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# Latest Results from JET

## R.J. Bickerton and the JET Team

*(JET Joint Undertaking, Abingdon, Oxon)*

The Joint European Torus (JET) is a large tokamak designed with the essential objective of obtaining and studying plasmas with parameters close to those envisaged for an eventual power-generating, nuclear-fusion reactor [1, 2, 3]. JET is situated on a site near Abingdon, Oxon, UK. JET is the largest single project of the nuclear fusion research programme of the European Atomic Energy Community (EURATOM). The tokamak started operation in mid 1983 after a five year construction period. The scientific and technical results achieved so far are summarised in this article.

**Basic Requirements for Fusion**

The fusion reaction favoured by a large cross-section and energy yield is that between the two isotopes of hydrogen, deuterium and tritium,

$$\mathrm{D} + \mathrm{T} \rightarrow \underset{(3.5\ \mathrm{MeV})}{{}^4\mathrm{He}} + \underset{(14.1\ \mathrm{MeV})}{\mathrm{n}}$$

To produce useful steady state power from this reaction requires a plasma with a temperature in the range 10 – 20 keV ($10^8 - 2\times10^8$ K), a particle density ($n$) of $\cong 10^{20}\mathrm{m}^{-3}$ and a degree of thermal insulation such that the energy confinement time ($\tau_\varepsilon$) is a few seconds. Such a plasma can in principle be confined by suitable magnetic fields and must be maintained sufficiently hot and dense in the core to produce the required reaction rate and at the same time rare and cool enough at the edges for contact with material walls to be supportable. The plasma must be held in pressure ($p$) equilibrium by the current density (**j**) in the plasma interacting with the local magnetic field **B** such that

$$\mathbf{j} \wedge \mathbf{B} = \mathrm{grad}\, p$$

Such systems are topologically toroidal. The tokamak, pioneered in the Soviet Union, is a particular example of toroidal magnetic confinement in which the confining field is the combination of a strong toroidal component produced by external coils and a weaker poloidal component produced by a toroidal current in the plasma itself [4].

**JET Aims**

The JET tokamak was built to study the behaviour of large high temperature plasma, plasma heating techniques, plasma-wall interactions and eventually the confinement and heating effects of α-particles produced in deuterium-tritium plasma. This requires preparation for remote maintenance of the machine and for the handling of tritium. These preparations are now well advanced and the capability to use a D-T mixture is scheduled for 1991.

**JET Parameters**

The broad technical parameters of the JET machine are listed in Table 1. Also shown are the performance levels already achieved. Notable is the operation at 7 MA plasma current, a level 45% higher than the initial design rating. The pulse length of high current in the plasma is typically 5 – 10 s.

The two plasma heating systems used are neutral beam injection (NBI) [5] and ion cyclotron resonance heating (ICRH). Two NB boxes are available on JET providing about 21 MW of heating power. The ICRH heating is accomplished by launching RF waves into the

**Table 1 — Parameters of the JET Machine**

| Parameter | Design Values | Achieved Values |
|---|---|---|
| Plasma major radius ($R_0$) | 2.96 m | 2.5-3.4 m |
| Plasma minor radius ($a$) | 1.25 m | 0.8-1.2 m |
| Plasma elongation | ≤ 1.6 | ≤ 1.7 |
| Plasma Current ($I$) | | |
| (a) Limiter mode | 4.8 MA | 7.0 MA |
| (b) Single null separatrix | Not foreseen | 5 MA |
| Neutral Beam Power | 20 MW | 21 MW |
| Ion Cyclotron Resonance Heating Coupled Power | 15 MW | 18 MW |

## Contents



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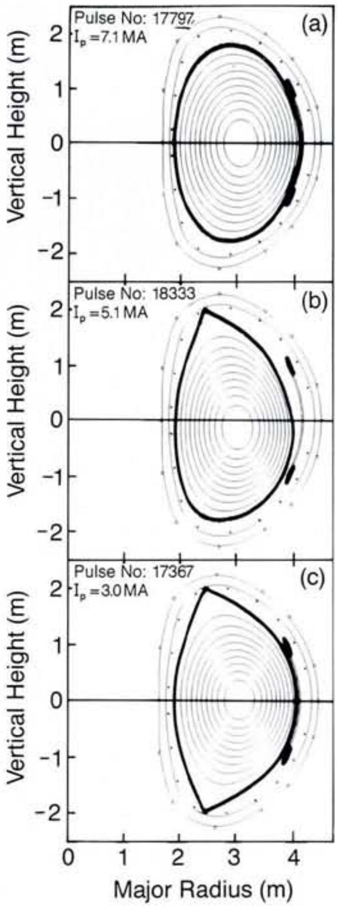


*Fig. 1 — Poloidal flux plots for the cases: (a) limiter bounded plasma; (b) single-null configuration; and (c) double null configuration.*

plasma. These are in the range 25–55 MHz tuned to resonate with the cyclotron frequency of a minority (few percent) species of ions deep in the plasma. The minority ions are accelerated to energies in the range 0.1–1.5 MeV and transfer energy primarily to the plasma electrons. So far, eight antennae have propagated a total of 18 MW of RF power into the JET plasma. Subsequently, this should be increased to ≅ 24 MW.

Note that JET is a machine with a large physical size and relatively low magnetic field strength. In these respects, it is within a factor of 2–3 in linear dimensions and field from an eventual fusion reactor in which the scales are determined by the thickness (1.5–2 m) of the surrounding neutron absorbing and tritium generating blanket together with the field limitations of superconducting coils.

**Discharge Types**

Discharges have been operated with different boundary conditions, heating scenarios, particle fuelling and particle pumping arrangements. Fig. 1 shows the poloidal flux plots for three cases: (a) with a limiter bounded plasma, (b) and (c) with single and double null magnetic separatrices. These flux plots show the cross-section of the magnetic surfaces generated by magnetic field lines passing many times around the major axis of the machine. The heating scenarios are variations and combinations of neutral beam and ion cyclotron resonance heating. The beams have been operated with deuterons at 70–80 keV, while the RF has been used with H or $^3$He minority ions in D or $^4$He plasmas. For RF the power deposition zone is narrow with a typical half width about the resonance layer of ≅ 0.3 m. The fuelling variations include gas-puffing from the boundary, the injection of small frozen deuterium pellets of diameter 2.7 or 4 mm at speeds ≅ 1 km/s [6] and neutral injection itself which provides particle sources inside the plasma. The particle pumping at the boundary can be varied by putting the plasma into contact with different surfaces in the vacuum vessel and by pre-conditioning these surfaces (*e.g.* by running initial helium discharges to reduce the gas inventory on carbon surfaces).

The radial profiles of electron temperature are measured from the intensity and broadening of laser-light Thomson-scattered from the plasma electrons. The ion temperature is measured from the Doppler broadening of carbon lines produced by charge exchange collisions between incoming neutral beam atoms and fully stripped carbon in the plasma interior. An important tokamak parameter is the so-called safety factor $q$ which on any given magnetic surface is the number of times that a field line must circle the major axis to go once around the minor axis. At any radius, $q$ is therefore a measure of the ratio between the average toroidal and magnetic field components.

There are many different discharge types. Only data from the three giving the highest thermonuclear performance are presented here.

*High Temperature Discharges*

Fig. 2 shows the profiles for a discharge in which special measures were taken to keep the plasma density low and hence to get the highest temperatures. In this example, both ion and electron temperatures exceed 10 keV in the centre. The effective ion charge, $Z_{eff}$ is characteristically rather high reflecting a significant impurity content.

$$Z_{eff} = (\Sigma_i n_i Z_i^2)/n_e$$

where the sum is over all ion species and because of quasi-neutrality $Z_{eff} = 1$ for a pure deuterium plasma. In low density discharges of this type $T_i \cong 23$ keV (250 MK) and $T_e \cong 12$ keV (130 MK) have been achieved.

*Pellet Injected Discharges*

Fig. 3 shows the profiles for a case in which initially a very peaked density profile was established by the injection of frozen deuterium pellets before the application of additional heating. In this way, central electron densities up to $2 \times 10^{20}$ m$^{-3}$ have been established in some cases during the ohmic phase. In the example shown here only the central vestige of the peaked density profile remains after the intense heating. Nevertheless, very high central pressures and pressure gradients are developed. Because of the strong central fuelling by the pellets the discharge is relatively clean with $Z_{eff} = 2$.

*H-mode*

Fig. 4 shows the data for a so-called H (for high) mode [7] in which the combination of a magnetic separatrix and a threshold neutral beam power causes a transition in which the energy confinement time, $\tau_\varepsilon$ = (Plasma Energy)/(Power Input) is approximately doubled. These discharges are characterised by very flat density profiles and high electron temperatures near the plasma boundary. With such discharges, values of $\tau_\varepsilon$ up to 1.2 s have been reached. This good energy confinement is accompanied by good particle confinement with the result that frequently the density rises throughout the H-phase which is then terminated when the radiated power level approaches that of the input. So far prolonged coupling of RF power to H-modes has not proved possible, impurity generation near the launching antennae causes rapid H-mode termination.

**Impurities**

The main impurities are carbon and oxygen with densities 1–10% of that of the electrons. Nickel is also present with relative concentration of $10^{-5}$–$10^{-4}$, the upper end of the range corresponding to RF heating; the antennae have nickel Faraday screens facing the plasma. The impurity concentration as reflected in $Z_{eff}$ tends to decrease for all discharge types as the mean density of the plasma increases. Radiation from the impurities does not play any significant role in the energy balance in the plasma interior. The primary effect is to deplete the density of deuterium in the core. The ratio of deuteron ($n_D$) to electron densities is reduced by impurities with charge $Z_i$ to $n_D/n_e = (Z_i - Z_{eff})/(Z_i - 1)$. For $Z_i = 7$, intermediate between carbon and oxygen, and with $Z_{eff} = 2$–$6$, $n_D/n_e = 0.8$–$0.15$. This depletion is confirmed by measurements of the D-D neutron yield from the various discharge types.

### Confinement and Transport

The energy loss is one to two orders of magnitude higher than that predicted by "classical" theory in which thermal conduction is due to binary collisions in a stable plasma. This is not a surprise since the plasma is known to be linearly unstable to a variety of modes. However, there is as yet no satisfactory non-linear theory which enables the performance of a tokamak to be predicted *a priori*. Consequently empirical laws are produced based on regression analysis of data. In fact, the JET data on the global confinement time $\tau_\varepsilon$ is well-represented by the Goldston law derived in 1984 using data from machines smaller than JET and with currents more than an order of magnitude lower. This gives:

$$\tau_\varepsilon = 3.7 \times 10^{-2}\, I\, R^{1.75}\, a^{-0.37}\, K^{1/2}\, P^{-1/2}$$

where $I$ is the plasma current (MA), $R$ *and* $a$ the major and minor plasma radii (m), $K$ the elongation of the plasma cross-section and $P$ the power input (MW). This formula reflects the essential features that the confinement improves with current and physical size, degrades with power input and is largely independent of density. The improvement of confinement time, $\tau_\varepsilon$, with increasing power is shown in Fig. 5. The remarkable H-mode results on JET fit the same formula but with the constant increased by a factor 2, see Fig. 6.

By local analysis of profile data, the electron and ion thermal conductivities, $\chi_e$ and $\chi_i$ as well as the particle diffusion coefficient $D$ can be extracted. It is found that generally $\chi_e \cong \chi_i$, while $D \cong \chi_e/5$. The values of $\chi$ in the plasma core range from 1–4 m$^2$/s depending on discharge type. The plasma is rich in perversity, for example peaked density profiles reduce the transport coefficients in the core of limiter-bounded plasmas, but only to the same level as that seen in the flat density profile H-modes. In the absence of a full theoretical understanding, the best empirical approach is to gain some control of important variables such as the density and current profiles.

### $\alpha$-Particle Physics

The long term goal is to have a plasma sustained against losses by the power released in $\alpha$-particles from D-T fusion reactions. These are born with 3.5 MeV and should be contained in the plasma if the plasma current exceeds $\cong$ 3 MA, they should then slow down transferring energy to the bulk plasma electrons. It is now widely accepted that such power into the plasma can be expected to cause confinement degradation in the same way as power from the outside. However, there is the possibility that ad-

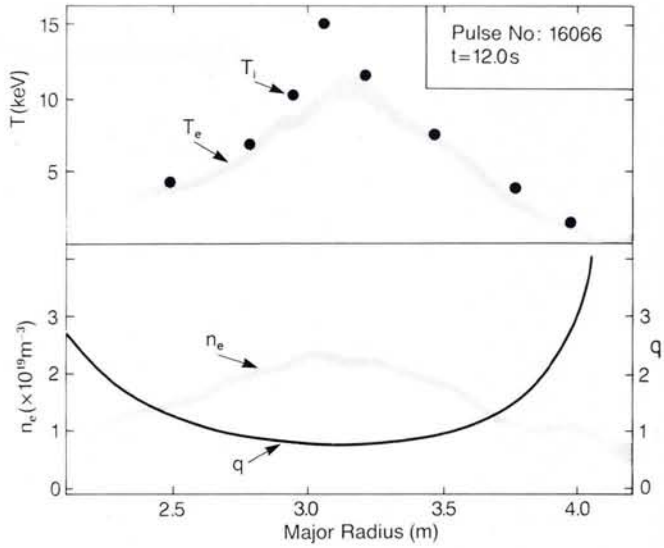


*Fig. 2 — Radial profiles of electron and ion temperatures, electron density and safety factor q in a 3 MA, low density discharge. $B$ = 3.1 T, $P_{RF}$ = 8 MW, $P_{NB}$ = 8 MW, $P_{TOTAL}$ = 16.5 MW, $Z_{eff}$ = 3.8, $\tau_\varepsilon$ = 0.4 s.*

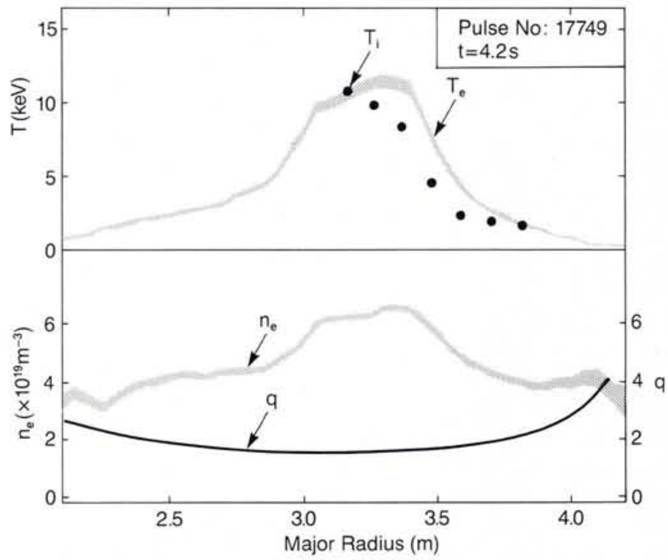


*Fig. 3 — Radial profiles of electron and ion temperatures, electron density and safety factor q in a 3 MA pellet injector discharge. $B$ = 3.1 T, $P_{RF}$ = 13 MW, $P_{NB}$ = 5 MW, $P_{TOTAL}$ = 19 MW, $Z_{eff}$ = 2.1, $\tau_\varepsilon$ = 0.26 s.*

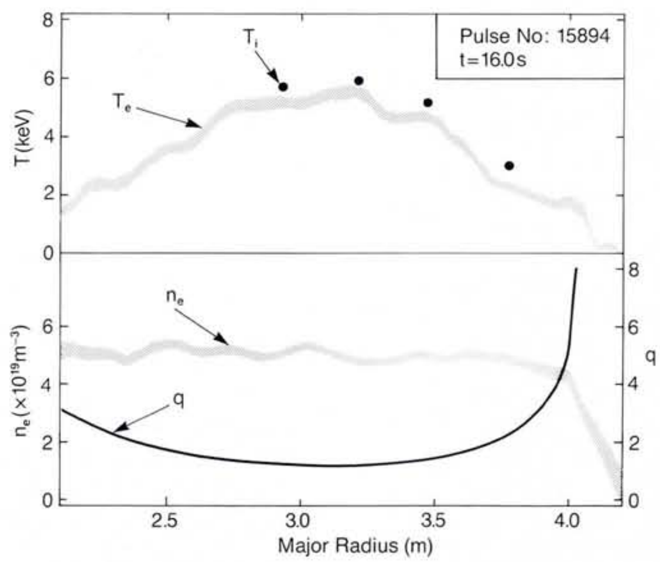


*Fig. 4 — Radial profiles of electron and ion temperatures, electron density and safety factor q in a 3 MA H-mode plasma. $B$ = 3.1 T, $P_{NB}$ = 7.5 MW, $P_{TOTAL}$ = 8 MW, $Z_{eff}$ = 3.3, $\tau_\varepsilon$ = 1.1 s, q(0) = 0.8.*

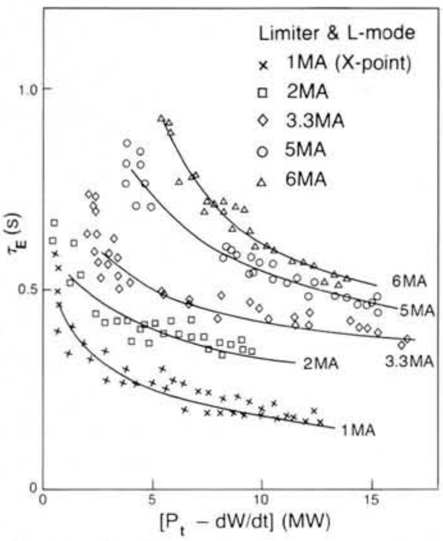


*Fig. 5 — Confinement time, $\tau_\varepsilon$, as a function of power for various plasma current values in the limiter configuraiton.*

ditional instability modes will be excited leading either to increased plasma or direct α-particle losses.

Some of these effects are in fact simulated in the minority ion ICRH heating experiments on JET. Table 2 lists the key parameters achieved in such experiments with $^3$He minority and compares them with those expected for α-particles in the eventual D-T operation of JET as well as in an ignited plasma of the type presently under consideration by the inter-bloc (USA, USSR, Japan, EEC) "ITER" team in Garching. It is evident from this table that many aspects of α-particle physics are reproduced in these experiments. The main difference is in the strong anisotropy of the minority ion distribution function compared with the isotropy expected for D-T α-particles.

In the experiments the generation of fast ions, transfer of energy to the electrons and the influence on plasma confinement all proceed as expected. Much work remains to be done on this subject but so far the evidence is that α-particle heating will not create any unexpected difficulties with the plasma physics.

**Fusion Product and Q**

In a D-T plasma with a mean ion temperature exceeding 7 keV, the ratio (*F*) of the α-particle power to the losses is,

$$F = 2 \times 10^{-22}\, \hat{n}_D\, \hat{T}_i\, \tau_\varepsilon$$

where $\hat{n}_D$(m$^{-3}$) is the central hydrogen isotrope density, assumed to be 50% D and 50% T, $\hat{T}_i$(keV) is the central ion temperature and $\tau_\varepsilon$(s) the global energy confinement time. The happy simplicity of this formula stems from the fact that the fusion cross-section velocity product $(\overline{\sigma V})$ varies with $T^2$ over this range. Thus, it is useful to present data in the plane $\hat{n}_D\, \hat{T}_i\, \tau_\varepsilon$ versus $\hat{T}_i$. This is shown in Fig. 7 for the JET data, where also are indicated the contours of constant $Q_{th}$, where

$$Q_{th} = P_{th}/(P_L - P_\alpha) = 5P_\alpha/P_{in}$$

where $P_\alpha$ is the α-particle power from thermonuclear reactions and $P_L$ the power lost from the plasma. $P_{th}$ is the total thermonuclear power output including neutrons and $P_{in}$ the power needed to sustain the plasma. The contours for $Q_{th}$ are calculated using density and temperature profiles typical of the experiments and the full form for the variations of $\overline{\sigma V}$ with temperature. $T_i = T_e$ is also assumed.

It is evident from the diagram that conditions corresponding to $Q_{th} \cong 0.1$ are achieved in all the three discharge types, namely high temperature, pellet fuelled and H-modes. The fast deuterons injected by the neutral beams give rise to a further "non-thermal" contribution to the fusion reaction rate. This is clearly seen in studies of the D-D neutron yield and will give rise to an approximate doubling of the fusion yield in D-T experiments.

Thus, we have achieved conditions in JET corresponding to a thermonuclear *Q* in D-T of ≅ 0.1 and a total *Q* of ≅ 0.2. Full exploitation of the present capabilities of the machine should lead to total *Q* values in the range 0.3 − 0.6 corresponding to a few megawatts of α-particle power.

**Improvements and Additions**

A number of technical improvements and additions to the apparatus are in hand which will widen the range of experiments and which should improve the performance further. These include:

(a) stiffening of the vacuum vessel to permit routine operation at the highest current level (*i.e.*, up to 7 MA);

(b) improved RF launching antennae with beryllium screens, facilitating coupling to H-modes;

(c) 10 MW, 3.7 GHz lower hybrid current drive system to control the current density profile;

(d) two specially designed limiters to pump particles at the boundary;

(e) single and subsequently multiple high speed pellet injectors (4-6 km/s) to permit central fuelling of higher temperature plasmas;

(f) replacement of carbon by beryllium as tile material for main power loaded components in the vacuum vessel;

(g) increase of neutral beam energy to 140 keV;

(h) installation of tritium and remote handling equipment for the eventual operation in D-T mixture.

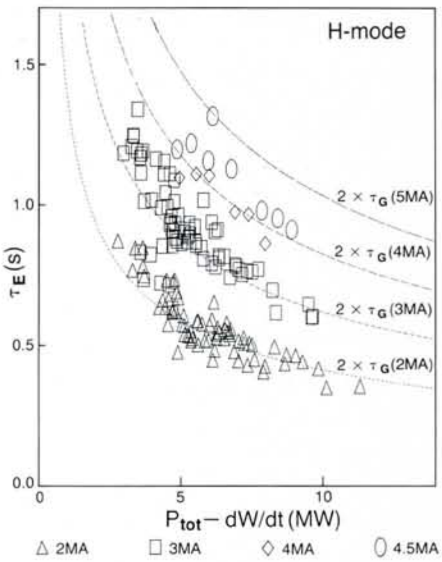


*Fig. 6 — Confinement time, $\tau_\varepsilon$, as a function of power for various currents in H-mode discharges. The curves show the calculated values for 2× Goldston formula, for the various plasma current values.*

**Summary and Conclusions**

(1) JET has operated with 7 MA in limiter mode and 5 MA with a single null magnetic separatrix;

(2) Central ion temperatures of 23 keV, central electron temperatures of 12 keV, central electron density of 2 × $10^{20}$m$^{-3}$ and energy confinement time of 1.2 s have been obtained in different discharges. Taken simultaneously they would give an ignited plasma, sustained by α-power in a D-T plasma;

(3) Plasma with an equivalent thermonuclear $Q$ ≅ 0.1 and total $Q$ ≅ 0.2 have been obtained;

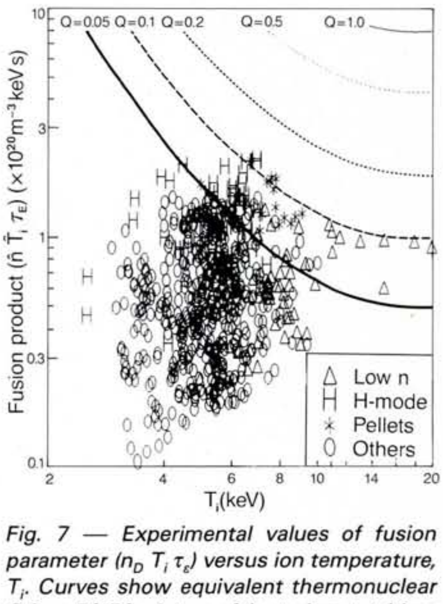


*Fig. 7 — Experimental values of fusion parameter ($n_D\ T_i\ \tau_\varepsilon$) versus ion temperature, $T_i$. Curves show equivalent thermonuclear Q for a 50:50 mixture of deuterium + tritium plasma.*

Table 2 — Key parameters achieved in α-particle simulation experiments

| Parameter | Heated $^3$He in JET Achieved Values | Expected α-particle parameters in D-T | |
|---|---|---|---|
| | | JET, $Q$ = 1 | Ignited ITER |
| $(n_\alpha/n_e)_0$ | $1\text{-}3 \times 10^{-2}$ | $10^{-3}$ | $7 \times 10^{-3}$ |
| $(\beta_\alpha)_0$ | 1% | 0.6% | 2% |
| $\bar{\varepsilon}_\alpha$(MeV) | 0.5-1.5 | 2 | 2 |
| $(p_\perp/p_\parallel)_0$ | 10-50 | 1 | 1 |
| $P_\alpha/P_{LOSS}$ | 0.8 | 0.1 | 1 |

In this table $n_\alpha$ is the density of α-particles, $\beta_\alpha$ the ratio of α-particle pressure to magnetic pressure, $\bar{\varepsilon}_\alpha$ the mean energy, $(p_\perp/p_\parallel)_0$ the ratio of α-particle pressures perpendicular and parallel to the magnetic field, $P_\alpha/P_{LOSS}$ is the ratio of the power transferred to the plasma from α-particles to the total loss from the system, $(\ )_0$ indicates central values in the plasma core.

(4) Some aspects of α-particle physics have been simulated by the RF heating of $^3$He minority ions. The behaviour is broadly as expected;

(5) Full exploitation of the machine in its present form should give total $Q$ values of 0.4 – 0.6 and corresponding α-power of a few MW;

(6) Technical changes and additions now in preparation will give greater control of the density and current profiles, reduce the impurity content and permit final operation in a deuterium-tritium plasma;

(7) Projected large experiments to study ignited, burning plasmas are under intense study both nationally and internationally around the world. JET is now and seems likely to continue to be a major source of experimental data and technical experience to underpin these projects.


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# 1989 Hewlett-Packard Europhysics Prize

The Hewlett-Packard Europhysics Prize for 1989 for outstanding achievements in solid state physics has been awarded jointly to:

Professor F. Steglich, Institut für Festkörperphysik, Technische Hochschule, Darmstadt

Dr. H.-R. Ott, Laboratorium für Festkörperphysik, ETH, Zurich

Dr. G.G. Lonzarich, Cavendish Laboratory, Cambridge

in recognition of their pioneering investigation of heavy-fermion metals. In 1975 the first indications of a new category of metallic compounds was given by the discovery that at low temperatures (< 0.3 K) the specific heat of Ce $Al_3$ was proportional to the temperature, with a coefficient of proportionality about a thousand times that of Na for example. It was as if the electrons were more massive than normal by about that factor. It was however the discovery in 1979 of superconductivity in Ce $Cu_2$ $Si_2$ — a discovery treated initially with great skepticism — that really broke open the new field of physics. Since then it has expanded rapidly and heavy fermions have become a major area of research.

The Hewlett-Packard Europhysics Prize is awarded annually by the European Physical Society for recent work in condensed matter physics particularly where there could be important applications in electronic, electrical or materials engineering. The award which includes a cash prize of Sw.Fr. 20000.– (in total) will be presented during the 9th General Conference of the EPS Condensed Matter Division to be held in Nice, 6-9 March 1989.

# Computational Physics Group

From 1 January 1989, following the elections held last year, the Board of the **Computational Physics Group** will comprise the members shown opposite.

The outgoing Chairman, R. Gruber of Lausanne, reports that most of the 437 members on the role at the time of the last Board meeting had expressed positive views on the work of the Group and looked forward to increased activity in the years to come. A highlight of the new programme will be the 2nd International Computational Physics Conference to be held in 1991 in Amsterdam immediately following the EPS 8th General Conference in September.

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