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The JET Team
Edited by D J Ward

JET Contributions to the ITER Physics Research and Development Programme (1997)

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JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA.

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TASK NO:	**1.1**
TASK TITLE:	**Disruption Database**
ORGANIZATION:	**JET**
CONTACT:	**M Johnson, A Tanga**

The effort to compile a database of JET disruptions has continued. Data from the whole of 1997 has been forwarded to ITER for inclusion in the ITER Disruption Database (IDDB). This includes data from the tritium operation carried out during 1997.

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TASK NO: **2.1, 2.2**

TASK TITLE: **Detached Plasmas**

ORGANIZATION: **JET**

CONTACT: **G. Vlases**

Explanatory Note: The operation of JET during 1997 was carried out using the Mk II AP divertor, in which the conductance of bypass leakage paths was substantially reduced. There was a brief period of operation at reduced vessel temperature to investigate the role of tile temperature in impurity sources. The increased tile temperature of normal operation had appeared to increase the impurity sources although not the plasma Zeff. Further information can be found in the JET progress report for 1997 and references contained therein.

2.1 Detached Plasma Data

2.1.1 In ohmic and L-mode plasmas, detachment occurs earlier in Mk IIA than in Mk I, due in part to closure, and in part to increased Carbon influx arising from higher temperature of the targets. In ELMy H-modes, there is little difference in detachment between Mk I and Mk IIA.

2.1.4 Detachment Mechanism. Recombination plays an important role and is needed in the modelling to describe I_{sat} reduction. Its presence has been confirmed experimentally using spectroscopic ($D\gamma/D\alpha$) measurements.

2.1.6 Helium Exhaust. Careful study of He enrichment, the ratio of helium concentration in the divertor gas to the helium concentration in the plasma core, has been carried out. Helium was puffed in to plasmas with different divertor configurations, and enrichment factors of up to one are found with the strike points in the corner of the divertor. Modelling suggests that this figure should be reduced by approximately a factor of two to account for the different pumping of helium and deuterium in the experiment.

2.2 Detachment Window. As with earlier divertor operation it was not possible to operate at high radiated power fraction or to reach densities in excess of the Greenwald limit whilst maintaining high confinement.

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TASK NO: **2.4, 2.5, 2.6**

TASK TITLE: **SOL Flows, Density Limit, Similarity Studies**

ORGANIZATION: **JET**

CONTACT: **G. Vlases, G. Matthews**

2.4 SOL Impurity Flows.

2.4.2 Pellet Injection. Injection of 3mm pellets at up to 5 Hz gave no measurable differences from gas puffing, except that each pellet triggered an ELM.

2.5 Density Limit

2.5.1 Scaling. The density limit was unchanged by reducing the conductance of the by-pass leak. The ohmic and L-mode density limits were noticeably increased when the target temperature was lowered, consistent with the reduced impurity influxes which were observed.

2.6 SOL Similarity Studies. Analysis of highly radiating plasmas in which collisionality and normalised gyro-radius were varied showed that confinement degraded as normalised gyro-radius reduced. This is in contrast to plasmas without strong radiation where this is not observed. The degradation is primarily in the edge plasma. These experiments suggest that the separate scaling of edge and core plasmas is necessary. A series of ‘CDH identity experiments’ was performed in which the plasma shape, q and core dimensionless parameters were made as close as possible to those in AUG. No evidence of density peaking or enhanced confinement was found and the radiated power fraction remained relatively low in comparison with the AUG CDH mode.

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TASK NO: **2.11, 2.12, 2.14,**

TASK TITLE: **Divertor Physics**

ORGANIZATION: **JET**

CONTACT: **G. Vlases, G. Matthews**

2.11 Wall Impurity Sources. Although it is not possible to un-ambiguously identify the dominant source of impurities as the inner wall or the divertor target, it was observed that doubling the carbon source from the divertor did not lead to an increase in core plasma impurity content. The carbon yield is consistent with either physical sputtering or chemical sputtering. When the operating temperature of JET was lowered, the impurity source from the main chamber fell by approximately 15% whilst the divertor source reduced by up to a factor of 3.

2.12 Tolerable ELMs

2.12.1 ELM Size. Analysis of the difference in ELM behaviour between ICRH heated and NBI heated plasmas continues. In general the edge pressure is higher and the energy loss in ELMs larger with NB heating. The confinement is similar, however, as a result of the more peaked power deposition with ICRH. Specific experiments to test the role of fast ions have been carried out and it was possible to increase the edge pedestal and the energy drop in ELMs by moving some of the ICRH power closer to the plasma edge. Changes in the applied torque and fuelling with NB did not affect the ELM behaviour.

2.12.2 Although ELMs always appear to burn through to the target, the impurity influx due to ELMs does not make a significant contribution to the Zeff of the plasma core.

2.14 Pellet Fuelling. A Limited amount of data was collected for 3 mm pellets injected with a velocity of up to 600 m/s at up to 5 Hz. The fuelling efficiency was very low, and most pellets induced ELMs. High-field-side pellet injection is being considered for the Mk IIGB phase.

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TASK NO: **2.18**

TASK TITLE: **Tritium Saturated Walls**

ORGANIZATION: **JET**

CONTACT: **P Andrew, P Coad, A Peacock**

In 1997, a significant portion of the Mk IIa divertor campaign was devoted to operation with tritium. Over 200 pulses had plasma tritium fractions > 40%. Control of the isotopic fraction was easily achieved by preceding the experiment with a few ohmic pulses to changeover the isotopic composition of the walls. With 100% tritium fuelling, plasma tritium fractions of > 90% were possible.

During this period, the tritium was supplied by the active gas handling system (AGHS) to both the torus, via a gas puffing module, and to one of the two neutral injection boxes (NIB's). The AGHS also recovered the exhaust gases from these systems and from the remaining NIB which received a small tritium exhaust from the torus. The total amount of tritium on site was 20g. Since the AGHS was able to reprocess exhaust gas, converting it back into pure tritium, it was possible to reuse the tritium many times. In total, 100g of tritium were delivered by the AGHS: 34.4g directly to the torus, and the remainder to the tritium NIB. Of the 65.6g delivered to the neutral beam system, 0.6g was then injected into the torus.

During the tritium campaign, it was possible to achieve nearly complete tritium recovery (>98%) from the tritium NIB. However, tritium was retained in the torus at a rate of about 30% of the torus input. When the tritium experiments were complete, the campaign continued with about 2 months of operation in deuterium and hydrogen, after which the torus inventory fell to 17% of the torus input (6g). This is over 3× larger than expected from the tritium retention results of the preliminary tritium experiment (1991). The plasma tritium fraction had fallen to ~ 0.1% in this time, so it was clear that this large inventory was not contributing significantly to the isotopic mixture.

The high level of tritium retention is related to D & T saturated carbon films located in the divertor. While co-deposited films have always been present in the JET vessel, the films in the Mk IIa divertor were unprecedentedly thick and hydrogen rich. The films were found in relatively cold regions of the divertor shadowed from direct contact with the plasma. Films forming on water cooled surfaces were found to flake off, probably on venting, leading to considerable debris in the bottom of the divertor. Even though the divertor hardware is similar on the inner and outer sides, the flakes were found exclusively on the inner side. The processes leading to the asymmetry and the high level of carbon erosion needed to form the films are not yet understood.

Post-mortem analysis is planned for the in-vessel tiles and flakes to identify the exact location of the tritium inventory still inside the vessel. This analysis will also determine the physical and chemical characteristics of the films.

A modelling exercise is being performed to try to find a mechanism for the formation of the films/flakes. Additional diagnostics are also being investigated to try to relate the films more directly to different types of plasma operation.

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TASK NO:	**2.20, 2.21**
TASK TITLE:	**Divertor Geometry**
ORGANIZATION:	**JET**
CONTACT:	**G. Vlases, L. Horton**

2.20 Divertor Geometry

2.20.1 Confinement with D_2 Puffing. As in the past, confinement degrades as the density is increased towards the Greenwald density limit. Vertical and horizontal target performance was similar.

2.20.2 Confinement with Impurity Seeding. Increasing the radiated power by adding impurity ions also leads to degraded confinement. At any given density (relative to the Greenwald limit) highly radiating seeded discharges have lower confinement quality than those without seeding.

2.21 Divertor Geometry and Divertor Function

2.21.1 Target Inclination. Detachment appears to begin earlier on the vertical targets. Otherwise, performance of vertical and horizontal targets, both with respect to confinement and Z_{eff}, are very similar. There is some indication that the L to H mode power threshold is higher on the vertical targets although the database is sparse.

2.21.5 Impurities and Geometry. The observation remains that divertor geometry does not have a large impact on core Zeff. The role of the impurities from the wall is being investigated, particularly using data from the reduced temperature operation.

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TASK NO: **3.2**

TASK TITLE: **ITER Demonstration Plasmas**

ORGANIZATION: **JET**

CONTACT: **T Jones**

The simulation of burning plasmas using Real Time Power Control has been further studied and more preliminary experiments have been carried out. The principle is to use auxiliary heating to simulate plasma heating by alpha particles. It is necessary to derive, using plasma measurements in real time, the appropriate simulated alpha power and to control the chosen heating system (NBH or ICRF) to follow the corresponding power demand. The technical feasibility of the scheme has been demonstrated using ICRH, where the simulated alpha power was derived, in separate experiments, both from electron temperature and DD neutron rate. In these experiments the scaling factor for the simulated alpha power was chosen, together with a density ramp rate, in a way which qualitatively corresponds to the operating trajectory foreseen for a reactor plasma. An important issue concerns the H-mode transition; further detailed scenarios have been worked out which maintain the same relation between plasma loss power and H-mode threshold as that expected in a reference ITER case (from empirical H-mode power threshold scaling laws) during the density ramp, although these have not been implemented yet.

A different application of the same concept was used in preparing for the JET DT alpha heating experiments. One of the requirements of the experiment was to distinguish between electron heating (due to alpha particles) and an increase in electron temperature due to an improvement in confinement with average ionic mass when comparing a DD reference and a DT discharge. Preparatory experiments in DD discharges simulated (with ICRH) the expected alpha particle heating during the discharge evolution; this gave an indication of the change of electron temperature from an equivalent amount of alpha particle heating in the absence of any isotopic effect. These results were a useful supplement to the main DT alpha heating experiment [P R Thomas et al, to be published in Phys Rev Lett] providing additional support to the conclusion that there is no significant isotope dependence at work.

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TASK NO: **4.1, 4.2, 4.3**

TASK TITLE: **Global Database and Scaling, ITER Demonstration Plasmas**

ORGANIZATION: **JET**

CONTACT: **J.G. Cordey, K. Thomsen.**

H-mode power threshold and confinement scaling discharges have been completed at JET with Deuterium, Tritium, mixed D-T, and Hydrogen plasmas. Plasma currents from 1MA to 3.8MA were investigated at toroidal fields to give the ITER q, while within the capability of the JET heating system β was matched across a wide range of the dimensionless Larmor radius scale length ρ^*. The variation in the isotopic mix of the plasmas was achieved by a combination of wall loading, gas fuelling, and the use of deuterium, tritium and hydrogen Neutral Beam Injection (NBI). The effective mass A (atomic units) of the plasma determined from edge recycling measurements ranges from 1 to ~3 in this isotope scaling study.

The isotope dependence of the confinement in ELM-free H-modes was found to be weakly negative $\tau_\varepsilon \propto A^{-0.2\pm0.35}$. This result is in line with the expected isotope dependence of gyro-Bohm transport which is $\tau_\varepsilon \sim A^{-0.2}$ when expressed in terms of the engineering parameters. It is, however, in contradiction with the existing ELM-free scaling expression ITERH93-P in which τ_ε scales as $A^{0.4}$. The ELMy H-mode data on the other hand is reasonably well fitted by the recently derived ELMy scaling expression EPS97-P(y) which has $\tau_\varepsilon \propto A^{0.2}$. However, it is found that $\tau_\varepsilon \propto A^{0.0\pm0.1}$ gives a better fit to the present data. The weak positive mass dependence (or lack of) in ELMy H-modes may be the result of a gyro-Bohm plasma core combined with a plasma edge pedestal which scales strongly with mass ($\propto$ A).

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TASK NO: **4.7**

TASK TITLE: **Particle Transport Modelling**

ORGANIZATION: **JET**

CONTACT: **A Taroni**

The problem of helium exhaust has been studied using the integrated code package COCONUT [1].

In this package the 2D scrape-off layer code EDGE2D/NIMBUS is coupled with the $1^1/_2$ D plasma transport codes JETTO (for energy and main plasma ion transport inside the separatrix) and SANCO (for impurity transport inside the separatrix).

The code was first benchmarked against JET experiments in order to determine the radial helium transport in the core and in the SOL. The simulations in this case were able to reproduce the experimental findings concerning the time evolution of the Helium density profiles and the helium enrichment in the divertor region. The findings were then applied in predictive modelling for ITER, expressing the results in terms of particle confinement times and enrichment.

The predictions for ITER have been found to be very sensitive to the transport model assumptions.

Two scenarios, one based on work by Kukushkin et al. [2] and the other based on the transport coefficients that fit JET results, gave rather different results, with the enrichment factor varying from a very optimistic value of 0.9 to 0.07 (insufficient for ITER present design). Thus even if we are in the position to perform consistent simulations that reproduce experimental findings in JET the current uncertainty of particle transport models must be reduced for a conclusive answer to the problem of helium exhaust in ITER.

[1] M. Fichtmueller et al., 13th PSI conference, San Diego, Ca., May 1998.
[2] A. Kukushkin et al., Contrib. Plasma Phys., 38, 20 (1998)

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TASK NO: **5.2**

TASK TITLE: **Effect of Alphas on Sawteeth**

ORGANIZATION: **JET**

CONTACT: **M F F Nave**

The sawtooth instability is likely to play an important role in determining the performance of ITER. A recent series of JET experiments using deuterium and tritium, has made it possible to study sawtooth stability in plasmas approaching thermonuclear conditions. In a sequence of discharges designed to study α-heating, an interesting new phenomenon was observed: the sawtooth period increases with tritium concentration. Internal kink stability for both high performance and α-heating experiment plasmas has been studied (in collaboration with K. McClemments from Culham Laboratory, U.K., and J.Manickan from PPPL, U.S.A).

Internal kink stability was studied for record fusion plasma 42976 at the time of maximum fusion power (P_{fus}=16MW). In this discharge there were 3 types of fast ions: due to NBI and ICRH heating as well as α-particles, all with similar pressure values. Calculations show that α-particles make a significant stabilising contribution to the potential energy of the m=1 internal kink instability.

In a sequence of beam-heated discharges, intended to study α-particle heating, the sawtooth period increases with tritium concentration. It has also been found that τ_{saw} strongly correlates with the perpendicular energy density of the fast ions, which in these plasmas is mostly due to beam ions. The latter implies a strongly positive correlation between the kinetic energetic ion component of the m=1 internal kink energy and the sawtooth period. Calculations indicate that the sawtooth period increases with tritium concentration through an increase in the slowing down time of the beam ions which in these plasmas is proportional to the mean ion mass.

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TASK NO: **5.3**

TASK TITLE: **Studies of TAE Modes in JET**

ORGANIZATION: **JET**

CONTACT: **S.Sharapov, D.Borba, C.Gormezano, D.Start,**
A.Fasoli (MIT, CRPP), J.Lister (CRPP)

The experimental effort within the JET/CRPP/MIT collaboration on the physics of Alfvén Eigenmodes (AE) was mainly focused on two specific problems associated with the deuterium-tritium (DT) phase of JET operation in 1997. First, a resonant interaction between the fusion-born alpha particles and AE, as well as between energetic ions generated by additional heating and AE, were of major importance and the passive measurements of intrinsically unstable AE were extensively investigated in all DT discharges on JET. Second, the active AE-excitation via external antennas has been performed in JET plasmas at different concentrations of deuterium, tritium and hydrogen in order to establish isotope dependencies of the AE frequency and damping rates.

The passive measurements of the electromagnetic perturbations in the AE frequency range, up to 500 kHz, were based on the new external magnetic pick-up coils diagnostics. Magnetic fluctuation spectra, recorded over 4 sec with a sampling rate of 1 MHz by magnetic pick-up coils, indicate the presence of Toroidal AE (TAE), Elliptical AE (EAE) and Triangular AE (NAE), driven by the ICRF-heated energetic ions in a variety of JET plasma conditions. Experiments with high-power (>10 MW) tritium NBI into tritium JET plasmas at low magnetic field, B_0 = 1.0 T, have also shown excitation of TAE, EAE and NAE by the NBI-produced ions with velocities approaching the Alfvén velocity, $V_{\|beam} / V_A \approx 0.7\text{-}0.85$. At higher magnetic field, e.g. in the high performance H-mode plasmas with NBI, an activity of high-n (n > 10) unstable modes is observed over a large frequency range below the TAE frequency. Possible interpretation of these electromagnetic modes as Beta-induced Temperature-Gradient driven eigenmodes (BTG) [1] is in progress.

In the best performance hot-ion H-mode DT experiments on JET with fusion powers up to 16.1 MW and central $\beta_\alpha(0) \approx 0.7$ %, no observable AE activity was found on the external magnetic measurements. The enhanced AE stability in best DT discharges was explained by the large value of plasma pressure in DT plasmas, which significantly affect the radial structure of AE. In shear-optimised DT discharges unstable AE are observed when ICRF heating ≥ 1 MW is applied. The quantitative identification of the alpha-particle contribution to the observed AE instability is however prevented due to the uncertainty in the estimate of competing effect from energetic ions generated by high power ICRF heating.

Measurements of eigenfrequencies and damping rates of low-*n* AE were performed by the external antennae in the 30 kHz to 500 kHz range in the limiter phases of most discharges at different isotope concentrations. For a higher time resolution the antenna system was modified to lock the drive frequency to that of a single AE mode and to track this mode in real time. Similar damping rates and absorption mechanisms were observed for low-*n* AE in different isotope plasmas with similar configurations. The eigenfrequencies of the excited/measured AE were found to vary at varying DT ratios in accordance with the Alfven scaling, $f_{AE}^{DT} \propto \left(1+1.5n_T / n_D\right)^{-1/2}$. Taking into account the increased time resolution of the AE excitation/measurements, this technique can be used for the diagnostic of the D:T ratio in the plasma centre.

[1] S.Sharapov et al., Interpretation of Electromagnetic Modes in the Sub TAE Frequency Range in JET, in progress (1998).

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TASK NO: **6.1, 6.2, 6.3**

TASK TITLE: **H-mode Power Threshold, Edge Parameters at L-H Transition**

ORGANIZATION: **JET**

CONTACT: **E. Righi, C. Lowry, J.G. Cordey.**

During 1997 a series of dedicated experiments were carried out on JET in tritium, deuterium and hydrogen plasmas to determine the dependence of the H-mode power threshold on the plasma isotopic mass. The scaling has now been confirmed over the whole isotopic range. This result makes it possible for a fusion reactor with 50:50 DT mixture to access the H-mode regime with above 20% less power than that needed in DD. Results on the first systematic measurements of the power necessary for the transition of the plasma to the Type I ELM regime are also in agreement with the scaling. For a subset of discharges measurements of T_e and T_i at the top of the profile pedestal have been obtained, indicating a weak influence of the isotopic mass on the critical edge temperature thought to be necessary for the H-mode transition. This result is consistent with the isotopic scaling of the power threshold and of the thermal energy confinement time for L-mode plasmas.

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TASK NO: **6.5**

TASK TITLE: **Error Field Locked Mode and Plasma Rotation**

ORGANIZATION: **JET**

CONTACT: **B Tubbing**

A highly successful campaign of error field studies was carried out in January 1998. The objectives were to improve the quality of the prediction of the critical error field levels in ITER, and to study the effects of plasma rotation induced by NBI.

The experiments have produced a large amount of novel information on the scaling and behaviour of error field induced locked modes. The new data significantly expands the parameter base (I, B, P) for scalings - up to 3.5MA, 3.5T in JET.

The scaling with toroidal field - at constant q - of the critical error field for mode penetration B_{pen} in ohmic plasmas was found to be weaker than that previously found in COMPASS-D. This has resulted in a more favourable projection for ITER, of about B_{21}/B_{tor} = 1.e-4.

The linear density scaling of B_{pen} was confirmed.

Active compensation of the machine intrinsic error field was observed to allow the unlocking and spinning up of error field generated m = 2, n = 1 islands.

The active compensation was also found to substantially reduce the probability of disruptions in these discharges.

Experiments with additional heating (NBI and ICRH) have shown the expected strong dependence of B_{pen} on plasma rotation, and the much weaker dependence on plasma pressure.

A detailed analysis of the results will be discussed in R. Buttery et. al., IAEA 1998.