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JET: Evolution, Status and Prospects

P.-H. Rebut and P. Lallia

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JET: evolution, status and prospects

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When the objectives and the parameters of JET were defined about ten years ago, the existing knowledge of plasma behaviour in tokamaks showed the advantages of the axial symmetry of magnetic configuration, as well as the leading role of the plasma current in heat confinement.

After two years of operation, JET has proved to be the world's most successful device in thermonuclear fusion research. Whereas achievement of the final aim (i.e. the confinement of plasma with temperature and density such that thermonuclear power dominates the heat losses) has never been nearer, results show that plasma behaviour is even more complex than initially anticipated and nonlinear physics, leading to turbulence or chaos, is involved. How this is likely to modify the JET programme is addressed, as well as the prospects for a future reactor.

1. Introduction

In October 1971, a working group was created by a body coordinating the fusion research in the European countries. The terms of reference of this group (later named 'The Joint European Torus Working Group') were 'to prepare preliminary designs for the various possible concepts of a future European Tokamak'. In its final report, issued in March 1973, the Group recommended that a project team should be established to design and construct a 3 MA tokamak (European Torus Working Group 1973). One of the report conclusions was: 'Both the objective of extending the allowable working range in the density–temperature plane and the objective of nuclear heating lead to the identification of the plasma current as the typical figure of merit.' The projected machine aimed at producing a plasma current one order of magnitude larger than any operating tokamak at that time.

The JET Design Team at the UKAEA Culham Laboratory, Abingdon began work in September 1973 and issued its 'JET Design Proposal' two years later. The objective of the experiment is to obtain and study plasma in conditions and with dimensions that approach those needed for a fusion reactor. This involved four main areas of research work (The JET Project 1973):

'(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;
(iv) the study of α-particle production, confinement and subsequent plasma heating'.

The design was maximized in three major areas: the plasma current, the so-called 'inverse aspect ratio' (i.e. minor radius: major radius) and the ratio of volume to surface. After lengthy discussions, especially on where the device should be built, the JET Joint Undertaking was established at Culham by a decision of the European Council of Ministers in May 1978. The partners in the Undertaking are the fusion research-oriented organizations of the countries who

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are part of the European Atomic Energy Community (EURATOM) plus Sweden and Switzerland. The organs of the Joint Undertaking are the JET Council and the Director of the Project, who was Dr H. O. Wüster until his sudden and untimely death in July 1985.

The construction started without delay and the first plasma was achieved on 18 June 1983, within the schedule established in 1975 (specifying 5 years for the construction) and within the planned budget (when taking account of inflation). Figures 1, 2 and 3 show respectively

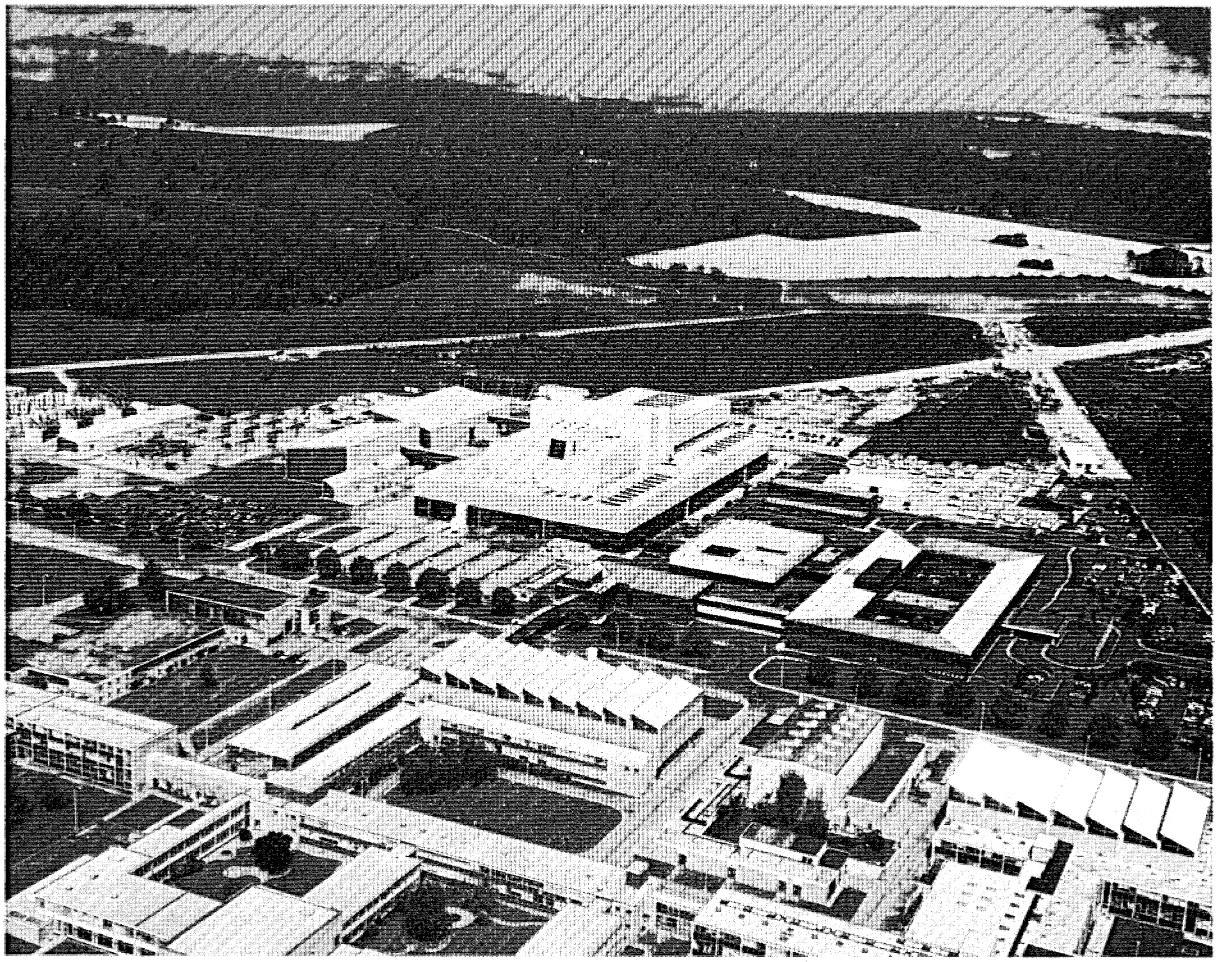

FIGURE 1. Aerial view of the JET site.

the JET buildings, the flywheel generators delivering the energy for the magnets, and the tokamak with its main components: the magnet and vacuum vessel systems. More details of the manufacture and the assembly of JET and on the plasma measurements are presented by Huguet (this symposium) and Stott (this symposium). Table 1 lists the main technical parameters of the machine.

In mid-1983, the project moved into its 'Operation Phase' with ohmic heating only, but a strong effort was also devoted to the construction and installation of additional heating systems. Indeed, as identified in 1971 the ohmic power available in a tokamak is limited by

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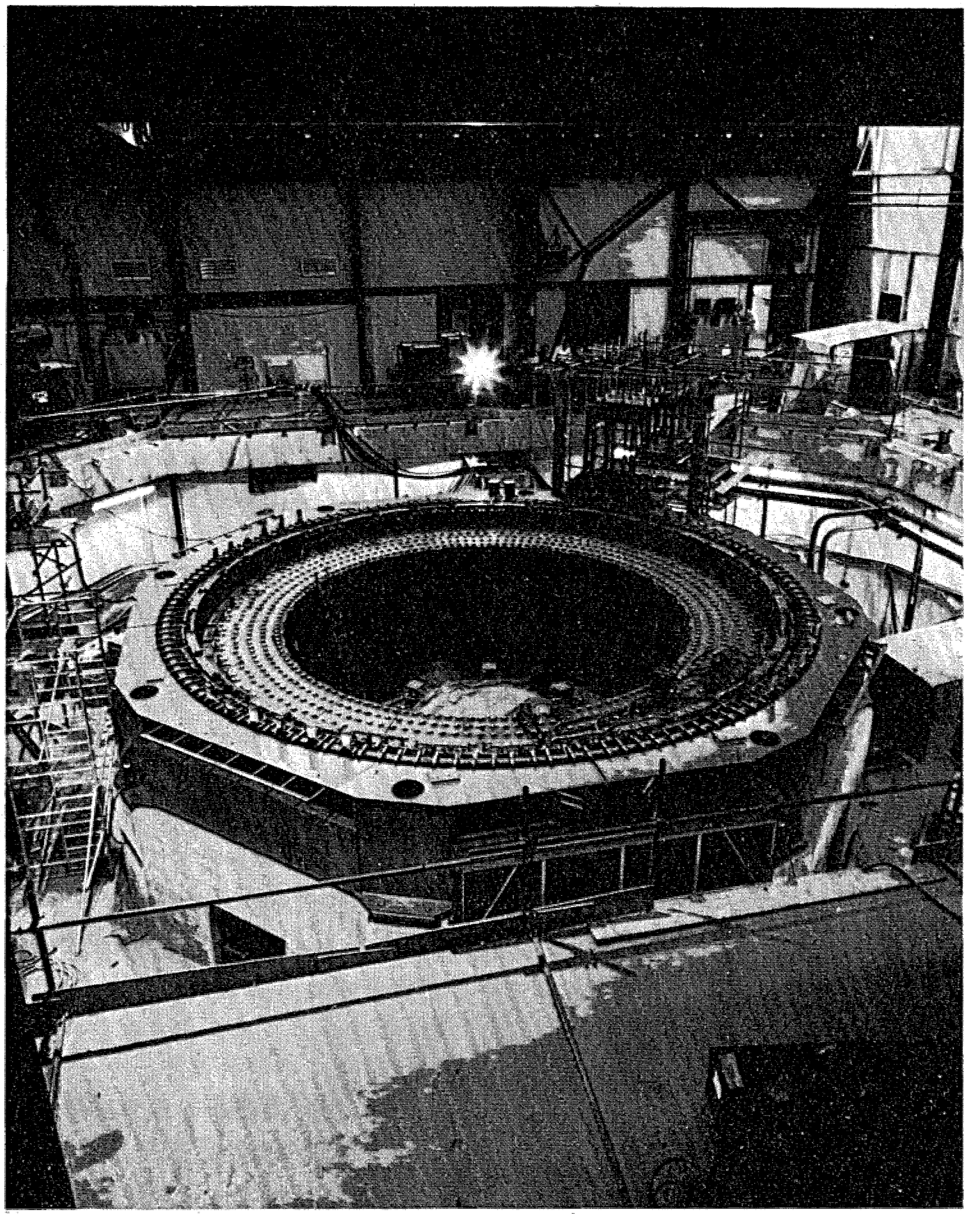

FIGURE 2. Flywheel generator under construction.

the maximum current that can be sustained and by the fact that the electrical resistivity of a plasma decreases with the electron temperature T_e as $T_e^{-\frac{3}{2}}$. The two methods of additional heating selected for JET were the most experimentally advanced at the time of decision: 1978 for the injection of high-energy neutral atoms (NBI) and 1981 for the coupling to the plasma of radio-frequency (RF) waves, with a wave frequency equal to the cyclotron frequency on one of the introduced minority-ion species (ICRF).

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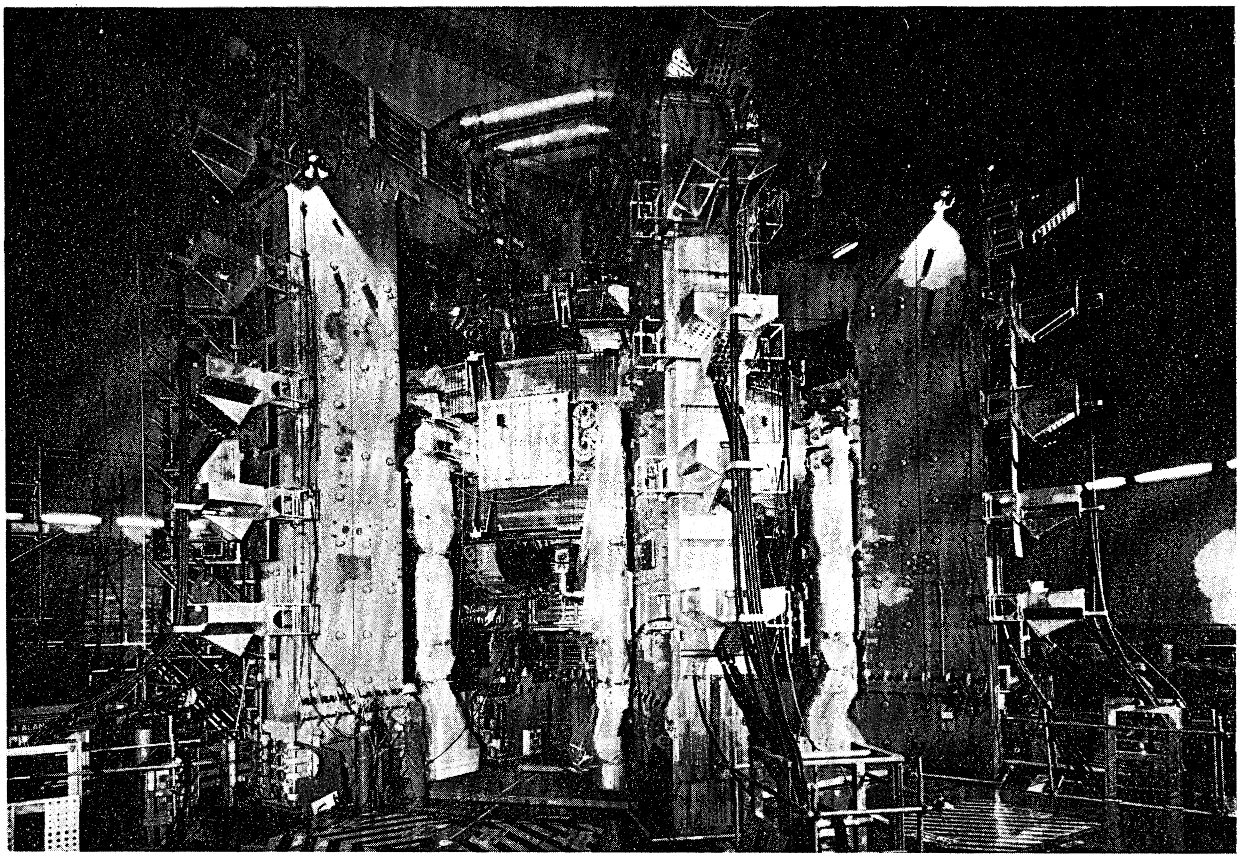

FIGURE 3. View of the machine: the two large outer poloidal-field coils above and below the medium port flange square can be distinguished. The pipes for the interspace gas flow heating of the vessel (up to 500 °C) are wrapped with thermal insulation and run from the floor to the midplane.

TABLE 1. JET'S MAIN DESIGN PARAMETERS

plasma minor radius (horizontal)	1.25 m
plasma minor radius (vertical)	2.10 m
plasma major radius	2.96 m
flat-top pulse length	20 s
mass of the vacuum vessel	100 t
mass of the toroidal field coils	384 t
mass of the iron core	2800 t
toroidal-field coil power (peak on 13 s rise)	380 MW
total magnetic field at plasma centre	3.5 T
plasma current circular plasma	3.2 MA
D-shape plasma	4.8 MA
volt-seconds available to drive plasma current	34 V s
additional heating power	25 MW

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2. LATEST RESULTS

The success of an experimental device is first measured by the fulfilment of its technical specifications, and table 2 shows that JET has indeed reached and sometimes exceeded its design values. The devoted efforts by JET staff in bringing the various components and sub-systems promptly to a working state must be acknowledged. To improve the efficiency of the operations,

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a system of two shifts per day, four days per week, was introduced at the beginning of 1985 leading to an average of around 80 successful tokamak pulses per week throughout 1985.

So far, the experimental programmes have been concentrated in three main areas: ohmic heating, radio-frequency heating and neutral injection. Figures 4 and 5 describe three JET pulses obtained in each of these programmes. For pulse no. 7285, the plasma current reaches 5 MA and maintains this value for 2 s. Pulse no. 7220 shows the effect of about 6 MW of ICRF power coupled to a 2.3 T, 2 MA discharge and pulse no. 7155 the effect of around 6 MW of NBI power injected into a low-density target plasma.

The present JET achievements can be compared to the plasma parameters required in a

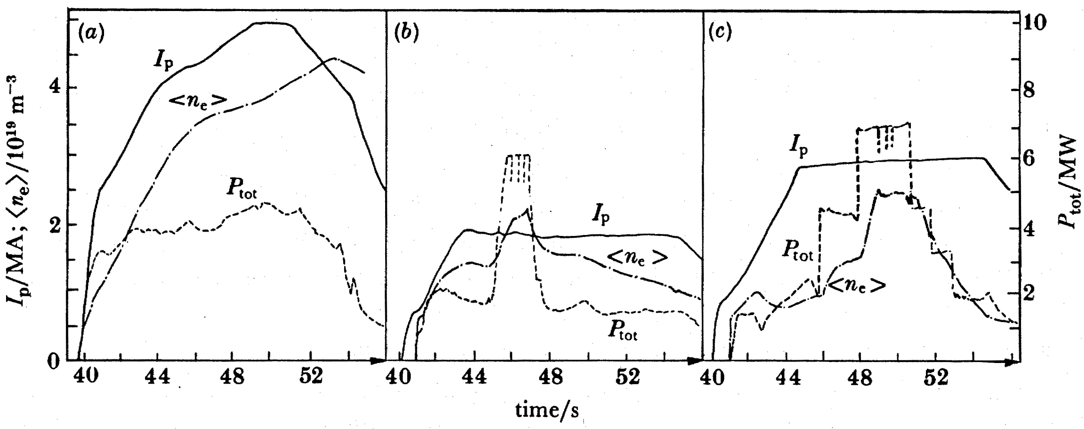

FIGURE 4. Time evolution of the plasma current I_p, the volume averaged electron density $\langle n_e \rangle$ and the total input power P_{tot} during three JET pulses ((*a*) no. 1285, (*b*) no. 7220, (*c*) no. 7155).

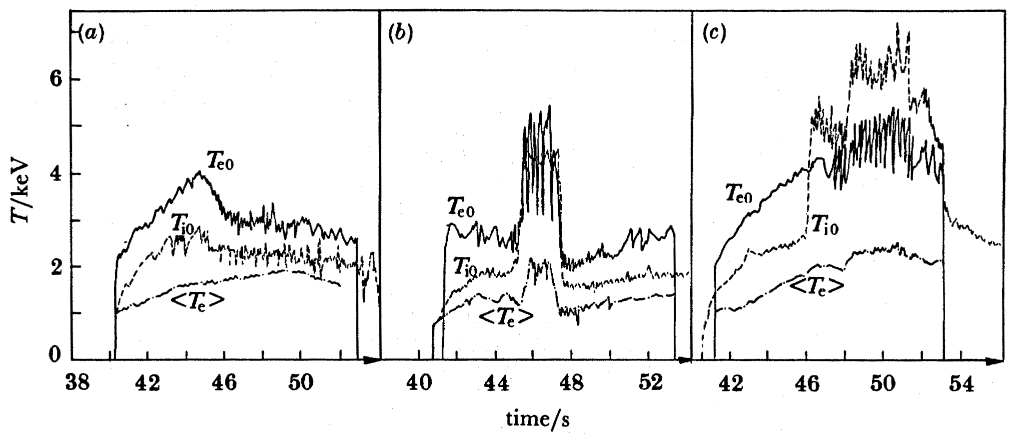

FIGURE 5. Time evolution of the central electron temperature T_{e0}, central ion temperature T_{i0} and volume averaged electron temperature $\langle T_e \rangle$ during the pulses shown in figure 4.

TABLE 2. COMPARISON BETWEEN JET'S MAIN DESIGN AND OPERATIONAL PARAMETERS

parameter	design values	operational values
plasma minor radius (horizontal)/m	1.25	0.8–1.2
plasma minor radius (vertical)/m	2.10	0.8–2.1
plasma major radius, R/m	3.0	2.5–3.4
(toroidal magnetic field at $R = 3.0$ m)/T	$\leqslant 3.45$	$\leqslant 3.45$
plasma current, I_p/MA	$\leqslant 4.8$	$\leqslant 5.0$

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reactor. These parameters are the central ion density $\hat{n}_i$, the central ion temperature $\hat{T}_i$ and the thermal insulation of the plasma, measured by the energy confinement time τ_E (i.e. the plasma kinetic energy divided by the total power losses). The product $\hat{n}_i \tau_E \hat{T}_i$ is an approximate but useful figure of merit of how far (or close) a deuterium–tritium plasma is from 'ignition'. When the power delivered by the α-particles resulting from the fusion reaction compensates the total losses at ignition, the product $\hat{n}_i \tau_E \hat{T}_i$ must reach 500×10^{19} m^{-3} s keV. Typical values for a reactor would be $\hat{n}_i \approx 10^{20}$ m^{-3}, $\hat{T}_i \approx 15$ keV and $\tau_E \approx 3$ s, but ignition could also be achieved with the parameters: $\hat{n}_i \approx 2 \times 10^{19}$ m^{-3}, $\hat{T}_i \approx 15$ keV and $\tau_E \approx 15$ s.

We shall now discuss the behaviour of each term of the product $\hat{n}_i \tau_E \hat{T}_i$.

As in other tokamaks, the density is limited by disruptions, when the plasma is suddenly lost. This occurs, when the electron density n_e is increased above a certain limit. This limit is proportional to B_T/Rq, where B_T is the toroidal field, R the major radius and q the safety factor (q is the number of turns around the vertical axis of the torus performed by a magnetic line of force to complete one turn around the magnetic axis). According to the moderate value of B_T and to the large major radius in JET, the peak electron density is limited to about 4×10^{19} m^{-3} in ohmic operations but it is increased to 6×10^{19} m^{-3} with neutral injection. The dilution caused by the presence of impurities in the plasma also reduces the deuterium density.

Record values of the confinement time ($\tau_E \approx 0.8$ s) have been obtained in JET in ohmic heated discharges as shown in figure 6, where τ_E is plotted against the so-called Neo Alcator scaling factor, which has been previously found to fit many ohmically heated tokamak data. As in other tokamaks, the quality of the thermal insulation deteriorates when additional heating is applied. Figure 7 shows the evolution of the plasma energy content W_k against the total input

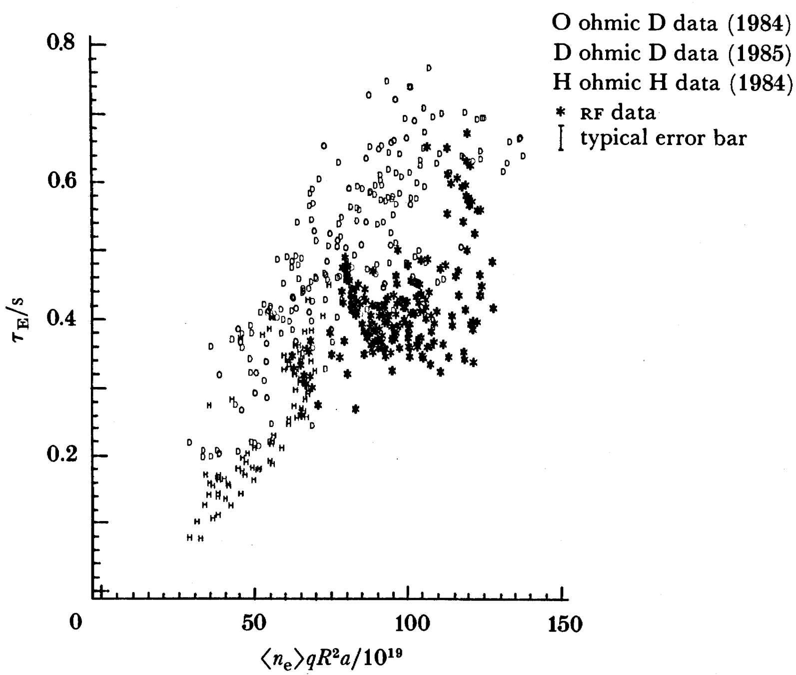

FIGURE 6. Global energy confinement time, τ_E, against the scaling factor $\langle n_e \rangle qR^2a$ for both ohmic and RF deuterium (D) heated and hydrogen (H) plasmas.

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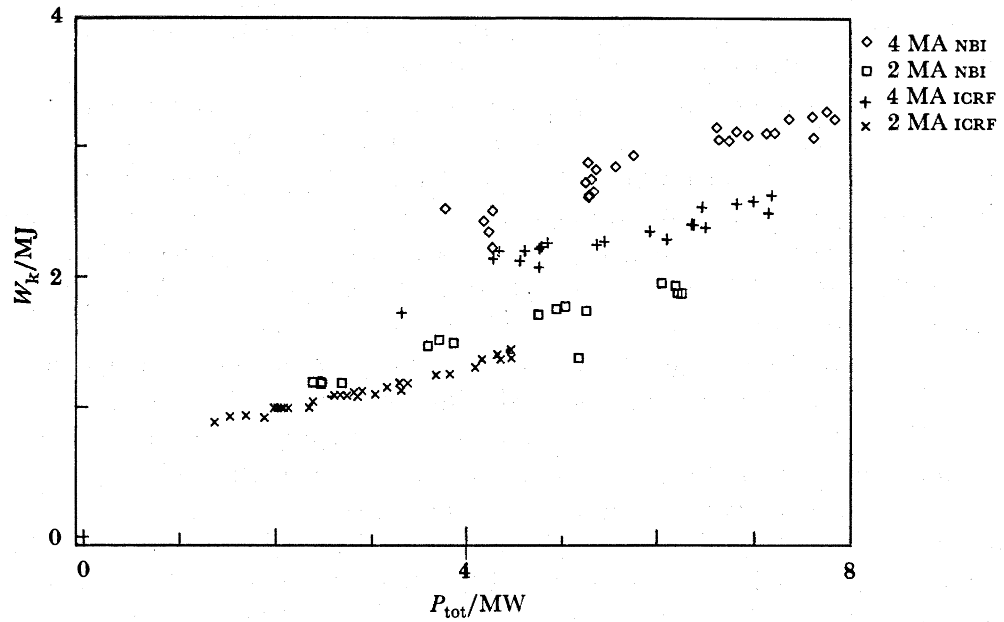

FIGURE 7. Plasma energy content W_k against the total input power P_{tot} obtained with either NBI or ICRF heating for two values of the plasma current: 2 and 4 MA. $B_t = 3.4$ T.

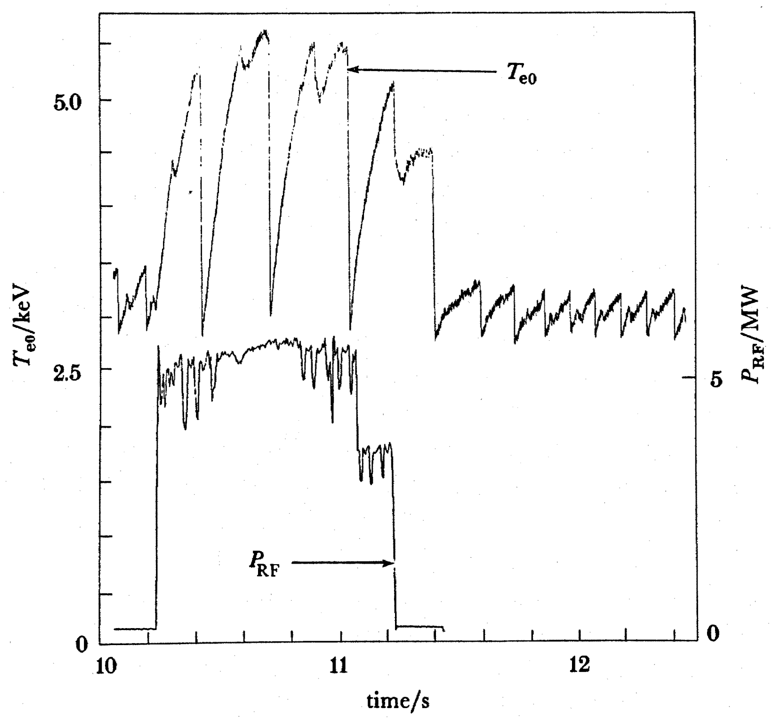

FIGURE 8. Time evolution of the central electron temperature T_{e0} and of the applied radio-frequency power P_{RF}.

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power into the plasma when ICRF and neutral injection heating are used in JET: the ratio of increase in kinetic energy of the plasma ΔW to the additional power ΔP is limited to 0.2–0.3 MJ MW^{-1}, depending on plasma conditions.

When the parameters of JET were proposed, it was argued that without additional heating it would be 'the world's largest cold Tokamak plasma'! Actually it was a surprise to obtain peak ion and electron temperatures reaching 2.5 and 4 keV, respectively, in ohmic discharges during the steady-state phase of the discharge. Application of additional power has increased the peak ion temperature up to 6 keV and the peak electron temperature above 5 keV. One of the peculiarities of additionally heated plasmas, especially with ICRF, is the large increase of the central electron temperature relaxation oscillation (sawtooth), which exists at low level before the RF pulse. Figure 8 shows that the electron temperature on axis is doubled at the top of the sawtooth while RF heating is applied. However, the volume-averaged temperature is increased by 40% only. A similar but less pronounced oscillation affects the central ion temperature, and later on the production of thermonuclear reaction. Clearly, it is important to understand the underlying physics of 'sawteeth'.

In summary, the highest ion temperature of *ca.* 6.5 keV was achieved with 6 MW of NBI power. The largest product $\hat{n}_i \tau_E \hat{T}_i$ of *ca.* 6×10^{19} m^{-3} s keV is not significantly higher than the best ohmic results with additional heating. A large increase of this product has been achieved with JET, but a factor of about 80 is still needed to obtain ignition in a reactor. The JET programme is oriented towards a reduction of this gap by controlling confinement and the central plasma parameters.

3. Outstanding questions and possible answers

As shown, the performances obtained after two years of operation have placed JET in a leading position among the thermonuclear fusion devices and the final objective has never seemed closer. However, in JET as in other tokamaks the thermal losses are much higher and behave differently than those predicted by an idealized theory, where the diffusion occurs through Coulomb collisions in a geometry of nested magnetic surfaces. A large theoretical effort is done in several directions.

One model can provide a qualitative explanation of various observed phenomena. According to this model, three types of magnetic field topology can coexist across the plasma: nested toroidal magnetic surfaces, magnetic islands centred on rational values of the safety factor and regions where the field lines have a chaotic (ergodic) behaviour (Rebut & Brusati 1986). It has been shown that a very small departure from the axisymmetry can create magnetic islands where the helical perturbation is constant along a closed magnetic field line, producing a condition of resonance. In this case, the safety factor has a rational value $q = m/n$ where m and n are respectively the poloidal and toroidal periodicities of the perturbed field. In standard tokamak discharges, the safety factor q increases from a value close to one at the centre to three or five at the boundary. Several layers of islands can coexist as shown in figure 9. The coupling betweeen the various modes induces secondary islands and a chaotic behaviour appears close to the X points, the tips of the separatrix, for a very low level of perturbation. Figure 10 shows how the chaotic regions around the separatrices join together when the magnetic islands start to overlap, i.e. when the overlapping parameter γ (which equals the ratio between the island thickness and their radial separation) approaches unity. Then, the electrons, especially the more energetic, can connect high and low temperature regions of the plasma by just flowing along

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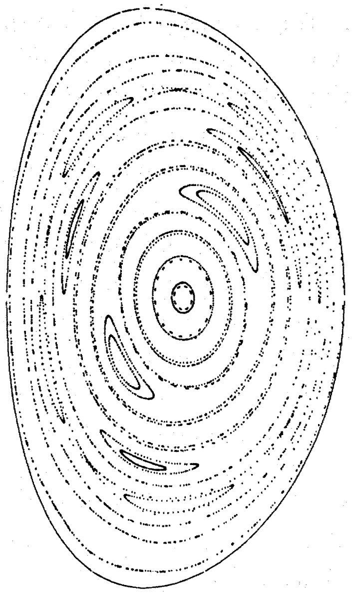

FIGURE 9. Magnetic islands distorting the magnetic surfaces of a JET plasma. Noticeable are the $m = 2$, 3 and 4 islands.

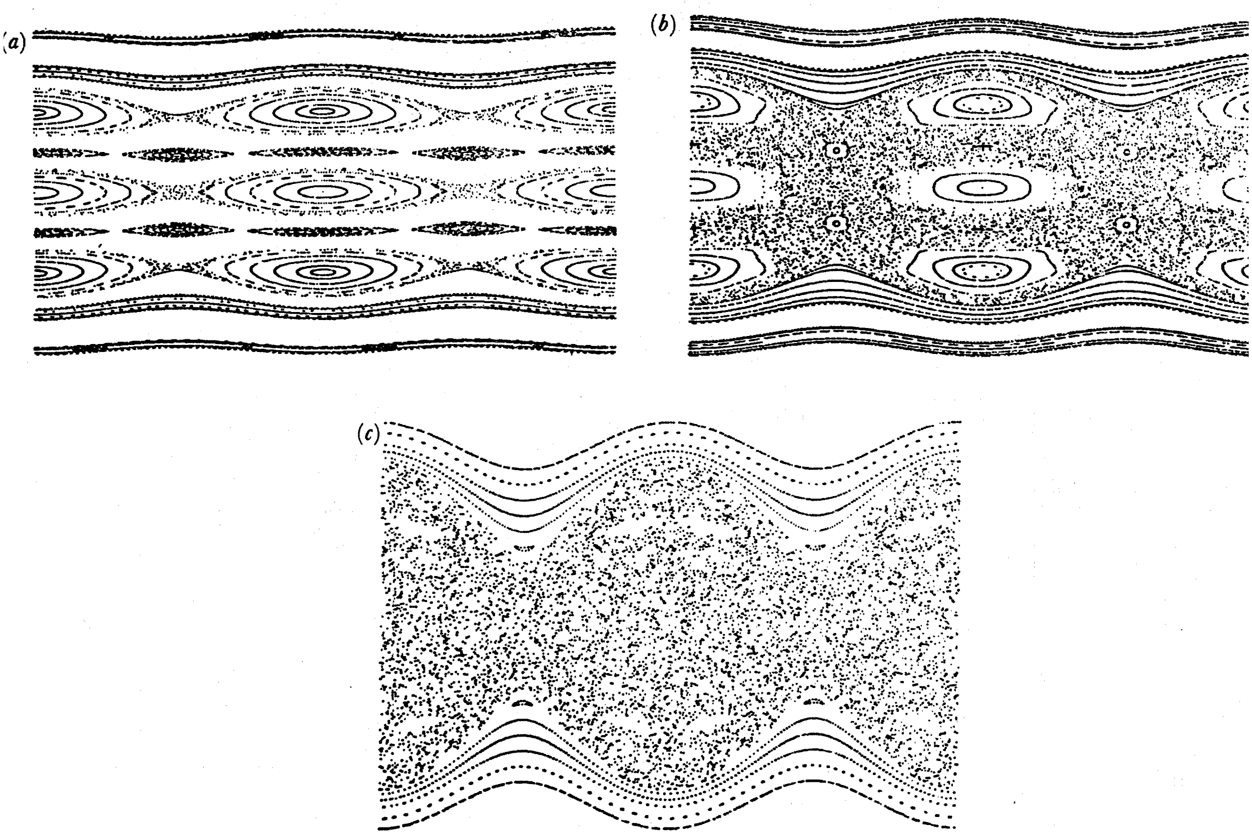

FIGURE 10. Interaction of magnetic islands showing the creation of chaotic (ergodic) field lines when the overlapping parameter γ is increased. (*a*) $\gamma = 0.63$. Formation of secondary islands and ergodic magnetic lines around the X point, No 'mixing' occurs. (*b*) $\gamma = 0.9$. The ergodic domain develops across the whole region. The primary and secondary islands still exist. 'Mixing' is already important. (*c*) $\gamma = 1.8$. The islands have been destroyed and the region is fully ergodic. Full 'mixing' has occurred.

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the magnetic field lines. The resulting electron heat transport is larger by many orders of magnitude than that expected from a 'classical' radial diffusion across the magnetic field by collisions. This transport reduces the radial electron temperature gradient that can be achieved for a given input power and consequently the efficiency of any heating.

According to thermodynamic arguments, it could be assumed that the heat flow from a hot to a cold region could generate the current responsible for the magnetic perturbation. This leads to a 'critical electron temperature gradient' directly linked to the degree of the magnetic-field-line chaos, as illustrated in figure 11. Any additional power delivered to the plasma enlarges the volume of the chaotic zone, which limits the increase of the electron temperature gradient. Fortunately, a saturation phenomenon should exist when the resonance condition between the pitch of the perturbation and the pitch of the field line is destroyed by the chaoticity itself. Then, the temperature gradient can increase again at the expense of a highly degraded thermal insulation. This phenomenon is predicted to be dominant where the radial gradient of q, q', is significant. Such a concept of 'critical electron temperature gradient' is consistent with the JET data (see figure 12), which show the electron temperature profiles measured by electron-cyclotron emission in various plasma conditions.

When q' is too small, only large islands are predicted to exist around rational values of q and chaotic regions do not appear. This should be the case near the axis of the tokamak discharge, inside the surface defined by the condition $q = 1$. Actually, as shown in figure 8, the almost linear increase of the electron temperature in the central region during the growth of a sawtooth indicates a near adiabatic heating and a much better confinement of energy than further out.

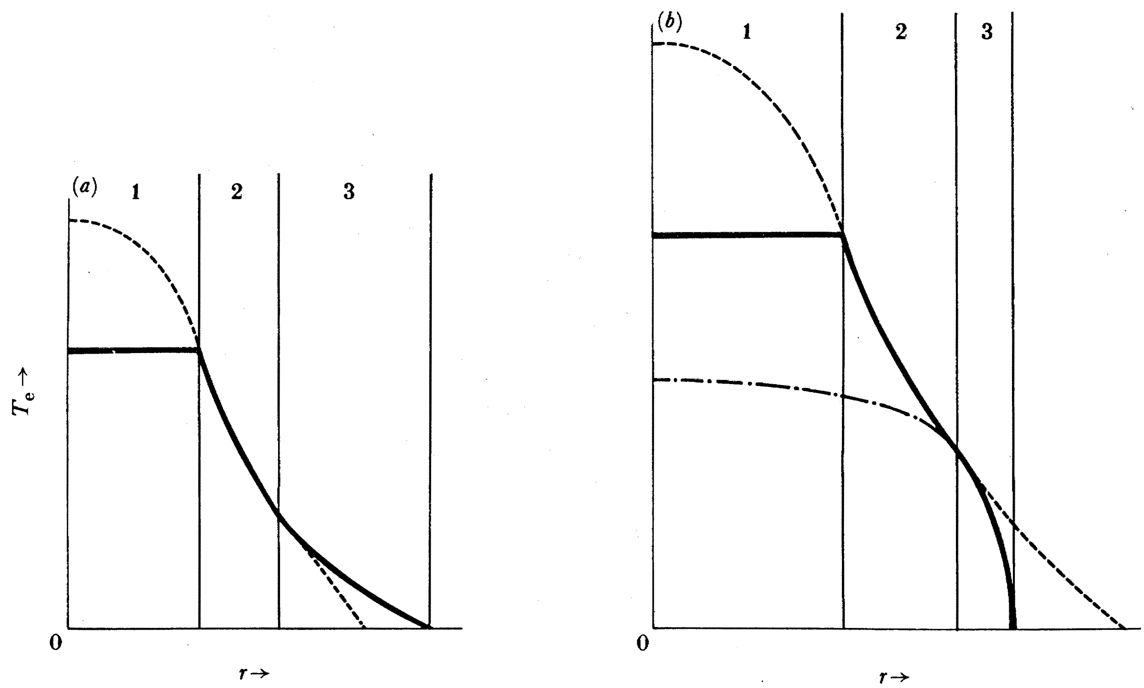

FIGURE 11. Different zones in a plasma, where the respective confinement properties differ strongly: in zone 1 the temperature profile is controlled by a sawteeth activity ($q' \approx 0$, $q \approx 1$); in zone 2 a critical temperature profile is established, $\nabla T \approx \nabla T_c$; in zone 3 edge effects dominate for (a) or the plasma is in a régime where chaos is saturated in (b). Actual electron temperature (——); critical electron temperature in the presence of partial (---) or complete chaos (—·—).

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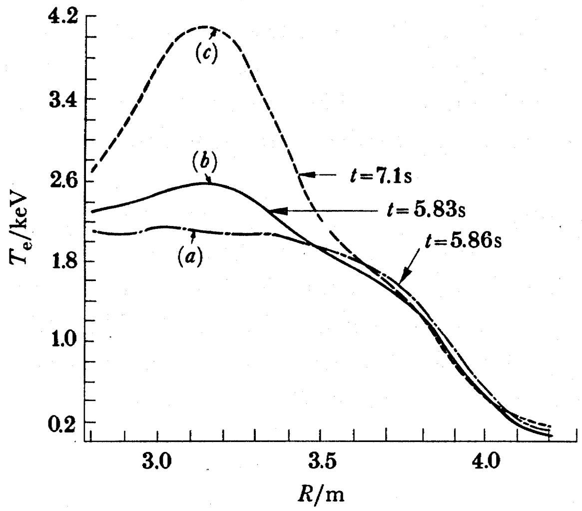

FIGURE 12. Electron temperature profiles measured at different times: (*a*) at the end of a sawtooth, (*b*) at the peak of a sawtooth, both during ohmic heating (1.58 MW) and (*c*) at the peak of a sawtooth during RF heating (2 MW) plus ohmic heating (1.43 MW).

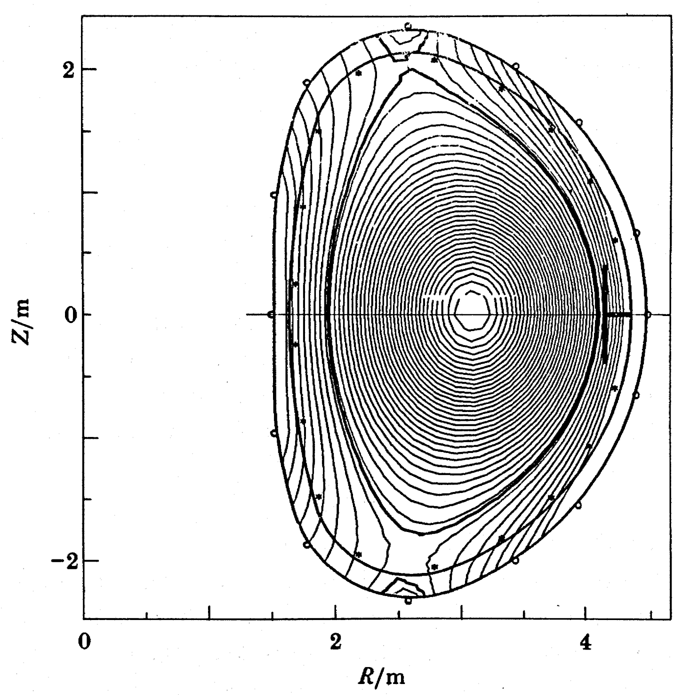

FIGURE 13. Formation of the magnetic separatrix inside the JET vacuum vessel. Pulse no. 5564; time, 17.3 s.

The sudden and fast relaxation is likely caused by a convective motion of the central part of the discharge as described by Wesson (1986).

The heat flow induced by the coexistence of islands and chaotic regions varies as $1/N^2$, where N is the number of chains of islands, which increases with the safety factor. Therefore, the heat flow may not be sufficient in regions of high q and the enhanced transport predicted

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by the model vanishes. High-q regions exist in the vicinity of the magnetic separatrix which, by a proper arrangement of the external current loops, can be formed inside the volume of the vacuum vessel and then can enclose the plasma discharge as shown in figure 13. Régimes of better thermal insulation (H régimes) have been observed in several tokamaks, following its discovery in Asdex (Wagner 1982). This model assumes that the heat was not transported by radiation.

When islands are large enough, they can provide good thermal insulation similar to that observed at the plasma centre ($q' \approx 0$) with the surrounding chaotic zone. For instance, a thermal instability and growing islands are expected to develop around the $q = 2$ surface when the radiated power exceeds the input power inside the islands. This phenomenon is proposed as one explanation of the density limit disruptions (Rebut & Hugon 1985). In addition, a sharp transition in the electron temperature gradient at $q = 2$ due to impurity radiation may also be one cause for disruptions.

4. Future programme for JET and possible outlines of a 'tritium burner'

The JET Development Plan is shown in figure 14. The principle of continuation until the end of 1992 has been accepted by the JET Council but has not yet been formally agreed by the European Council of Ministers. Periods of operation are alternated with shutdowns of the machine to allow installation of new equipment. In particular, the main developments are, in order of occurrence.

(*a*) Increase of the additional heating systems to full performance (10 MW of NBI; 15 MW of ICRH).

(*b*) Modification of the magnetic configuration and the reinforcement of the vacuum vessel mechanical supports to produce a magnetic separatrix and to attempt reaching 'H-mode' of auxiliary heated discharges.

(*c*) Installation of a toroidally axisymmetric limiter made of graphite or beryllium tiles to withstand the large power injected into the plasma (25 MW) and to reduce the power lost by radiation in the external region of the plasma (the belt limiter).

(*d*) Installation of pellet injectors and pump limiters to gain control of the density during the discharge.

(*e*) Completion of a tritium reprocessing plant and of the various remote-handling (RH) systems needed for the active phase of JET operations.

(*f*) Development and installation of a radio-frequency system capable of driving part of the plasma current in a non-inductive way. Even limited control of the radial safety-factor profile should allow stabilization of sawteeth relaxations and to keep the plasma temperature higher on axis. Two methods are presently under investigation. The first called 'Lower Hybrid Current Drive' (LHCD) has been successfully tested on smaller tokamaks. The corresponding frequency for JET would be around 4 GHz. The second, based on the cyclotron absorption of waves by electrons (ECRH), requires powerful microwave generators with a frequency of around 80 GHz, which are only just becoming available.

Tokamak research is progressing speedily, especially in the new generation of larger tokamaks where the size and the associated longer characteristic times allow a better identification of the mechanisms prevailing in the plasma. Without doubt, the results obtained on JET and the

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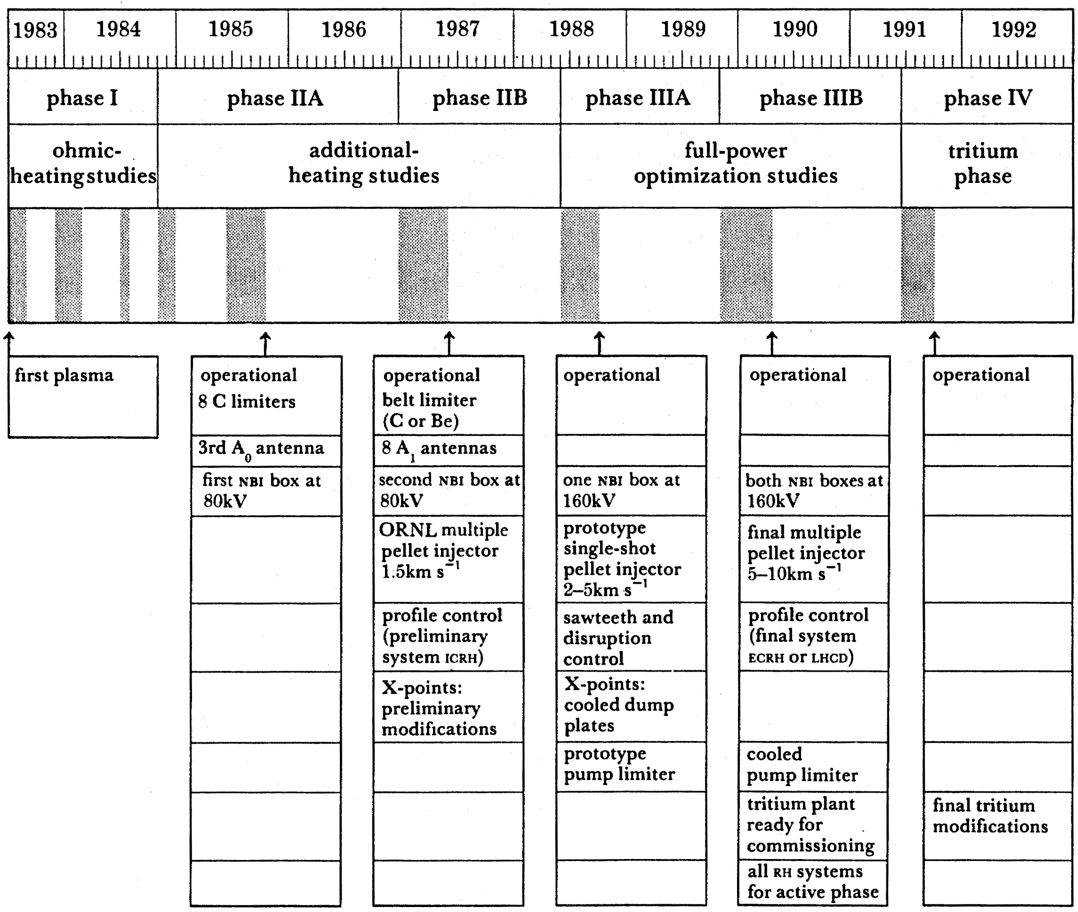

FIGURE 14. The JET programme. The shaded areas represent shutdowns; the unshaded areas represent operational periods; A_0 and A_1 describe the non-water-cooled antennas (short pulse) and water-cooled antennas (long pulse), respectively, used for launching ICRH (ion-cylotron resonance heating); ORNL is the Oak Ridge National Laboratory, U.S.A., who provide the first injector of pellets of solid hydrogen; see text for other abbreviations.

understanding of the plasma behaviour are likely to play an increasing role in the definition of a future D–T burner. As large increases of the electron temperature are observed with increased plasma size, in agreement with the qualitative prediction based on magnetic topology, it is possible to conceive a D–T burner tokamak without external additional heating, with a major radius a little more than twice that of JET, a plasma volume of around 2000 m^3 and a magnetic field slightly higher than in JET. Under these conditions, a 15 keV plasma and a confinement time of 15–25 s could be reached with ohmic heating only at a density half to a third that in JET but still satisfying the ignition criterion. Then, the thermonuclear power output of the D–T burner would be increased by injecting fuel pellets: the thermal insulation would degrade as the additional heating provided by the α-particles increased, keeping the temperature approximately constant and the burn control would be entirely performed through density control, further stressing the importance of mastering the disruptive density limit.

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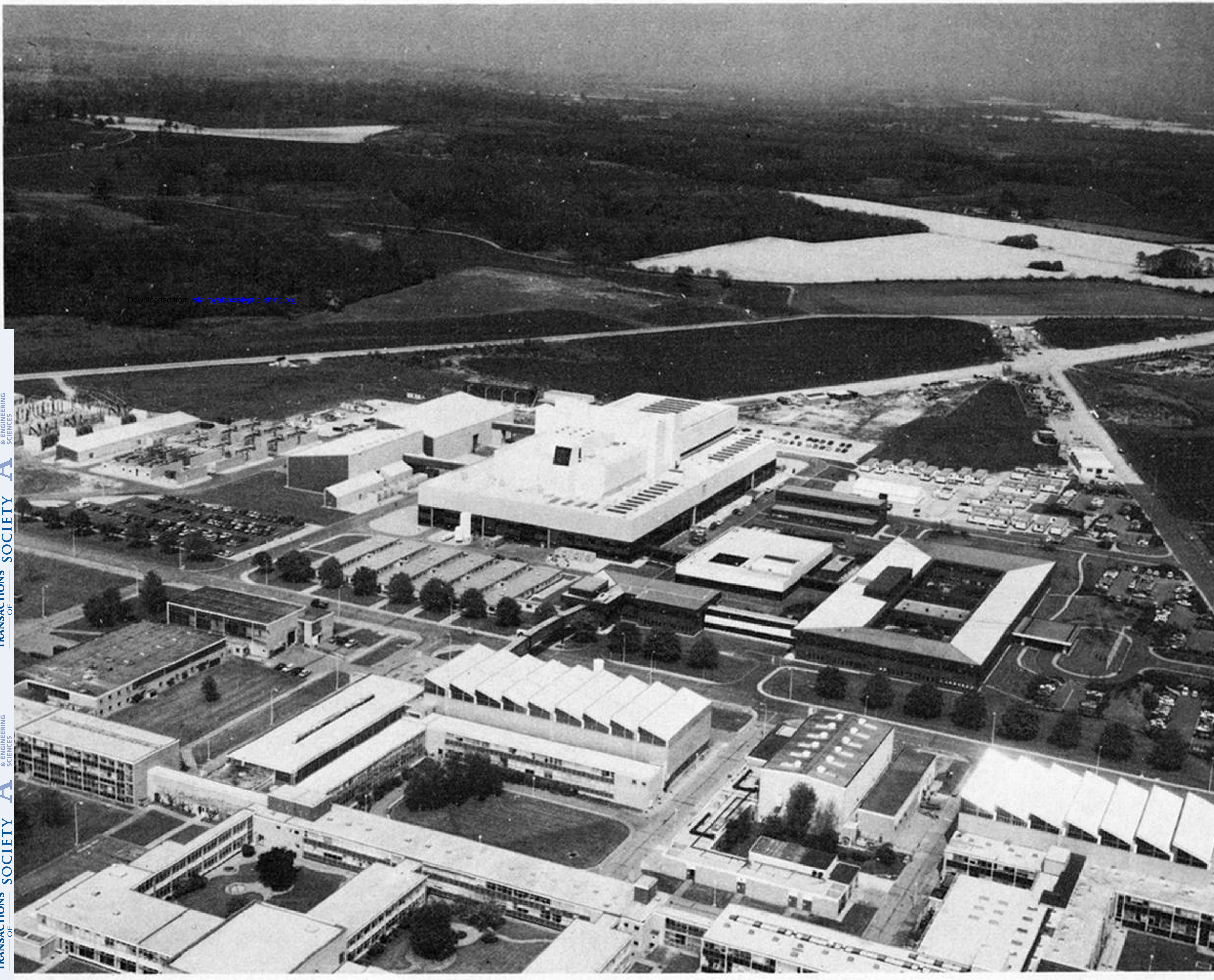

FIGURE 1. Aerial view of the JET site.

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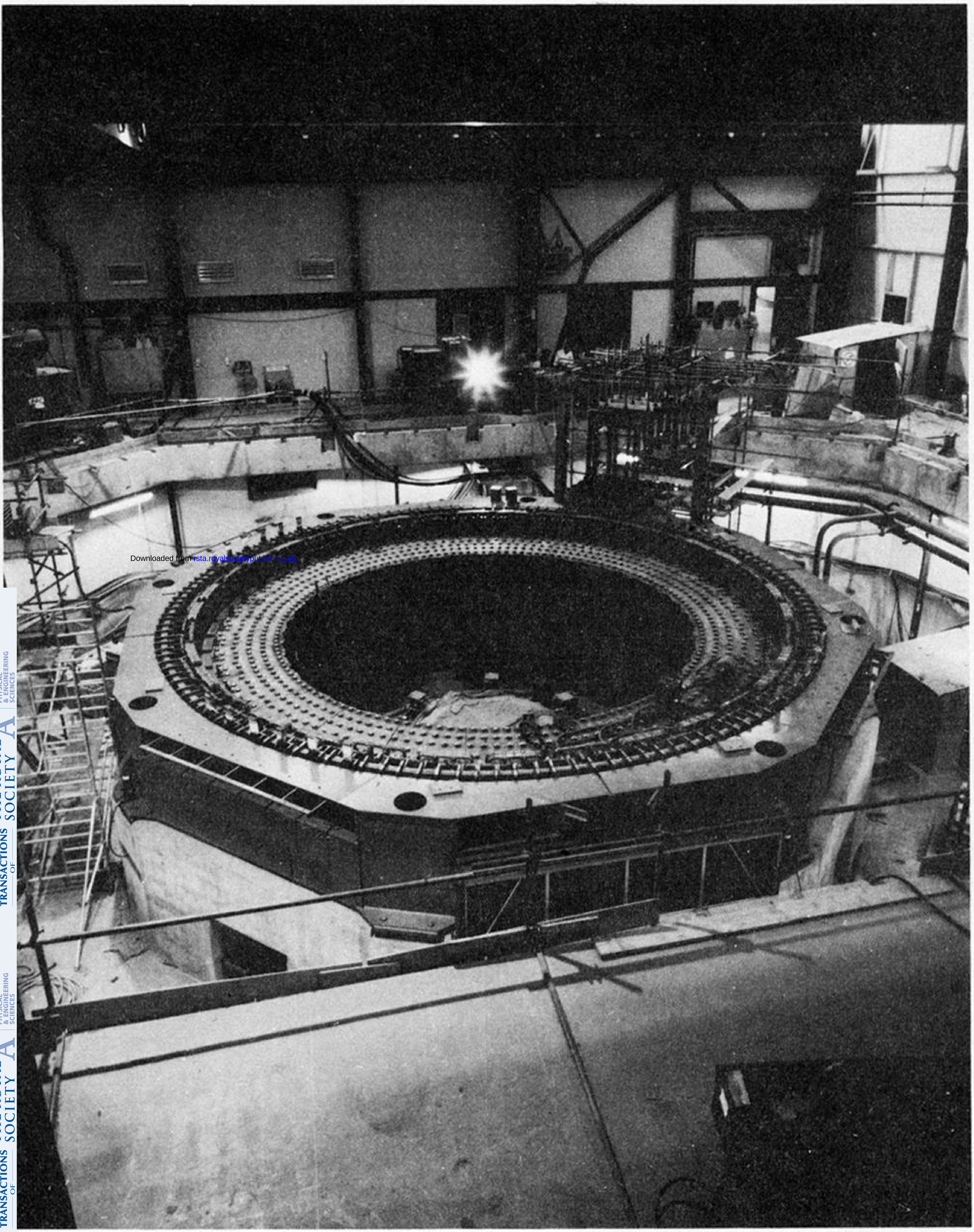

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FIGURE 2. Flywheel generator under construction.

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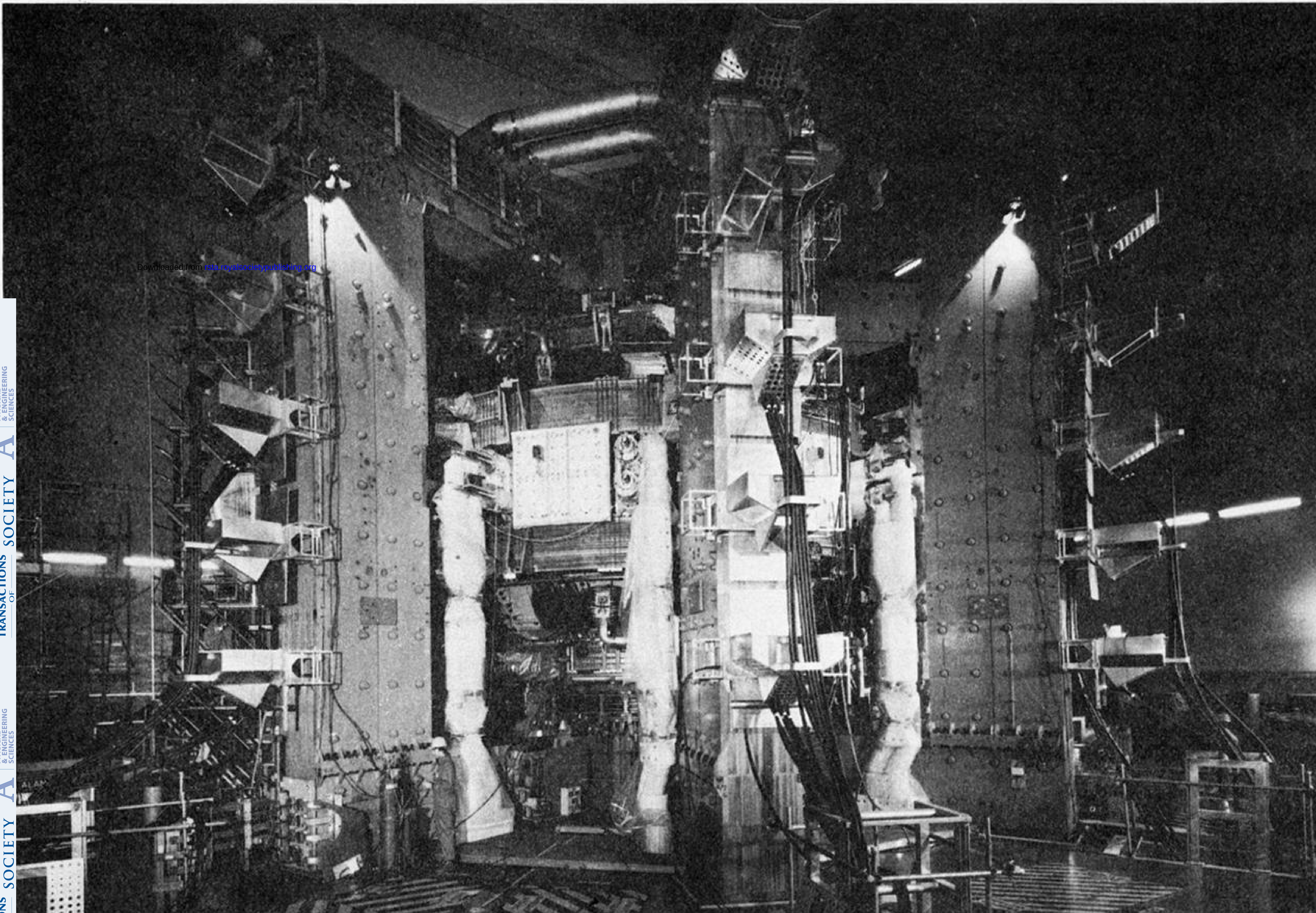

FIGURE 3. View of the machine: the two large outer poloidal-field coils above and below the medium port flange square can be distinguished. The pipes for the interspace gas flow heating of the vessel (up to 500 °C) are wrapped with thermal insulation and run from the floor to the midplane.

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