A total power input of 100MW lower hybrid power alone was used in these calculations. Ignition was obtained with lower hybrid heating alone, resulting in a fusion power output of 2GW. The alpha-particle heating profile was strongly peaked. With the resulting peaked temperature and pressure profiles, the bootstrap current distribution had a maximum near the plasma centre and decreased towards the plasma edge. In the steady-state phase, a hollow current density profile was obtained. The corresponding currents in a still transient phase (after 1000s) are shown in Fig.42. With a bootstrap current of 9MA and the lower hybrid current drive of 4.5MA, the total current was driven non-inductively. The power input could be redistributed between LHCD and Fast Wave Current Drive (FWCD), to provide full current profile control over the whole plasma cross-section. The total power requirements should be similar in this case, as comparable current drive efficiencies can be expected for LHCD and FWCD in ITER conditions.

ITER Related Issues

Global Confinement Analysis

Simulation of L-mode Discharges

Two local transport models, one of the Bohm type and the other of the gyro-Bohm type, have been determined empirically for the simulation and prediction of results in L-mode tokamak discharges. The number of non-dimensional parameters entering the models have been minimised, while aiming to take into account the most important local and global energy transport features of L-mode discharges.

The models have been tested with a predictive $1^1/_2$D equilibrium-transport code against a set of steady-state and time dependent discharges. These discharges were chosen from experiments aiming to characterise important features of L-mode local energy confinement in JET, current ramp and on-axis/off-axis heating experiments.

In agreement with results of interpretive analysis, the Bohm model performed better than the gyro-Bohm model in simulating JET L-mode discharges. However, taking into account the experimental errors, the gyro-Bohm model could not be ruled out.

The performance of ITER predicted by both models has been studied. As expected, while the gyro-Bohm model allowed ignition (but very marginally) even in L-mode, the Bohm model required a substantial enhancement of transport above L-mode (2-3 times) for the same result.

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.

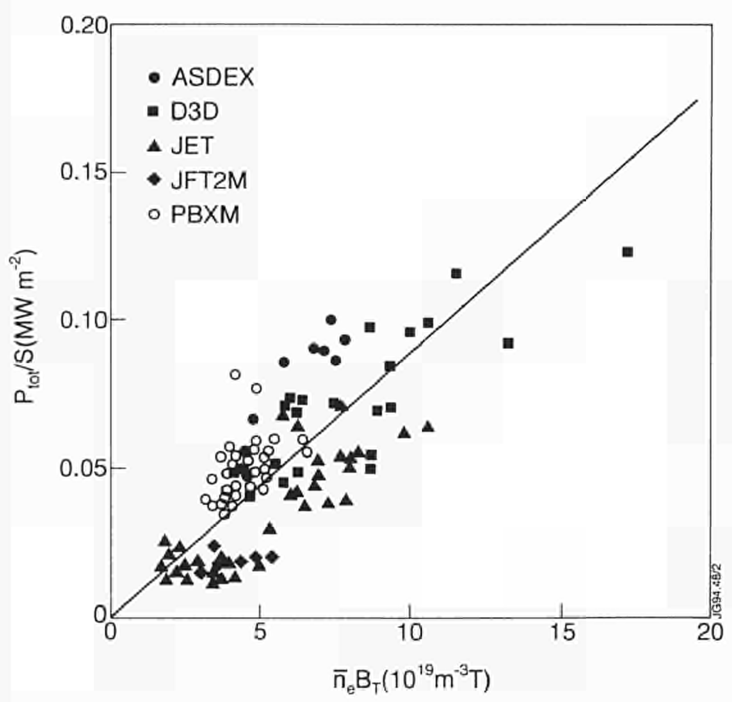


Fig.43: Power threshold normalised by the plasma area (S) versus $n_e B_T$ for five tokamaks worldwide

H-mode Confinement Data-base

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 applied above a certain threshold power value, a transition occurs to an improved plasma confinement (H-mode) regime, which depends upon the toroidal magnetic field. Fundamental characteristics include a rise in energy content and plasma density. An increase in electron temperature also occurs near the separatrix, which produces a pedestal in the temperature profile, and a flatter density profile with a steep gradient near the separatrix. The energy confinement time in the H-mode exceeds that with limiter discharges (L-mode) by more than a factor of two.

Energy confinement predictions for H-mode operation in Next Step tokamaks require a scaling law based on tokamaks of different dimensions. JET has continued to add new data to the H-mode database for global confinement scaling, throughout 1993, at the request of the ITER Project. The work is performed as a combined effort from JET and from other tokamaks (DIII-D (General Atomics, USA), ASDEX (IPP Garching, FRG), JFT2M (JAERI, Japan), PBXM and PDX (PPPL, USA)). The database now contains measurements from a variety of heated H-modes (electron cyclotron resonance, ICRF and neutral beams). In 1993, the Group has analysed in detail the thermal H-mode confinement data in the ITERH.DB2 database. The analysis has led to the following two (ITER93H-P) power law scaling expressions for thermal H-mode confinement [3,4].

ELM-free:

$$\tau_{th}=0.036 \times I^{1.06}B^{0.32}n^{0.17}P^{-0.67}R^{1.79}\kappa^{0.66}\varepsilon^{-0.11}M^{0.41} \quad (1)$$

ELMy:

$$\tau_{th}=0.022 \times I^{0.76}B^{0.15}n^{0.42}P^{-0.70}R^{2.60}\kappa^{1.05}\varepsilon^{0.3}M^{0.3} \quad (2)$$

with thermal confinement time τ_{th}, plasma current I, toroidal magnetic field B, plasma density n, loss power P and major radius R in units of s, MA, T, $10^{19}m^{-3}$, MW and m, respectively. The remaining quantities are elongation κ, inverse aspect ratio ε and effective mass M in atomic units.

More data has been added to the joint H-mode power threshold database ITERTH.DB1 in order to improve its condition. Progress has also been made in the analysis of the data from five tokamaks worldwide (ASDEX, DIII-D, JET, JFT-2M and PBX-M). Key parameters and their dependencies in each device have been identified. An increase in the power threshold with increasing density and toroidal magnetic field is common to all five machines. A subset of the data (standard threshold dataset) has been identified which forms the basis for the power threshold scaling analysis. Emphasis has been placed on including only the variation with density and magnetic field for each tokamak, so that a power threshold scaling with density, magnetic field and size parameters could be obtained. The simplest model which describes the power threshold (P_{th}) reasonably well is $P_{th}/S=CnB$, where S is the plasma surface area. The standard threshold dataset gives $C=8.9x10^{-3}$ with P_{th}, S, n and B in units of MW, m^2, $10^{19}m^{-3}$ and T, respectively (see Fig.43).

The VH-Mode

During the series of hot-ion H-mode experiments completed during the 1991/92 campaign, a new enhanced confinement regime was found. The new regime is similar to the VH-mode seen in DIII-D, with values of the confinement time about twice the usual ITER H-mode

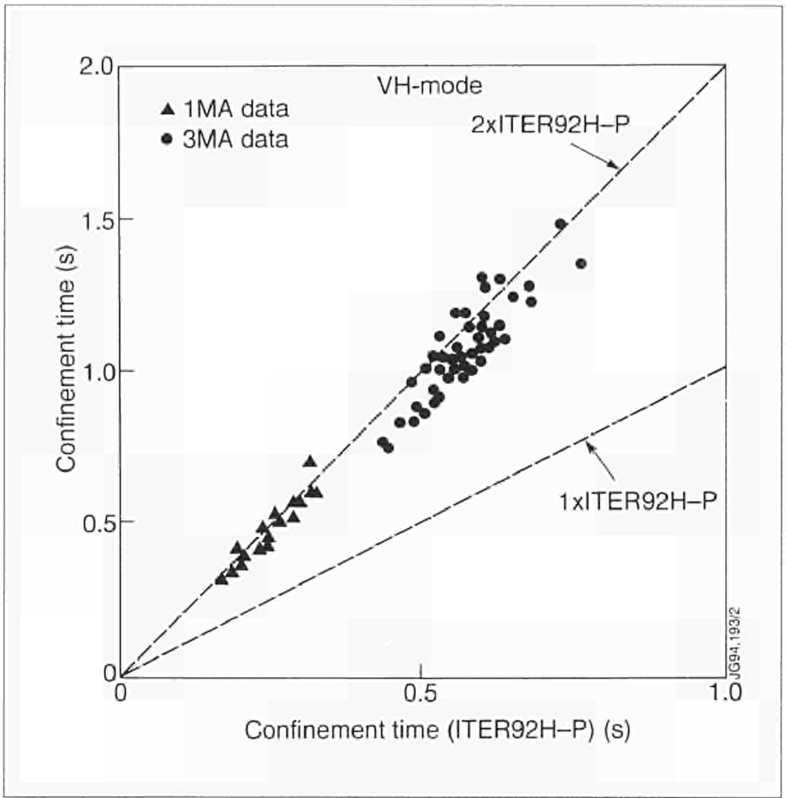


Fig.44: Confinement time for VH-mode plotted versus ITER (92H-P) scaling for current values of 1 and 3MA

scaling and in excess of a factor three above the L-mode scaling expression. This improved confinement follows a second transition during the H-mode. The transition is clearly visible and is usually coincident with the disappearance of ELMs during the H-mode. The high confinement is associated with reduced energy transport near the edge. The improvement in confinement from L-mode to H-mode coincides with the development of steep gradients in the temperature and density profiles near the edge. The improvement in confinement in H-mode to VH-mode is a consequence of the broadening of the steep gradients. Figure 44 shows the confinement time for the VH-mode plotted versus the ITER (92H-P) scaling for values taken at currents of 1 and 3MA.

During the high confinement phase, a large bootstrap current appears near the edge, associated with a large pressure gradient, and the total current profile broadens. The high edge current results in the coalescence of the first and second regions of stability against ballooning modes, giving unconditional stability, within a substantial fraction of the plasma volume close to the separatrix. This effect has been identified as being relevant to the attainment of the VH-mode, but a causal link has not been established. One possibility which has been put forward for the establishment of the VH-mode is the development of shear in the radial electric field in the outer region of the plasma. For neutral beam heated discharges, the radial electric field - due mainly to plasma rotation - may indeed have some shear during the VH-mode. However, for ICRF heated discharges, there is only a small electric field, which casts doubt on the above explanation.

Next Step Physics Issues

Certain work has been carried out on issues of particular relevance to Next Step devices, that are not already part of the JET experimental programme. The main highlights are set out below.

Implications of AC Operation

The mainstream of fusion research points towards tokamak fusion reactors operating with high plasma currents of ~20-25MA. At these levels, full non-inductive current drive (NICD), and therefore steady-state operation, is precluded by the large recirculating power fraction, consumed by the NICD system. Thus, there is a strong incentive to develop tokamak operation at lower plasma currents. This would open the way to fusion reactors of smaller size, which could be more readily integrated with existing electricity production networks. JET is making a strong contribution to this research, by exploring advanced tokamak operating scenarios in a wide sense: a search for regimes of enhanced confinement and stability, accessible with profile modification, and a search for improved NICD efficiency.

If such low current regimes are comprehensively demonstrated, this can lead to reactors operating in steady-state. However, the advances that lead to steady-state operation, also make pulsed, inductive operation of such machines attractive. In particular, without the constraint of a high bootstrap current fraction, such reactors could be optimised to deliver higher fusion powers when operated inductively. In view of the many issues of R&D affecting the economics of steady-state and pulsed reactors, it is premature to make a detailed analysis of their relative costing.

If the advanced regimes are not sufficiently demonstrated, it might have to be accepted that the first generation of fusion reactors will have to operate at high current, and with inductive current drive.

Toroidal Field Ripple Experiment

Further analysis was performed on the recent JET experiment with 16 toroidal field coils, versus the normal 32 coils. For the analysis of fast particle losses, a novel code was developed, in which the effect of ripple is represented by a diffusion coefficient.

Analysis of the high ripple discharges with neutral beam injection revealed that the measured loss of stored energy could not be explained by the predicted combination of ripple-induced thermal plasma losses plus beam energy ripple losses. Thus, it appeared that at least one of these processes should be anomalous. From an analysis of the (thermal) D-D neutron emission in the ohmic phase of identical discharges with high and low ripple, ion temperatures were consistently lower in the high ripple discharges, thus pointing to the thermal loss channel being anomalously high.

The new code was used for the analysis of losses of ICRF generated minority particles in the 16 coil discharges. The conclusion is that reasonable agreement exists between the experiment and the code predictions. Clearly, the observed losses could not be modelled without inclusion of stochastic diffusion.

Preparation is underway for an extension of these experiments, in which the two sets of 16 toroidal field coils will be driven at different currents, thus making the ripple continuously variable. Important issues to be studied quantitatively are the effect of ripple on the quality of the H-mode, and the effect of the direction of the magnetic field gradient drift on fast ion losses.

JET Work for ITER

In 1993, a new Next Step Unit was created with the purpose of coordinating work undertaken by JET for the Next Step, and in particular for ITER. The Unit covers both the technological and physics areas. Within the framework of the European Home Team, JET has a specific responsibility for physics areas of ICRF heating, bulk plasma confinement issues, operational scenarios, and single particle alpha losses. In technology, JET will concentrate on the areas of divertor and plasma wall interface, remote handling, and pumping/active gas handling.

Significant contributions were made by JET , in cooperation with ITER and the Associations, on a conceptual design of an ICRF heating

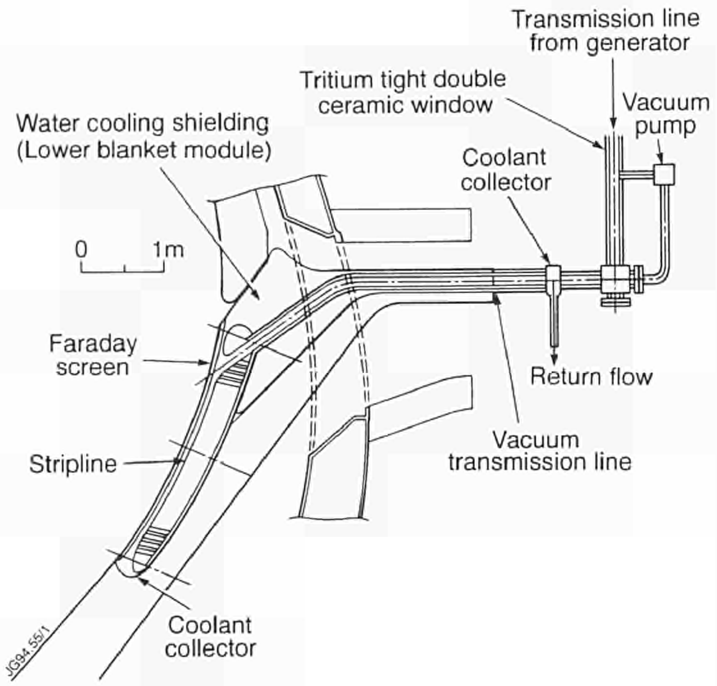


Fig.45: Poloidal section of the proposed ITER antenna.

system for ITER, a conceptual design of a compact 500kV neutral beam system, and on the evaluation of ITER operations scenarios (breakdown, flux consumption, and position control).

ICRF Antenna Proposal for ITER

A variety of ICRF scenarios have been proposed for heating and current drive in ITER which will require operations over a broad band of frequencies, from typically 20-85MHz. To achieve the broad-bank response required for ITER antennae, JET has proposed the so-called 'violin concept' antenna in which each transmission line is connected to two strip-lines of greatly un-equal length and resonance frequency. Initial analysis at JET using 2-D coupling and plasma codes predicts that peaks in the power coupling to the plasma occur throughout the required frequency spectrum. Whilst the power coupled to the plasma by the short strip-line is low, at certain frequencies it cancels out the reactive part of the input impedance of the main strip-line, allowing better coupling from the feeding transmission line voltages. The peaks in coupling can be arranged to coincide with the required scenario frequencies by a suitable choice of strip-line geometries.

The violin concept proposed by JET has been incorporated into the current ITER Outline Design as illustrated in Fig.45. Each antenna is capable of launching typically 3MW. The violin concept has resulted in a rigid current strap offering good support at the end of the vacuum transmission line. The result is a design free of ceramic components within the torus vacuum. The double ceramic window placement far from the plasma will allow excellent neutron shielding and minimised degradation due to irradiation. This design has resulted in an elegant and relatively simple antenna construction that promises the performance and reliability required for the ITER environment.

Progress towards a Reactor

During the 1991/2 experimental campaign, significant progress had been made in JET in determining the conditions required in a reactor. By using tritium, it had been possible to check predictions made in previous years concerning the power output and to assess whether the thermonuclear Q in JET with a D-T mixture was actually valid. In particular, the tritium experiments enabled detailed checks of computer codes used in predictions of D-T performance. The outcome was that indeed the previous code predictions of Q_{DT} close to breakeven had been fully justified. During 1992/93, further analysis of the high performance discharges obtained during the first tritium series of experiments was completed. The overall picture was unchanged with the hot-ion H-mode plasmas having the highest Q_{DD} ($5x10^{-3}$) and the extrapolated Q_{DT} was 1.14.

In 1992, a series of 7MA limiter L-mode plasmas with high power combined ICRF and NB heating had been developed. Although these pulses achieved a high stored energy (~12MJ), the fusion product ($n_D T_i \tau_E$) produced was about $1.4x10^{20}m^{-3}$keVs at a temperature of 4.5keV. The main problem encountered was the high impurity levels giving rise to a low deuterium concentration, $n_D/n_e<0.5$. The actual preliminary tritium pulses had a somewhat lower Q_{DT} than the highest values obtained. The actual equivalent value Q_{DT} was 0.46. This was due to the reduced value of the fusion product ($n_D T_i \tau_E$) in these particular pulses caused by the early onset of the "carbon bloom".

During 1993, considerable progress has been made on other experiments worldwide. In Japan, JT-60U obtained a new high β_p

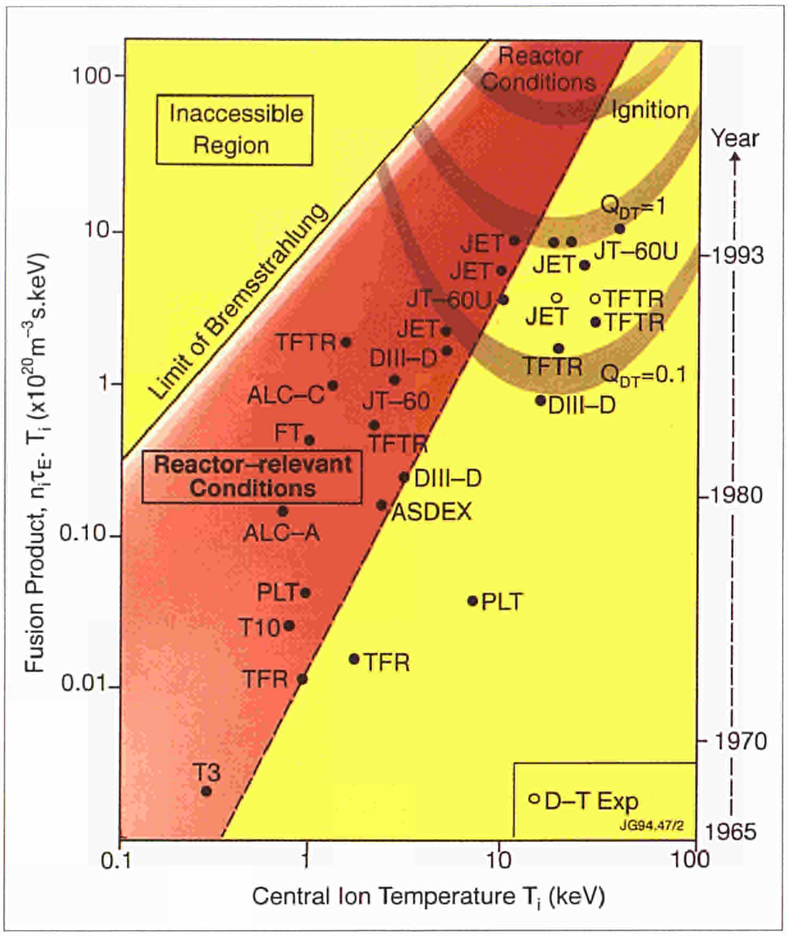
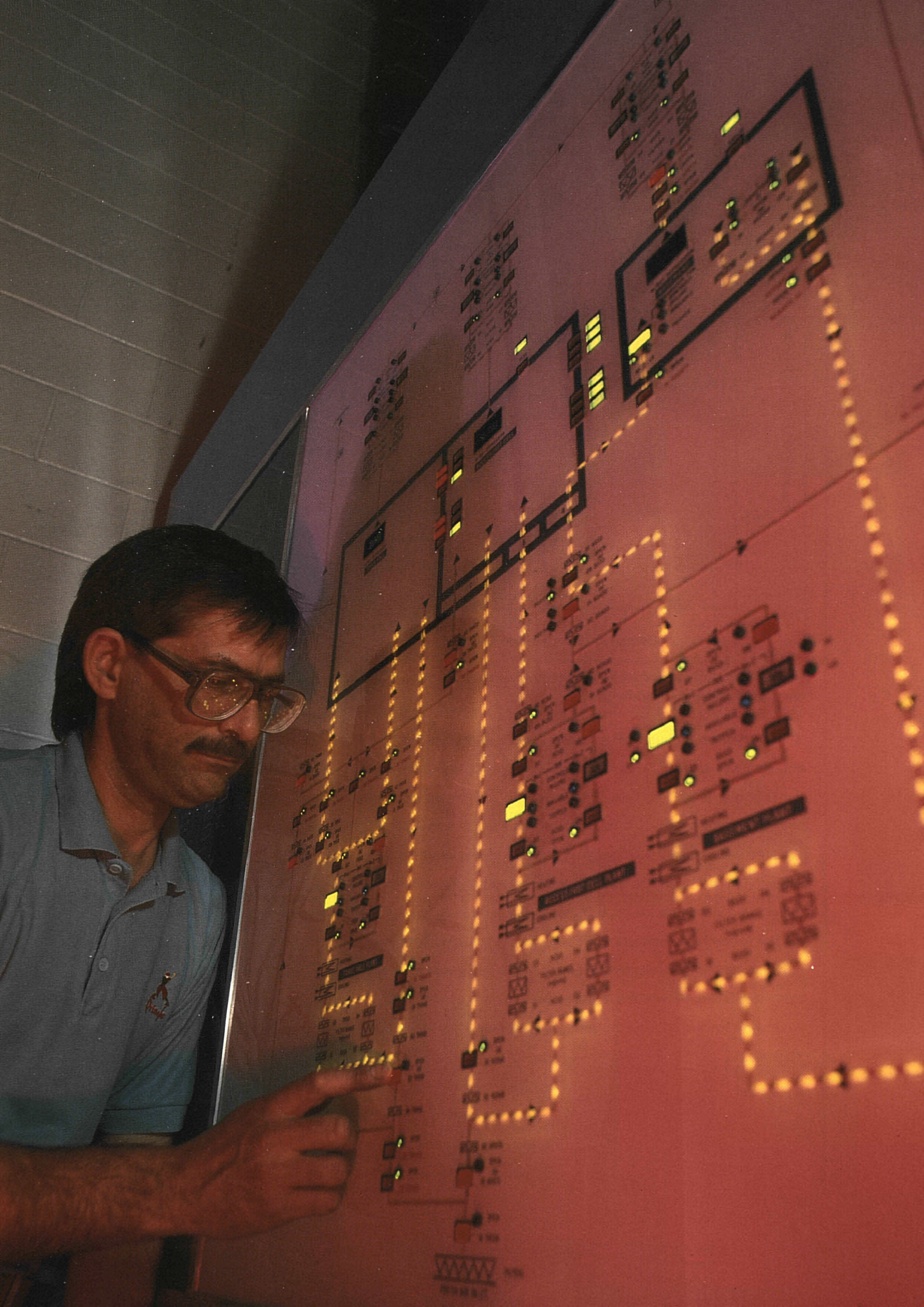


Fig.46: Triple fusion product as a function of ion temperature, T_i, for a number of tokamaks worldwide.

H-mode regime in deuterium plasmas. A best fusion product ($n_D T_i \tau_E$) obtained was $1.1 \times 10^{21} m^{-3}$keVs at an ion temperature of 35keV. In the TFTR machine, PPPL, USA, an initial set of D-T experiments was undertaken during 1993. A fusion power of 6.2MW was obtained in a plasma with an approximate 50:50 mixture of deuterium and tritium. The main contribution to the fusion output was from beam-thermal reactions and the total Q_{DT} was ~0.2.

The fusion triple product, $n_D T_i \tau_E$, values of the high performance pulses in both impure deuterium and in the D-T pulses for JET are compared in Fig.46 with the latest results from other machines worldwide to illustrate the progress that has been made over the last 30 years.



Future Programme

Introduction

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

'The essential objective of JET is to obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclear reactor. These studies will be aimed at defining the parameters, the size and the working conditions of a Tokamak reactor. The realisation of this objective involves four main areas of work:

i) the scaling of plasma behaviour as parameters approach the reactor range;

ii) the plasma-wall interaction in these conditions;

iii) the study of plasma heating; and

iv) the study of 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 1993, the Project was in the midst of a major shutdown which began in February 1992 and continued throughout

Objectives of JET

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

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

1993. It should be completed in January 1994 after a prolonged period of intensive work. During this period, the interior of the JET vacuum vessel has been essentially replaced. Following completion of this work, JET will be in a position to begin its planned programme of operations to demonstrate effective methods of power exhaust and impurity control in operational conditions close to those envisaged for ITER.

Since the beginning of its experimental campaign, extensive studies had been made in the first and third areas of work of JET's objectives: reactor relevant temperatures (up to 30 keV), densities (up to $4 \times 10^{20} m^{-3}$) and energy confinement times (up to 1.8s) had been achieved in separate discharges. The second area of work had been well covered in the limiter configuration for which JET was originally designed. However, the highest performance JET discharges had been obtained with a 'magnetic limiter', (or X-point configuration). The duration of the high performance phase of these discharges exceeded 1.5s; this was achieved by careful design of the targets and specific operation techniques, but is limited, ultimately, by an unacceptably high influx of impurities, characterized by a rapid increase in electron density, effective ionic discharge and radiated power (referred to as the 'bloom').

The fourth area of work had been started by earlier studies of energetic particles produced as fusion products or by ion cyclotron resonance heating. It was addressed further during 1991 by the first tokamak plasma experiments in deuterium-tritium mixtures. The high performance achieved in deuterium discharges, together with experience gained in making substantial modifications in a beryllium environment and with significant vessel activation, gave confidence that an experiment with about 10% tritium in the plasma could be performed and would provide data that could be used to plan an effective campaign of deuterium-tritium experiments in 1996.

During 1991, the JET Council had approved the policy of a step-wise approach to the introduction of tritium in advance of the full D-T phase of JET operations. As a first such step, after having obtained all necessary regulatory approvals, JET successfully carried out a preliminary tritium experiment (PTE-1) in November 1991. A release of fusion energy in the megawatt range in a controlled fusion device was achieved for the first time in the world.

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

In late 1991, the Council of Ministers approved a modification to the Statutes, which prolonged JET's statutory lifetime by four years until 31st December 1996. The extension will allow JET to implement the new Pumped Divertor Phase of operation, the objective of which is to establish the effective control of plasma impurities in operating conditions close to those of the Next Step. This programme of studies will be pursued before the final phase of full D-T operations in JET.

During 1993, a large proportion of JETs effort was devoted to shutdown work for the new pumped divertor phase of operations. The first stage of the shutdown in 1992 had involved removal of components and replacement of faulty toroidal magnetic field coils. The second stage in 1992/93 involved assembly of the four divertor coils and casings inside the vacuum vessel. It is believed to be the first time that a full manufacture and assembly of coils had been undertaken in such a confined space, and the work was done to demanding standards to ensure the highest reliability during subsequent operations. The third stage of the shutdown began in mid-1993, with the final positioning of the coils. The rails that fix the position of the tile carrier beams of the divertor modules were then individually machined for correct alignment and installed on the attachment pads. Following welding of heavy supports to the vacuum vessel walls, the inner wall guard limiters, RF antennae and poloidal limiters were installed, together with the target plates, upper and lower saddle coils, and the divertor cryopump and baffles. At the year end, work was continuing on installation of remaining in-vessel components prior to vessel closure, commissioning of power supply and vacuum systems, leak testing and conditioning in preparation for initial operations in the divertor configuration.

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 ($n_i T_i t_E$). For the energy confinement time, t_E, this involves maintaining, with full additional heating, the values that have already been reached. For the density and ion temperature, it means increasing their central values $n_i(0)$ and $T_i(0)$ to the extent that D-T operation would produce alpha-particles in sufficient quantities 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 alpha-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 involves the following:

a) Increasing the Central Deuterium Density $n_D(0)$ by:
   - injecting deuterium pellets and high energy deuterium 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 outer 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, ICRH, and 20MW, NB)

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

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

In parallel, preparations for the full D-T phase of operations have continued. In particular, JET has completed installation of all the main components of the active gas handling system and pre-tritium commissioning has continued. At the end of the shutdown, JET will be in a position to begin its programme of operations to demonstrate effective methods of power exhaust and impurity control in operational conditions close to those envisaged for ITER, before the final phase of full D-T operations. ITER relevant studies will provide stimulation to JET and JET's results will make an important contribution to the development of the ITER design. The following sections describe various developments underway on JET to implement these systems.

Future Plans

The JET Programme was divided into phases governed by the installation of new equipment and fitting within the accepted life time of the Project. Phase I (Ohmic Heating Studies) was completed in September 1984, and Phase II (Additional Heating Studies) in October 1988. Phase III (Full Power Optimization Studies) ended in February 1992. The scientific aims of Phase III were to obtain maximum performance in limiter configuration (currents up to 7MA) and to optimize X-point operation (currents up to 6MA) including a comparison of H-modes in X-point configuration using beryllium (lower X-point) with carbon (upper X-point) dump plates. The programme to 1996 is shown in Fig.47.

JET future plans are dominated by the insertion of a new phase of the Project (Phase IV: Pumped Divertor Configuration and Next-Step Oriented Studies). This phase is subdivided into a Divertor Characterization Plasma and a Full Tritium Compatibility Phase. The

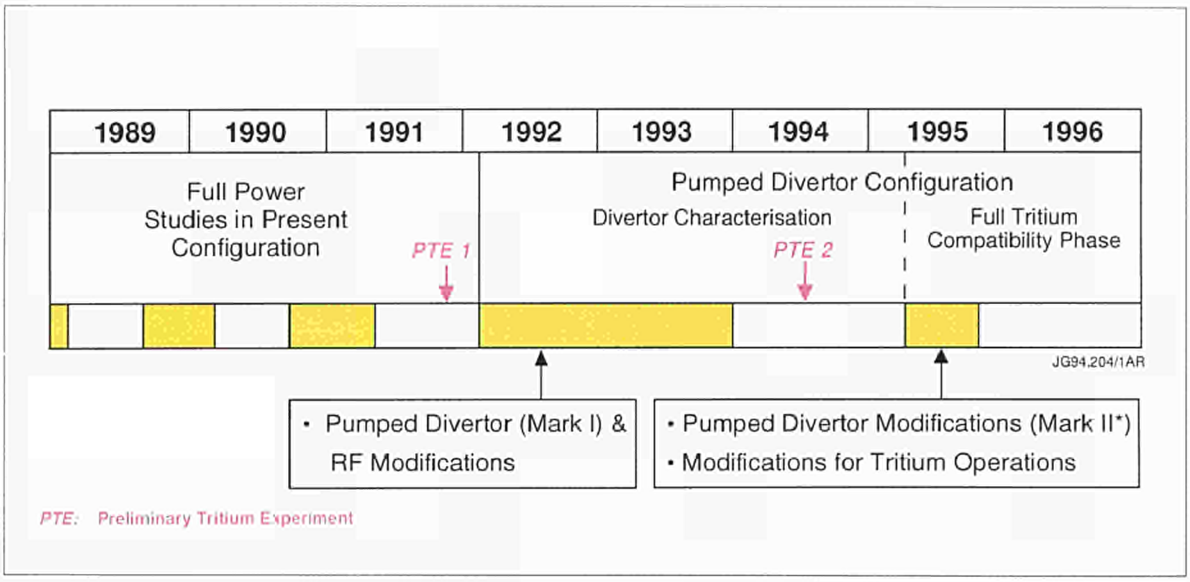


Fig.47: The JET Programme Schedule to 1996

final Full Tritium Compatibility Phase, is now scheduled to start in 1995. This new phase extended the lifetime of the Project by four years up 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 (10-60s) of 'thermonuclear grade' in a single-null axisymmetric pumped divertor configuration. This configuration can only be achieved in JET by using divertor coils internal to the vessel.

More information on the future phases of the Project are indicated below.

New Phase (first part): Pumped Divertor Configuration Phase IVA (Divertor Characterization Phase) (February 1992 - February 1995)

The shutdown which began in February 1992 should be completed during January 1994. In-vessel work during the shutdown has largely involved the installation of the divertor coils and other components for the Mark I Divertor. The Mark I Divertor has a relatively low static power handling capability. This makes it necessary to "sweep" the magnetic configuration over the target tiles. This is possible for the main horizontal target, but not for the vertical side walls, whose power handling capability is therefore very limited, even though some improvements were made prior to installing the target tiles.

Experiments during the operating period in 1994 will concentrate on establishing and characterising plasma behaviour in the pumped divertor configuration. The Programme in this phase will focus on:

- establishing reliable operation in the new configuration;
- studying the control of impurities, plasma density and exhaust;
- assessing power handling using the full range of ancillary equipment;
- extending performance to high power, long pulse operation;
- studying specific physics and ITER related issues.

A centrifugal pellet injector will be commissioned for repetitive fuelling. In addition, a prototype fast pellet injector which is being tested would deliver a single pellet per tokamak discharge, mainly for pellet ablation studies.

The RF capabilities of JET have been enhanced significantly with the installation of the set of eight new RF antennae and of the full power LHCD launcher. The exploitation of these systems in a range of heating and current drive scenarios will be an integral part of the Programme during this phase.

The initial objective in the restart of operations is to produce, by the end of March 1994, a 2-3MA diverted plasma with 10MW of additional heating for a few seconds. Some commissioning of hardware systems, diagnostics and operational scenarios will continue after this time, but wherever possible these activities will be pursued in parallel with the experimental programme. The programme will concentrate on divertor assessment, high performance plasmas and RF heating and current drive studies. Operation with high performance plasmas, with the greatest rate of neutron production, is scheduled for late summer 1994. The detailed programme includes a limited comparison between CFC and beryllium divertor target tiles but does not include a second Preliminary Tritium Experiment (PTE-2).

Carbon fibre composite (CFC) divertor target plate tiles have been installed for initial operations with the Mark I divertor. This will allow a more rapid characterisation of plasma behaviour and build-up of high performance in the divertor configuration. These tiles will be used during most of the 1994 experimental campaign. During a short intervention towards the end of the operating period, the CFC tiles will be replaced by beryllium tiles and a limited comparison made. This will concentrate on repeating with beryllium one or two discharge conditions established for divertor operation with carbon.

The JET Director considers that the disruption to other programme objectives necessary to accommodate a PTE-2 in 1994 cannot be justified when a separate and much more extensive programme of rather similar D-T experiments is currently being undertaken in TFTR.

New Phase (second part): Pumped Divertor Configuration - Phase IVB (Full Tritium Compatibility Phase) (March 1995 - December 1996)

The next major shutdown is scheduled to start in March 1995. All JET systems and sub-systems will be brought to full tritium compatibility and, subject to the approval of the JET Council, a Mark II divertor will be installed. Though still inertially-cooled, the Mark II divertor would have a considerably higher static power handling capability than the Mark I divertor, particularly on the vertical side plates. The new divertor configuration uses close-fitting, precisely-aligned large target tiles which result in a much larger plasma "footprint" on the targets. The Mark II divertor would also be more "closed", facilitating the production of a low temperature, high density, high recycling, radiative divertor plasma in which atomic processes (such as radiation and charge-exchanged neutral losses) reduce the conducted power to the targets.

Operations will resume in September 1995. The programme would develop towards long pulse, high performance operation during 1995/96, before the final phase of D-T operation. Divertor studies would aim to optimise JET's performance in several regimes including long duration, high fusion yield deuterium operation. RF studies would begin to explore advanced tokamak concepts based on current profile control and non-inductive current drive. D-T operations would concentrate on a final phase of six to twelve months of full D-T operations for a significant programme of experiments on the physics of α-particle production, confinement and heating and to gain technical experience of tritium operations (tritium handling, recovery and retention, remote maintenance and plasma diagnostics in large neutron and gamma backgrounds) on a reactor relevant scale that would provide information for ITER design and construction.

It must be emphasised that the programme areas of divertor studies, advanced tokamak concept studies and D-T operations are strongly interdependent. The divertor must withstand the loads placed upon it by the various high performance reactor relevant experiments needed, ultimately, for the final phase of full D-T operation. Long pulse operation must be compatible with acceptable power handling and good impurity control. A considerable level of success in the divertor programme is therefore a prerequisite for progress in the other programme areas and this is the object of installing the Mark II divertor.

If, however, the JET Council decides during 1994 not to install the Mark II divertor, the effect on the Programme Plan would be minimal. A shutdown would still be required in 1995 to make modifications in the light of experience and to prepare for full D-T operations, but the main Programme areas would be pursued only as far as possible on the basis of further exploitation of the Mark I divertor (including its use in the full tritium phase). Most of the advanced divertor work and most of the advanced tokamak concept studies, both of which are relevant to ITER and to DEMO, would not take place.

Furthermore, a programme based solely on the Mark I divertor for the whole of the period to end 1996 carries a high risk that the performance achieved would not be sufficient and that JET's objectives, particularly high performance D-T operation, would not be met.

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 de l'École Royale Militaire - Laboratorium voor plasma-physica van de Koninklijke Militaire School') and on behalf of the Université Libre de Bruxelles' ('Service de physique statistique, plasmas et optique non-linéaire de l'ULB'); and of the 'Centre d'Études de l'Energie Nucléaire (CEN)/'Studiecentrum voor Kernenergie' (SCK);

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

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

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

The Hellenic Republic, Greece;

The Forskningscenter Risø (Risø), Denmark;

The Grand Duchy of Luxembourg, Luxembourg;

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

Ireland;

The Forschungszentrum Jülich GmbH (KFA), Germany;

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

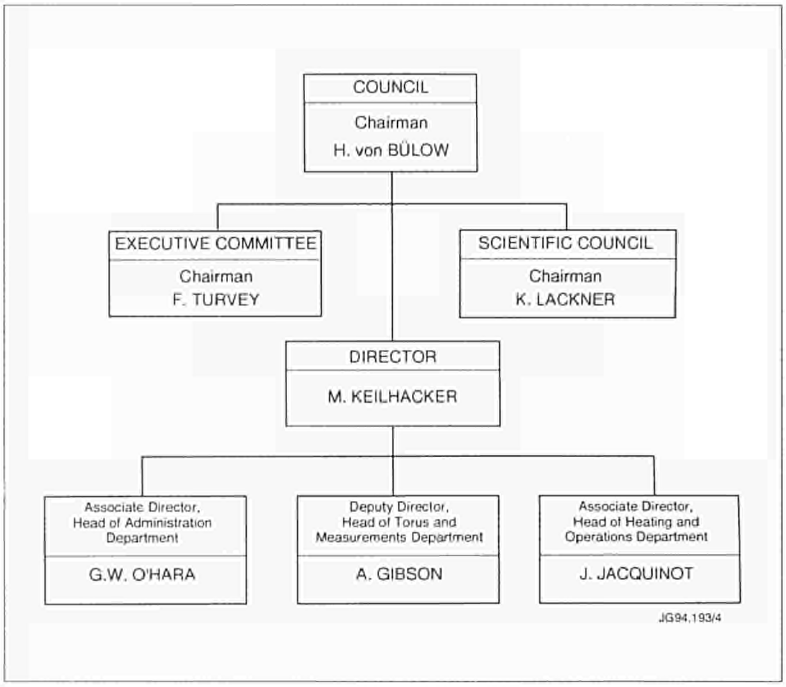


Fig.48: Overall Project Structure

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 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.48).

JET Council

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

- Nomination of the Director and Senior Staff of the Project with a view to their appointment by the Commission or the Host Organisation as appropriate;
- Approval of the annual budget, including staffing, as well as the Project Development Plan and the Project Cost Estimates,

- Ensuring collaboration between the Associated Laboratories and the Joint Undertaking in the execution of the Project, including the establishment of rules on the operation and exploitation of JET.

Four meetings of the JET Council were held during the year on 26th February, 24th-25th March, 9th-10th June, and 13th-14th October 1993. 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 11th-12th February, 22nd-23rd April, 8th-9th July, 16th-17th September, 4th-5th November and 9th-10th December 1993.

JET Scientific Council

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

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

The Scientific Council met twice during the year on 25th-26th February and 19th - 20th May. It organised a one day workshop, which was also attended by other experts from the Associated Laboratories, to examine:

- the basis for the ITER relevance of divertor experiments on JET in the context of the other experimental programmes on divertor physics in Europe; and
- the relative merits of the different divertor configurations proposed by JET and the code calculations presented in support of their choice.

The JET-SC Chairman reported to the JET Council on three occasions, providing an assessment of the JET Forward Programme, including:

- plans for an inertially-cooled, more optimised Mark II divertor structure;
- options for the D-T programme on JET; and
- unique contributions which JET could make to a tokamak reactor.

The toroidal field coil faults that have occurred on JET were also assessed by the JET-SC. The JET-SC recognised that only a limited part of JETs potential would be exploited in the 1996 timeframe and endorsed the intention of the JET Director to present his proposals for the JET Forward Programme to the European Joint Working Group.

The full Scientific Council membership is detailed in Appendix III.

Host Organisation

The United Kingdom Atomic Energy Authority, as the Host Organisation for the JET Joint Undertaking, has made available to the Joint Undertaking, the land, buildings, goods and services required for the implementation of the Project. The details of such support, as well as the procedures for co-operation between the Joint Undertaking and the Host Organisation, are covered by a 'Support Agreement' between both parties. In addition to providing staff to the JET team, the Host Organisation provides support staff and services, at proven cost, to meet the requirements of the JET Project.

Project Team Structure

The Director of the Project

The Director of the Project, Dr. M. Keilhacker, is the chief executive of the Joint Undertaking and its legal representative. He is responsible to the JET Council for the execution of the Project Development Plan, which specifies the programme, and for the execution of all elements of the Project. The Project Development Plan covers the whole term of the Joint Undertaking and is regularly updated. The Director is also required to provide the JET 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 three Departments and the Directorate. The three Departments are:

- Torus and Measurements Department;
- Heating and Operations Department;
- Administration Department.

The Project Departmental and Divisional structure is shown in Fig.49.

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

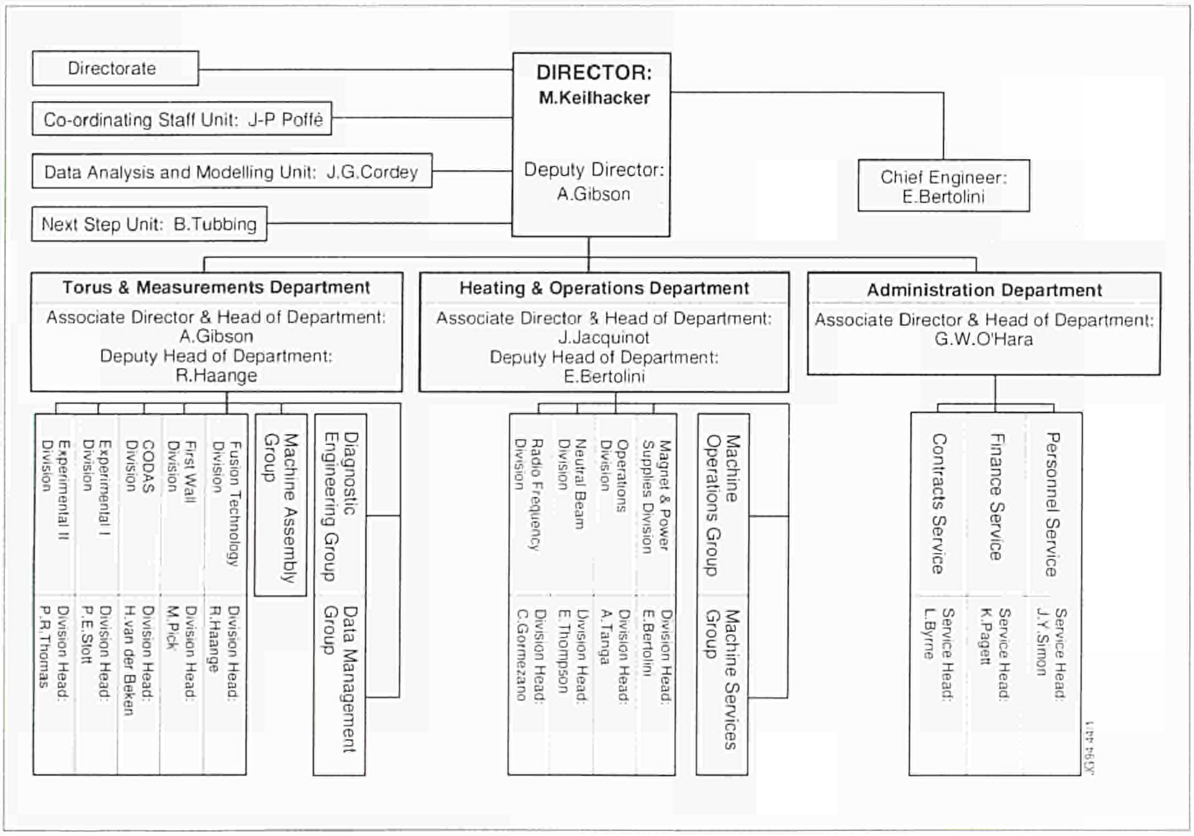


Fig.49: JET Departmental and Divisional Structure

Project Cost Estimates. The JET Council Secretariat provides Secretarial Services to the JET Council and to the Executive Committee and also to the JET Project Board.

Within the Directorate, are three technical units and a Chief Engineer, which all report directly to the Director. The main responsibilities are as follows:

(a) *The Co-ordinating Staff Unit* is responsible for the availability of a comprehensive environmental and safety project organisation; for the provision of centralised engineering support services and for the implementation of specific co-ordinating tasks at the Project level. It comprises five Groups: Safety Group; Health Physics Group; Quality Group; Technical Services Group; and Drawing Office

(b) *The Data Analysis and Modelling Unit* is responsible for the provision of software for the acquisition and processing of the data from JET diagnostics; for confirming the internal consistency of the processed data and assembling it into public databases; and the development and testing of theoretical models against JET data. In addition, the Unit is responsible for prediction by computer simulation of JET performance, interpretation of JET data and the application of analytic plasma theory to gain an understanding of JET physics. It comprises three groups; Analytic Theory Group; Simulation Group; Data Processing and Analysis Group.

(c) *The Next Step Unit* is responsible for co-ordinating contributions from JET to the European effort in support of the ITER-EDA. This responsibility includes drawing up proposals, initiating relevant work programmes on JET and taking part in their execution and evaluation.

In addition, there is a *Chief Engineer*, who reports to the Director, and is responsible for ensuring the overall coherence of technical aspects of JET operations.

Torus and Measurements Department

The Torus and Measurements Department has overall responsibility for the performance capacity of the machine: this includes enhancements directly related to this (excluding heating) and the long term planning associated with integration of these elements to achieve ultimate performance. The Department is also responsible for: fusion technology requirements for the active phase including tritium handling and processing; for construction and operation of necessary measurement diagnostic systems and the interpretation of experiment data; and for data systems comprising data control, acquisition and management.

The main functions of the Department are:

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

The Department consists of five Divisions and three Groups (Machine Assembly, Diagnostic Engineering and Data Management):

(a) *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 the first wall systems and its components such as limiters, wall protections and internal pumping devices. The area of responsibility encompasses the mechanical integrity of the vacuum vessel as a whole and the development and implementation of mechanical and Remote Handling techniques;

(b) *Fusion Technology Division*, is responsible for all nuclear engineering aspects of this Project including tritium and gas handling, vacuum systems, waste management and regulatory approvals;

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

(d) *Experimental Division 1 (ED1)*, which is responsible for specification, procurement and operation of about half the JET diagnostic systems. ED1 undertakes electrical measurements, electron temperature measurements, surface and limiter physics and neutron diagnostics;

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

Heating and Operations Department

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

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

The Department consist of two Groups (Machine Operations and Machine Services) and four Divisions:

(a) *Operations Division* plays a major role in the efficient planning and execution of JET's experimental programme and in the integration of existing or imminent systems into an effective experimental programme. In addition, it is responsible for effective methods of fuelling the plasma including the development of methods based on solid high speed hydrogen pellets;

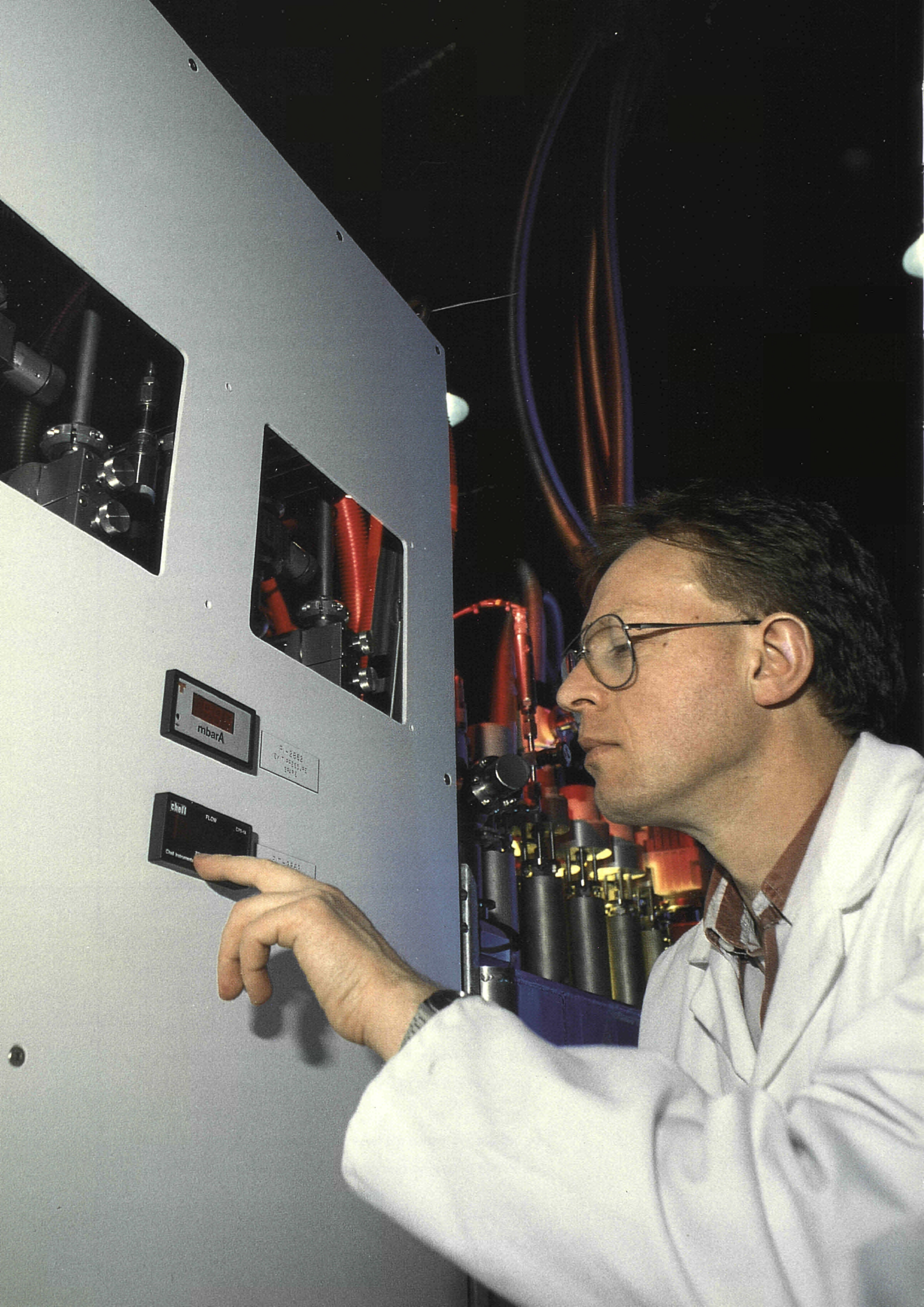
(b) *Neutral Beam Heating Division*, which is responsible for construction, installation, commissioning and operation of the neutral injection system, including development towards full power operation. The Division is also responsible for all cryo-systems and also participates in studies of physics of neutral beam heating;

(c) *Radio Frequency Heating Division*, which is responsible for the design, construction, commissioning and operating RF heating and current drive systems during the different stages of its development to full power. The Division is also responsible for the TAE excitation system and also participates in studies of the physics of RF heating;

(d) *Magnet and Power Supplies Division* is responsible for the design, construction, installation, operation and maintenance of the tokamak electromagnetic system and of plasma control. The area of responsibility encompasses the toroidal, poloidal and divertor magnets, mechanical structure, methods for controlling plasma position and shape and all power supply equipment needed for magnets, plasma control, additional heating and auxiliaries.

Administration Department

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

Introduction

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

Finance

The initial budgets for 1993 were approved at 85.06 MioECU for Commitments and 90.29 MioECU for both Income and Payments. The Commitments and Payments Budgets each are divided into two phases of the Project - Extension to Full Performance and the Operational Phase; subdivisions distinguish between investment, operating, and personnel costs, each with further detailed cost codes.

The Commitments, Payments and Income Budgets included 0.20 MioECU for specific work for the European Fusion Programme.

During the year the Commission Services of the European Communities agreed to reimburse directly all costs incurred by JET under the Assigned Associate Staff Scheme. As a result, 5.4 MioECU have been removed from JET Programme Costs. In the Commitments Account the resulting unutilised appropriations are carried forward to future years and in the Payments Account, the unused appropriations are carried forward to reduce Members' contributions in 1994.

Commitments

Of the total appropriations in 1993 of 107.73 MioECU (including 22.67 MioECU brought forward from previous years), 89.95 MioECU was committed and the balance of 17.78 MioECU was available for carrying forward to 1994. The details of the commitment

COMMITMENT APPROPRIATIONS	MioECU
INITIAL COMMITMENTS BUDGET FOR 1993	85.06
AMOUNTS BROUGHT FORWARD FROM PREVIOUS YEARS.	22.67
	107.73
COMMITMENTS MADE DURING THE YEAR	89.95
BALANCE OF APPROPRIATIONS AT 31 DECEMBER 1993 AVAILABLE FOR USE IN 1994	**17.78**

Table 7: Commitment Appropriations for 1993

appropriations available (Table 7) and of the amounts committed in each Phase during the year (Table 8) are summarised as follows:

- In the extension to Full Performance Phase, 2.9 MioECU was committed leaving 4.09 MioECU commitment appropriations not utilised at 31 December 1993, to be carried forward to 1994;
- In the Operational Phase, 86.96 MioECU was committed leaving a balance of 13.69 MioECU to be carried forward to 1994.

Income and Payments

The actual income for 1993 was 89.14 MioECU, to which was added 1.28 MioECU available appropriations brought forward from previous

		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	7.08	2.99	2.26	1.49
PHASE 3	**OPERATIONAL**				
TITLE 1	PROJECT INVESTMENTS	8.87	7.05	14.13	12.69
TITLE 2	OPERATING COSTS	43.09	36.36	39.05	37.72
TITLE 3	PERSONNEL COSTS	48.69	43.55	51.13	42.19
TOTAL PHASE 3		100.65	86.96	104.31	92.60
PROJECT TOTAL - ALL PHASES		**107.73**	**89.95**	**106.57**	**94.09**

Table 8: Commitments and Payments for 1993

INCOME AND PAYMENTS	MioECU	
INCOME		
BUDGET FOR 1993		90.29
INCOME RECEIVED DURING 1993		
(I) MEMBERS' CONTRIBUTIONS	87.32	
(II) BANK INTEREST	1.78	
(III) MISCELLANEOUS	0.04	
(IV) UNUSED APPROPRIATIONS BROUGHT FORWARD FROM 1991	1.28	
TOTAL INCOME		90.42
VARIATION FROM BUDGET		0.13
REPRESENTING:		
(I) INCOME IN EXCESS OF BUDGET CARRIED FORWARD FOR OFF-SET AGAINST MEMBERS' FUTURE CONTRIBUTIONS.	0.33	
(II) SHORTFALL OF INCOME FOR SPECIFIC FUSION RESEARCH REDUCING AVAILABLE PAYMENT APPROPRIATIONS.	(0.20)	
		0.13
PAYMENTS		
BUDGET FOR 1993	90.29	
AMOUNTS AVAILABLE IN THE SPECIAL ACCOUNT TO MEET OUTSTANDING COMMITMENTS AT 31 DECEMBER 1992	16.28	
REDUCTION IN APPROPRIATIONS CORRESPONDING TO SHORTFALL OF INCOME FOR SPECIFIC FUSION RESEARCH	(0.20)	
REDUCTION IN APPROPRIATIONS RELATING TO THE ASSIGNED ASSOCIATED STAFF SCHEME	(5.38)	
TOTAL AVAILABLE APPROPRIATIONS FOR 1993		100.99
ACTUAL PAYMENTS DURING 1993	94.09	
FROM SPECIAL ACCOUNT TRANSFERRED TO INCOME.	1.55	
		95.64
UNUTILISED APPROPRIATIONS AT 31 DECEMBER 1993 CARRIED FORWARD IN THE SPECIAL ACCOUNT TO MEET OUTSTANDING COMMITMENTS AT THAT DATE.		5.35

Table 9: Income and Payments for 1993

years, giving a total of 90.42 MioECU. No income was received in 1993 for Specific Fusion Research work and the shortfall in income of 0.20 MioECU was offset by a corresponding reduction in the available Payments Budget. The excess of other income over budget, totalling 0.32 MioECU, is carried forward to be offset against future contributions of Members. The total payment appropriations for 1993 of 106.57 MioECU were reduced by 0.20 MioECU due to the shortfall in income from Specific Fusion Research work and by 5.38 MioECU due to the reimbursement of payments made under the Assigned Associated Staff Scheme; the payments in the year amounted to 94.09 MioECU and 1.55 MioECU was transferred from the Special Account to income.

MEMBER	%	Mio ECU
EURATOM	80.0000	69.85
BELGIUM	0.2141	0.19
CIEMAT, SPAIN	0.2722	0.24
CEA, FRANCE	1.7510	1.53
ENEA, ITALY	2.1933	1.92
RISO, DENMARK	0.0680	0.06
LUXEMBOURG	0.0018	0.00
JNICT	0.0682	0.06
KFA, GERMANY	0.7994	0.70
IPP, GERMANY	2.3746	2.07
KFK, GERMANY	0.6381	0.56
NFR, SWEDEN	0.2199	0.19
SWITZERLAND	0.4221	0.37
FOM, NETHERLANDS	0.4053	0.35
UKAEA	10.5720	9.23
	100.0000	**87.32**

Table 10: Percentage Contributions to JET for 1993

The balance of 5.35 MioECU was transferred to the Special Reserve Account to meet commitments outstanding at 31 December 1993. (Payments are summarised in Tables 8 and 9).

Contributions from Members

The budget for Members' contributions was 87.32 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 contribution from Euratom towards the cost of their Association Contracts.

Table 10 gives contributions from Members for 1993.

Bank Interest

During the year, funds are received on a quarterly basis in respect of Members' contributions and intermittently for other items. Therefore, the Project has funds not immediately required for the discharge of its commitments; these funds are placed on deposit accounts at market interest rates. During 1993, earned interest amounted to 1.78 MioECU.

Appropriations from Earlier Years

The unused payment appropriations and excess income over budget of 1.28 MioECU arising in 1991 and held for reduction of Members' future contributions were transferred to income in 1993.

FINANCIAL TRANSACTIONS	MioECU
CUMULATIVE COMMITMENTS	1,406.1
CUMULATIVE PAYMENTS	1,372.1
UNPAID COMMITMENTS	34.0
AMOUNT CARRIED FORWARD IN SPECIAL ACCOUNT	5.3
AMOUNT AVAILABLE FROM 1992 AND 1993 FOR SET OFF AGAINST FUTURE CONTRIBUTIONS FROM MEMBERS	8.9

Table 11: Summary of Financial Transactions at 31 December 1993

Summary

Table 11 summarises the financial transactions of the JET Joint Undertaking as at 31 December 1993, which have yet to be audited. The final audited accounts will be published in due course.

Contracts Service

Contracts Activity

The contract activity for 1993 is shown in Table 12. Many of the larger contracts involve advance and retention payments for which bank guarantees are required by JET. The total value of guarantees held as at 31 December 1993 was 5.4 MioECU.

Imports and Exports Services

Contracts Service is also responsible for the import and export of JET goods. 958 imports were handled in 1993, while the total exports amounted to 425. There were also 1380 issues of goods to UK firms. The total value of issues to all countries for the year was 14.245 MioECU.

FORMAL TENDER ACTIONS	NUMBER	
SUPPLY	87	
SERVICE	24	
PERSONNEL	24	
TOTAL	**135**	
CONTRACTS PLACED	QUANTITY	VALUE (MioECU)
MAJOR (>75 kECU)	87	23.383
MINOR (<75kECU)	5,979	37.176
DIRECT ORDERS	14,007	2.913
AMENDMENTS	865	1.137
WARRANTS	72	1.200
TOTAL	**21,010**	**65.809**

Table12: Formal Tender Actions and Contracts Placed during 1993

COUNTRY	VALUE (kECU)	% OF TOTAL
UK	525,823	54.31
GERMANY	162,377	16.78
FRANCE	88,222	9.12
ITALY	61,121	6.32
SWITZERLAND	44,702	4.62
DENMARK	13,111	1.35
NETHERLANDS	16,735	1.73
BELGIUM	11,618	1.20
SWEDEN	6,825	0.71
IRELAND	1,026	0.11
OTHERS	36,248	3.75
TOTALS	**967,808**	**100.00**

Table 12: Allocation of JET Contracts

Stores Organisation

The bulk of JET material is procured on a "just in time" basis and the Stores Organisation provides a receipts and delivery service for this material to the Project. The total number of such receipts in 1993 amounted to 21,233.

Administration of Contracts

The distribution of contracts between countries is shown in Tables 12 and 13. Table 12 includes all contracts with a value of 10,000 ECU and above placed prior to 1984, together with all contracts placed during the period 1984-93. Table 13 is an allocation of "high-tech"

COUNTRY	VALUE (kECU)	% OF TOTAL
UK	136,041	26.82
GERMANY	142,405	28.07
FRANCE	77,572	15.29
ITALY	53,554	10.56
SWITZERLAND	36,536	7.20
DENMARK	7,457	1.47
NETHERLANDS	15,614	3.08
BELGIUM	5,043	0.99
SWEDEN	4,555	0.90
IRELAND	454	0.09
OTHERS	28,072	5.53
TOTALS	**507,303**	**100.00**

Table 13: Allocation of JET "High-Tech" Contracts

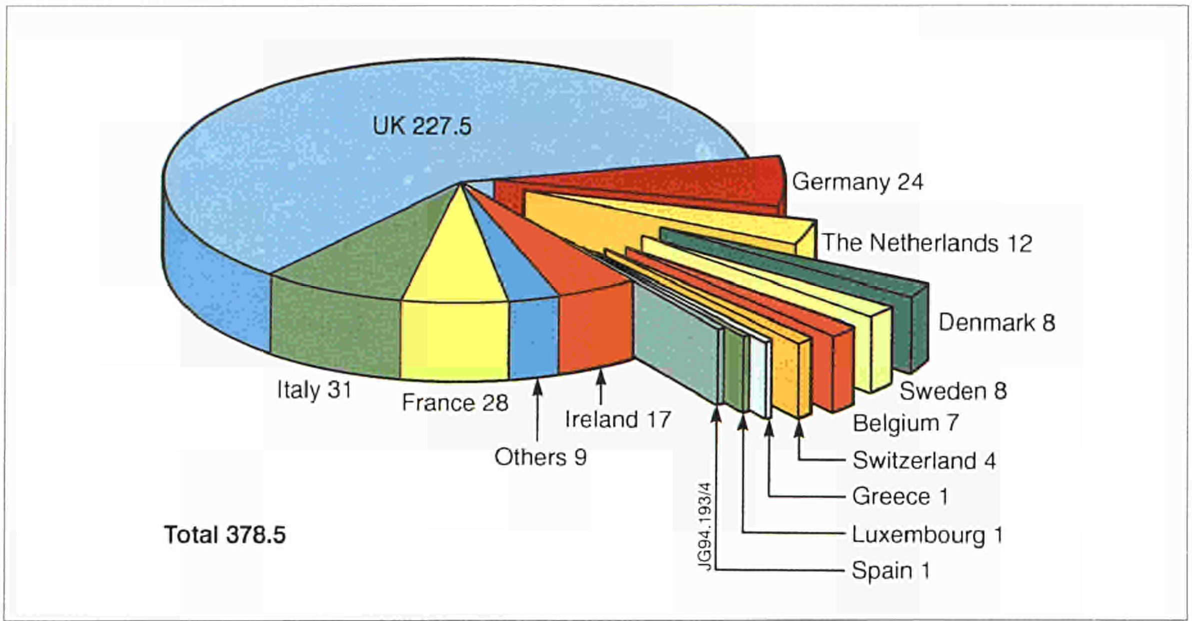


Fig.50: Composition of the JET team by nationality

contracts, which is based on the figures shown in Table 12, but excludes all contracts below 5,000 ECU and contracts covering civil works, installation, pipework, consumables (including gases), maintenance operations and office equipment (including PCs).

Personnel Service

During 1993, the work of Personnel Service was concerned with staffing and conditions of service of the various categories of personnel, training and general administration.

Staffing

The JET Team strength declined during the year from 402.5 on 31 December 1992 to 378.5 on 31 December 1993 (Table 14). The composition of team staff by nationality is shown in Fig.50. In

TEAM POSTS	POSTS FILLED END 1992	POSTS FILLED END 1993
AEA	230.5	228.5*
EURATOM	164	143
DGXII	8	7
TOTAL JET TEAM	**402.5†**	**378.5**

* Includes 11 part-timers, each counted as 0.5 posts
† Corrected from 401.5 used in 1992 Annual Report

Table 14: Team posts filled

addition to the JET team, 351 contract staff were on site at 31 December 1993, charged to Title 3 of the JET Budget.

Thirty-four staff left the Project in 1993 (25 Euratom and 9 AEA, representing 32.5 posts vacated), compared with 42 in 1992. A significant factor in 1993 was JET staff obtaining positions in the ITER teams (1 AEA, 15 Euratom). As well as routine retirements and resignations (4 AEA, 2 Euratom), seven team staff including one AEA employee left to take up posts with the Commission and two returned to AEA. One Euratom staff member returned to his parent organisation. Two team members' contracts expired in 1993 (1 AEA and 1 Euratom). Changes in the hours of work of three staff led to a further reduction of 0.5 posts filled.

There were ten internal selections within the team, mainly to fill senior vacancies which arose. The annual JET promotion exercise lead to 35 staff being promoted to a higher grade.

Recruitment

The restricted recruitment policy established in late 1991 continued throughout 1993, aiming to reduce the size and cost of the JET team by limiting recruitment to essential cases.

Two Euratom recruits were appointed early in 1993. An AEA initiative to recruit young science graduates provided two JET recruits, and four existing AEA staff were assigned to JET to fill vacancies on the JET team. One ex-JET team member was re-appointed (AEA staff).

Conditions of Service

The employers' conditions of service were administered as appropriate, with new rules coming into force on AEA travel expenses. At the request of the JET Council, the AEA reviewed the JET Retention of Experience Allowance and decided that while no improvements could be incorporated into the scheme, it should continue on the existing basis until the end of the Project. The allowance, representing up to 15% of annual salary, was paid in 1993 to 229 of the 235 AEA JET team staff (including part-time staff who each count as 0.5 posts filled) in post at the year end.

Some staff were affected by the termination by AEA of the home-to-work bus service. Fourteen AEA staff at JET who had regularly used the service received some financial compensation and help with their revised transport arrangements.

The intensive scheduling of shutdown work meant that staff were required to work on public and privilege holidays in 1993. This necessitated special overtime arrangements and deferment of annual leave in a number of cases.

Matters relating to working conditions at JET were discussed jointly by JET Management and the Staff Representatives Committee at two meetings during the year: the topics discussed included language training, the future of JET, shutdown working schedule, smoking, and conference attendance.

Joint Working Parties involving JET Management, JET SRC, the two employers and their staff representatives were also convened on specific subjects: training of team staff, future careers of team staff, and Euratom staff recruitment.

Industrial Action

The Trade Unions/Staff Associations representing AEA staff at JET continued their campaign of industrial action in pursuit of their claim for equal pay and conditions with their Euratom colleagues. Five one-day strikes in 1993 resulted in a loss of 741 man-days. Discussions towards finding a solution were conducted by JET management as well as the JET Council, the European Parliament, the Commission and the AEA. The decision by the European Parliament to block part of the Fusion Budget late in 1993 brought the dispute and the Project into a new situation, which is being addressed by all parties affected.

Fellows

The number of Fellows at JET conducting research under the European Union's human capital and mobility programme, has remained stable following changes in the scheme's rules and selection procedure. At the end of 1993, there were 24 Fellows, (15 scientists and 9 engineers). Of the research projects undertaken, 8 were at post-doctoral level and 16 at post-graduate level.

In October 1993, the JET Council decided to raise the ceiling on the number of Fellows at JET from 25 to 30, with an emphasis to be placed on post-doctoral research.

LABORATORY		MAN-YEARS
UKAEA	(UK)	13.0
IPP	(GERMANY)	5.8
CEA	(FRANCE)	1.8
NFR	(SWEDEN)	1.1
CRPP	(SWITZERLAND)	1.0
JNICT	(PORTUGAL)	0.6
ENEA	(ITALY)	0.5
TOTAL		**23.8**

Table 15: Staff Assignments from Associated Laboratories during 1993

Assigned Associate Staff

There was a slight reduction in staff assignments to JET from the Associate Laboratories in 1993, which was not surprising in view of the continuing shutdown at JET. The total contribution for 1993 was 23.8 man-years compared with 24.9 man-years in 1992. Tables 15 and 16 show the contributions made by the Associations in 1993 and the distribution of Assigned Associate Staff within the Project.

In September 1993, representatives of all Associated Laboratories met JET management to discuss ways of increasing the availability of Assigned Associate Staff to JET, which had peaked in 1986 at 42 man-years. In view of the economic recession affecting many Associations, increased staff availability without full funding by the Commission or JET was not possible. Further exploration of the funding question did not yield a satisfactory solution, and the scheme is continuing in its existing form.

Visiting Scientists

Scientists from countries without an association with Euratom may work at JET for periods of up to 24 months at the JET Director's

DEPARTMENT	MAN-YEARS
TORUS AND MEASUREMENTS DEPT	13.5
DATA ANALYSIS AND MODELLING UNIT	6.8
HEATING AND OPERATIONS DEPT	2.5
DIRECTORATE	1.0
TOTAL	**23.8**

Table 16: Assigned Staff effort within the Project during 1993

discretion, as AEA temporary research associates. In 1993, six new appointments were made, one from USA and the others from Russia.

Consultants

Fourteen consultants were appointed by JET in 1993 at Divisions' request, to work for a total of 204 man-days, on scientific/ technical matters.

Students

Sixty-seven student assistants were appointed to JET during 1993 under contract from a local employment agency. The majority of student placements were undertaken by students in their later years of study. About half were for three months or more in duration. Students were recruited from all JET member states except Luxembourg.

Training

Training of all categories of personnel working on the JET site in 1993 amounted to over 3000 man-days. The estimated average time per team member spent on training activities in 1993 was 6 days, a reduction on 1992, reflecting the pressures of the JET shutdown schedule. The major training opportunity for scientists and engineers is attendance at conferences and workshops (112 team members attended at least one) and in-house Science Meetings. Safety training, including a significant amount of induction training for contract staff new to the site, continues to be essential at JET. A limited amount of language tuition (English and other EU languages) was funded. Recall of staff by parent organisations occurred at a low level, totalling about 60 man-days.

At the initiative of the Commission, a Joint Working Party was set up to propose an additional training programme to be adopted and developed over the coming years with a view to easing the future career development of JET staff. Certain proposals are expected to be effected in 1994.

General Administration

JET is benefitting from improved management information on telecommunications costs from the call-logging system which is integrated in to JET's telecommunications system (phones, radio-pagers/bleeps, etc.).

A large number of missions (3681) occurred in 1993, reflecting requirements of shutdown work. However, for 1994 a large reduction is expected due to restrictions imposed on missions and the recommencement of JET operations.

Personnel Service provided 1357 site-security passes to all categories of personnel. This was about 20% fewer than last year, reflecting the second phase of the shutdown. JET hosted 14 meetings of governing and advisory bodies, for which transport and accommodation was organised.

Safety and Health Physics

Safety

The JET Director is responsible for safety and is required by the Statutes to undertake all organisational measures to satisfy relevant safety requirements. JET continues to meet all the requirements of relevant UK and EC legislation and, in accordance with the Host Support Agreement, JET complies with the safety regulations of the Host Organisation.

The JET Safety Group provides a general safety service, including training, monitoring, coordination and planning of statutory inspections. Special attention has been paid to training with particular emphasis on the long shutdown.

During 1993, 470 people attended Safety Induction and 137 people attended Basic Safety courses. Basic Radiological courses were attended by 125 persons and the same number attended Beryllium Introductory courses. Manual Handling courses were attended by 99 people, with about 300 staff attending short Fire Fighting courses and 250 attending CPR courses. In total, there were 2299 attendances at Safety courses in 1993.

In 1993, 135 accidents on site were reported to JET Safety Group. These were classed as minor except for six accidents which were reported to the UK Health & Safety Executive, mainly because these involved more than 3 days of absence. Total lost time from all accidents in 1993 was 163 days. In addition, seven Incident Safety Review Panels were set up to investigate incidents which involved damage to equipment or had the potential to cause damage to equipment or cause personnel injury. The panels made recommendations to prevent further occurrences. All recommendations were implemented.

Health Physics

The Health Physics Group provides a comprehensive radiological protection and occupational hygiene service, dosimetry service, beryllium analysis and environmental monitoring, both on- and off-site.

The divertor shutdown, which started during 1992, continued throughout 1993. The radiation dose rate in-vessel at the start of the year was 5 μSv per hour falling, by decay, to 1.7 μSv per hour in December. These levels were much lower than during the previous year; consequently individual and collective radiation doses were low. The collective dose during 1993 due to in-vessel work was 0.039 man-Sv: the total collective dose for the project was 0.042 man-Sv. These collective doses are approximately 20% of those recorded for 1992. The highest individual dose arising from in-vessel work during calendar year of 1993 was 1.43 mSv.

Tritium contamination in-vessel remained at very low levels posing no significant radiological hazard - no additional precautions were necessary due to residual tritium contamination over and above those already in place to protect against beryllium contamination. There have not been any intakes of tritium, at JET, which have led to a recorded dose.

Exposure to airborne beryllium at JET is quantified for each individual by means of personal air sampling. During 1993, 14,281 samples were analysed in JET's own beryllium analysis laboratory; 99.9% of these samples indicated exposures below the UK's occupational exposure standard (for beryllium) of 2 $\mu g/m^3$ (8 hour time-weighted average). This monitoring data continues to demonstrate compliance with the Control of Substances Hazardous to Health Regulations 1988.

Committees

There are currently three committees on safety-related matters:

- The JET Safety Policy Board, chaired by the Director, which meets once a year to review safety policy and define new actions;
- The JET Fusion Safety Committee, chaired by the Head of Coordinating Staff Unit and includes non-JET members. It keeps under review the safety aspects of the Project during design, commissioning and operation, arising from the use of tritium;
- The JET Safety Working Group, chaired by the Head of Coordinating Staff Unit, which includes members from JET management, staff associations and the Host Patrol Service. It receives reports of Safety

Audits, inquiries into accidents and reviews all matters which affect the health and safety of all employees on the JET site.

Press and Public Relations

With the Project in a reconstruction phase and not generating new scientific results, the year was a relatively quiet regarding media attention. However, there was one exception. This concerned the long-running dispute in which the British staff have made a claim for parity with their Euratom colleagues and for which there was considerable local media coverage throughout the year. This tended to overshadow the challenging technical work being undertaken to build the pumped divertor inside the torus. However, this aspect was covered by a number of technical journalists during the year, including three television crews (from Germany, Italy and the UK) and three radio reporters.

Since the Torus Hall was open throughout the year, many individual visitors and groups took conducted tours around JET. Among the more distinguished visitors were Ministers from several European countries, including Professor Colombo (Italy), Mr Fillon (France), Mr Lehment (Germany) and Professor Thomaz (Portugal). On the diplomatic front, there were visits from the Luxembourg Ambassador and a party of 25 from the London Diplomatic Science Club.

A wide range of professional groups also made visits to the site. As in previous years, students from schools and universities were among the visitors to JET. These included groups, not only from the UK, but also from Denmark, France, Germany, Italy, The Netherlands and Sweden. JET staff also gave a number of lectures to professional groups around the country.

JET's good relations with the neighbouring population was maintained with briefing meetings with local council officials, invitations to civic dignitaries and guided tours for local groups. Farmers participating in the Project's crop sampling exercise were invited for a briefing on the future programme of JET and a tour of the site.

Publications Group

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

Conferences

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

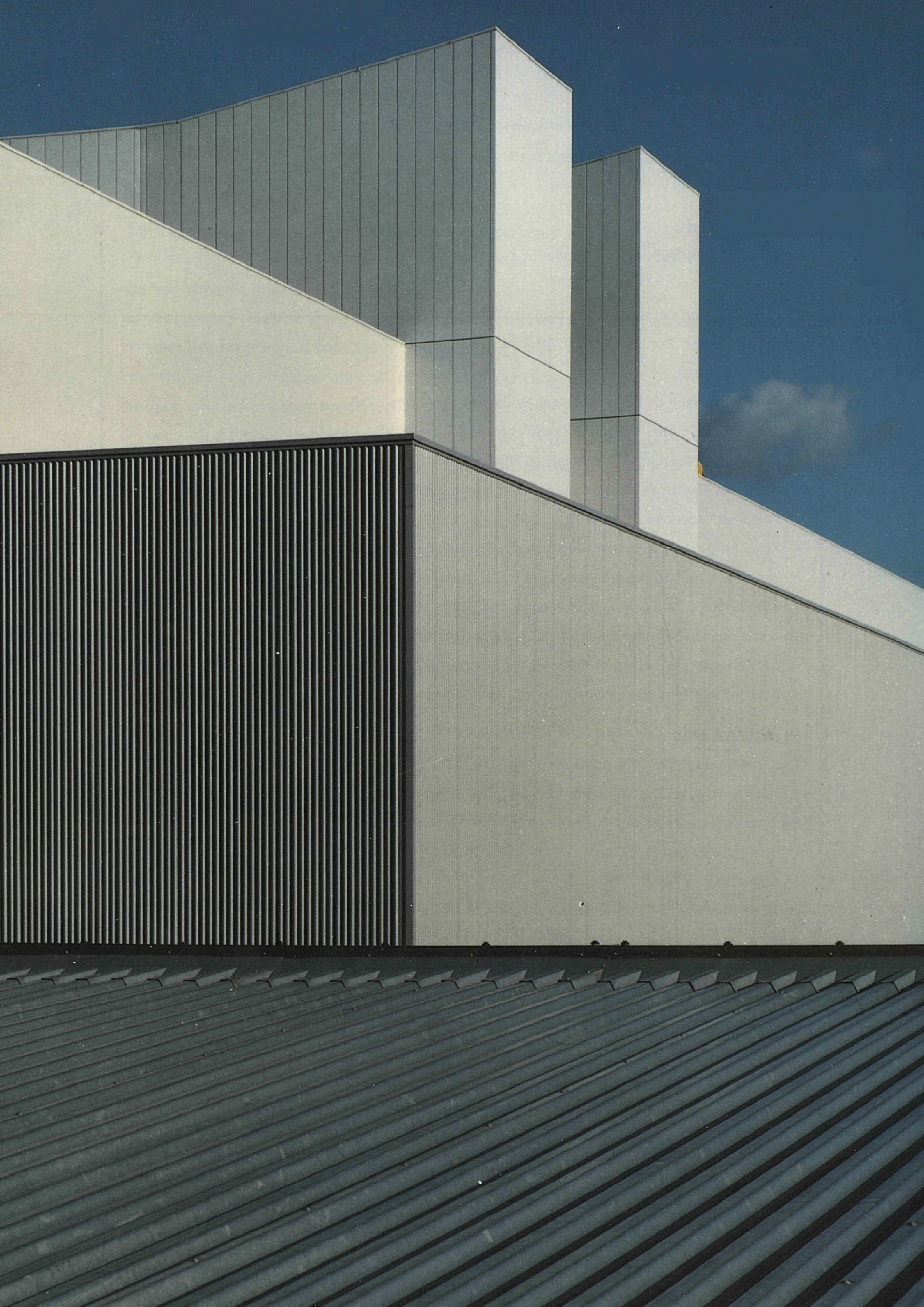
- 20th European Conference on Controlled Fusion and Plasma Physics, Lisbon, Portugal, 26th - 30th June 1993 (2 Invited Papers and 33 Posters);
- 15th Symposium on Fusion Engineering (SOFE-15), Hyannis, USA, 11th - 15th October 1993, (2 Invited Papers and 14 Posters);
- 35th Annual Meeting of the American Physical Society - Division of Plasma Physics, St. Louis, USA, 1st - 5th November 1993, (1 Invited Paper and 11 Posters);
- 4th IAEA Workshop on H-mode Physics, Naka, Japan, 15th - 17th November 1993, (2 Invited Papers and 6 Posters).

In total, the Group prepared 130 Papers and 82 Posters for presentations to about twenty different Conferences throughout the world. Arrangements were also made by the Group for 129 participants to attend these major meetings during the year.

Publications

The Publications Office is responsible for the clearance and production of all JET presentations (including Journal Papers, Reports, Conference Papers, Poster Contributions, Lectures, etc.). Throughout 1993, over 360 publications were cleared for external presentation.

During the year, 318 documents were published from the Project and the full list is included as an Appendix to the 1993 JET Progress Report. This total included 7 JET Reports, 107 JET Preprints, 8 JET Internal Reports and 9 JET Divisional Notes. All these documents are produced and disseminated by the Group on a wide international distribution. In addition, 130 papers were published in scientific Journals. In total, the Group produced 3645 new illustrations and figures and 3233 photographs for publications and other disseminated material during 1993.



APPENDIX I
The JET Council

Member	Representative
The European Atomic Energy Community (EURATOM)	P. Fasella (Chairman to June) C. Maisonnier
The Belgian State, acting for its own part ('Laboratoire de Physique des Plasmas de l'École Royale Militaire - Laboratorium voor plasma-physica van de Koninklijke Militaire School') and on behalf of the Université Libre de Bruxelles' ('Service de physique statistique, plasmas et optique non-linéaire de l'ULB'); and of the 'Centre d'Études de l'Energie Nucléaire (CEN)/'Studiecentrum voor Kernenergie' (SCK)	P.E.M. Vandenplas T. van Rentergem
The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain	A. Grau Malonda
Commissariat à L'Énergie Atomique (CEA), France	D. Escande R. Aymar
The 'Ente per le Nuova Tecnologie, l'Energia e l'Ambiente' ('ENEA') representing all Italian activities falling within the Euratom Fusion Programme including that of the 'Consiglio Nazionale delle Ricerche', (CNR); dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	R. Andreani C. Mancini
The Hellenic Republic (Greece)	A. Katsanos
The Forskningscenter Risø (Risø), Denmark	H. von Bülow (Vice-Chairman to June; Chairman from June) J. Kjems
The Grand Duchy of Luxembourg (Luxembourg)	J. Hoffmann Mrs. S. Lucas
The Junta Nacional de Investigação Cientîfica e Tecnológica (JNICT), Portugal	C. Varandas Mrs. M.E. Manso
Ireland	M. Brennan (to September) M. Benville (from September) F. Turvey
The Forschungszentrum Jülich GmbH (KFA), Federal Republic of Germany	G. von Klitzing
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	K. Pinkau
The Swedish Natural Science Research Council (NFR), Sweden	G. Leman H. Wilhelmsson
The Swiss Confederation	F. Troyon (Vice-Chairman from June) 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 D.R. Sweetman

Secretary: J. McMahon, JET Joint Undertaking

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 de l'École Royale Militaire - Laboratorium voor plasma-physica van de Koninklijke Militaire School') and on behalf of the Université Libre de Bruxelles' ('Service de physique statistique, plasmas et optique non-linéaire de l'ULB'); and of the 'Centre d'Études de l'Energie Nucléaire (CEN)/'Studiecentrum voor Kernenergie' (SCK)	R. Vanhaelewyn
The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain	F. Manero
Commissariat à L'Énergie Atomique (CEA), France	C. Samour R. Gravier
The 'Ente per le Nuova Tecnologie, l'Energia e l'Ambiente' ('ENEA') representing all Italian activities falling within the Euratom Fusion Programme including that of the 'Consiglio Nazionale delle Ricerche', (CNR); dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	A. Coletti M. Samuelli
The Hellenic Republic (Greece)	A. Theofilou (to September) N. Chrysochoides (from September)
The Forskningscenter Risø (Risø), Denmark	Mrs. L. Grønberg V.O. Jensen
The Grand Duchy of Luxembourg (Luxembourg)	R. Becker
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal	J. Bonfim (to April) J. da Costa Cabral (from April) F. Serra
Ireland	F. Turvey (Chairman) D. Taylor
The Forschungszentrum Jülich GmbH (KFA), Federal Republic of Germany	V. Hertling
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	Mrs. I. Kramer
The Swedish Natural Science Research Council (NFR), Sweden	G. Leman (Vice-Chairman) L. Gidefeldt
The Swiss Confederation	A. Heym (to July) M. Tran (from July) L. de Faveri
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	A. Verhoeven L.T.M. Ornstein
The United Kingdom Atomic Energy Authority (UKAEA)	T.J. Elsworth D.C. Robinson

Secretary: J. McMahon, JET Joint Undertaking

APPENDIX III
The JET Scientific Council

Members appointed by the JET Council

K. Lackner (Chairman)
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Staff Secretary: M.L. Watkins, JET Joint Undertaking