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** See Annex*

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HIGHLIGHTS OF RECENT JET OPERATION

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1. *Introduction*

The JET experimental programme in 1991 has again embraced a wide variety of experiments and has included the testing of plasma–facing components, the development of new operational scenarios, studies of divertor and edge processes, the investigation of global and local current–drive techniques, the pursuit of high fusion yield, as well as the exploitation of new enhancements of the JET subsystems. A broad range of tokamak physics studies addressing such areas as mhd stability, impurity generation and control and confinement and transport issues has continued in parallel.

2. *Enhancements to the JET Tokamak*

The most significant enhancement to JET in the last 12 months was the installation of quasi–continuous targets in the upper and lower X–point regions. The targets consisted of a series of 32 massive inconel plates on which small (~10×10cm) machined tiles, which make up the power–handling surfaces, were fixed to approximate a toroidal surface. Carbon fibre composite (CFC) tiles were utilized on the upper X–point target and beryllium tiles on the lower. The belt limiter configuration was also modified in that the lower beryllium belt was replaced by graphite (the upper beryllium belt was retained) to permit the completion of the comparison of limiter materials which began in 1989.

Several other new facilities have been utilized extensively during the recent campaign. These include: improvements in the poloidal field circuit to permit X–point operation at higher current and to allow JET to be operated as an AC tokamak; upgrading of the energy of the second neutral injector box (NIB) to 140keV; use of the ICRF heating system as a phased array for fast wave current drive studies; an extended gas introduction system for radiative divertor studies; and an improved Plasma Fault Protection System which has allowed, in particular, softer termination of the plasma on indication of an approaching disruption. In addition, new diagnostics, such as a range of 14MeV neutron diagnostics, which played a key role in the preliminary tritium experiment (PTE), an edge charge exchange spectroscopy system for poloidal rotation and ion temperature measurements, a motional Stark effect diagnostic for q–profile measurements, and an active neutral particle analyzer have yielded new insights into plasma behaviour.

3. *Plasma–Wall Interactions and Divertor Studies*

Control of the heat and particle flux to the the first wall and of the resultant impurity influxes to the plasma is perhaps the most important problem currently facing the development of fusion as a viable energy source. The new phase of the JET experiment, based on the installation of a Pumped Divertor, is designed to address this problem and to develop techniques for its satisfactory resolution. A programme of research has, therefore, been undertaken to investigate the performance of the present divertor configuration in JET to address the problems of impurity control and to obtain baseline data for comparison with the predictions of simulation code calculations.

Investigation of the performance of diverted plasmas utilizing the newly installed toroidal X–point targets was a central activity. The choice of beryllium tiles for the lower target and CFC tiles for the upper permitted a careful study of the relative merits of the two materials in this role. In addition, in the course of these experiments, two designs of CFC tile were examined and this allowed the limitations arising from heating of tile edges to be studied. The principal aims of the target assessment were: to establish the power handling capabilities of different target materials and of different target designs; to investigate the causes of limitations in the power handling capabilities; and to study the influence of different target materials on bulk plasma performance.

The targets performed broadly as expected, though the power handling capability of the first design of CFC tiles, which was limited by power flux on tile edges, proved to be better than calculations had predicted. The improved design of target tile, which shielded the tile edges by appropriate machining, yielded approximately a factor 2 improvement in power handling capability. Comparisons of H–mode performance using CFC and Be targets showed that the two materials gave similar results at moderate to high densities, but that the CFC targets permitted considerably better fusion yield to be achieved in the relatively low density hot–ion H–modes used in the PTE. Significantly, it was found that reliable H–modes could be achieved using the Be targets even after extensive (deliberate) surface melting. While the performance in all H–mode plasmas was limited ultimately by impurity influxes, since neither target was actively cooled, a significant improvement in power handling capability was observed at high density. As a result, extensive gas puffing was used successfully to reduce power loading on the targets and thereby delay impurity influxes.

From theoretical modelling of divertor behaviour, it is expected that divertor impurity retention should increase rapidly above a certain 'threshold' density which depends on the power flow into the scrape–off layer. This dependence arises from the strong variation of impurity retention with divertor ion temperature ($T_{i,div}^{-3.5}$). A series of experiments was, therefore, carried out on both C and Be X–point targets to investigate how impurity retention varied with divertor density at fixed power, the divertor density being controlled by preprogrammed gas puffing into either the torus midplane or the X–point region. Measurements were obtained at high and low power levels.

Experiments using the Be target showed that Be influxes increased with increasing gas puff rates (corresponding to increasing target density), an effect which counteracts the improved impurity retention observed at higher divertor densities. This behaviour is not unexpected as the sputtering yield for Be is insensitive to temperature for $T_e > 10eV$ (which, therefore, necessitates the attainment of rather high densities to depress the ion temperature sufficiently to obtain high impurity retention). Similar measurements obtained on the C target are the subject of current analysis. In addition, detailed observations of divertor and scrape-off layer parameters are being used to validate numerical simulations of Pumped Divertor operation.

4. Tokamak Physics Studies

4.1 Energy Transport and Confinement. Several specific experiments have been performed to elucidate the confinement properties of various plasma regimes. A series of standard discharges has been used during the experimental period to accumulate data on the influence of isotopic mass, A, and charge, Z, on confinement. Experiments using H, D and ^{3}He NBI in L-mode plasmas have shown that the global energy confinement of D and ^{3}He plasmas is essentially the same, but that of H plasmas is slightly (~20%) lower. The JET data does not, therefore, support the $A^{0.5}$ dependence observed in smaller tokamaks.

To investigate the effects of poloidal field and magnetic shear on energy confinement, an experiment was performed in which the plasma current was ramped while other parameters, including input power were held constant. These studies suggest that the product of current and inductance, rather than simply current, determines the scaling of global energy confinement. Local transport analysis indicates that the origin of the current scaling lies mainly in a dependence of the local thermal diffusivity, χ, on the poloidal field. Moreover, the data is well reproduced by the Rebut-Lallia-Watkins form for the thermal diffusivity. Studies of plasma behaviour at high toroidal beta, β_t, also allowed the scaling of confinement with toroidal field to be investigated, but in this case for H-mode plasmas. A variation of the kinetic energy confinement time, $\tau_{kin} \propto B_T^{0.25}$, was obtained, although this behaviour might equally well have been explained by a dependence on safety factor.

Investigation of the PEP H-mode constituted a further major area of study. In this regime, local transport, mhd stability and the evolution of the current profile appear to be inextricably linked, and the range of behaviour observed makes generalization difficult. Nevertheless, significant advances in understanding were made. In particular, unambiguous evidence of reversal of the shear in the plasma centre during the enhanced confinement phase was obtained from polarimetric measurements of the q-profile, supporting earlier deductions from observations of localized mhd modes. It is thought that this reversal of shear is fundamental to the enhanced central confinement observed in the PEP H–mode, but there is no complete understanding of the phenomenon. In the course of these experiments, exploitation of two–minority ICRF heating scenarios (H, ^{3}He) produced ion and electron temperatures simultaneously in the region of 15keV.

A variety of studies of local transport properties were performed in the course of the campaign. Perturbative measurements of suprathermal electron diffusion showed that the suprathermal electrons accelerated by LHCD exhibited a radial diffusivity which was a factor of 3–5 greater than the electron thermal diffusivity (approximately equivalent to the ratio of thermal velocities involved) which lends support to the proposal that micromagnetic fluctuations are the source of anomalous electron thermal transport. Analysis of impurity transport using laser ablation of impurities has continued. The most remarkable result of these experiments is the existence of a region of reduced anomalous diffusivity in the central plasma. This region appears to be largely independent of whether q(0) is above or below unity, whether the plasma is ohmically or additionally heated and whether the central gradients of the plasma profiles are positive or negative.

4.2 H–Mode Studies. Exploitation and investigation of plasma behaviour in the H–mode is a major component of the JET experimental programme and several aspects of H–mode behaviour have been addressed for the first time in JET. NBI counter–injection experiments established that the power threshold for the H–mode was perhaps 10–20% lower than for co–injection. Injection of high–Z impurities (Ni) by laser ablation showed some evidence of central impurity accumulation, as is observed in smaller devices, but this did not pose a significant problem as low–Z impurities (C, Be), which are dominant in JET, did not exhibit this behaviour. Overall, therefore, transport of intrinsic impurities and the resultant radiation losses were similar to co–injection H–modes and the time evolution and duration of ELM–free H–modes were similar in the two cases. The most significant difference in behaviour was, in fact, observed in central mhd behaviour. With counter injection, frequent, small–amplitude sawteeth were observed which maintained flattened central plasma profiles. As a result, the energy confinement of counter–injection H–modes was somewhat reduced relative to that obtained with co–injection, with only the best counter–injection cases exhibiting energy confinement times equal to twice those predicted by Goldston L–mode scaling.

Considerable efforts have been made to understand ELM behaviour and to investigate techniques for reliable ELM production so as to permit steady–state H–modes to be established. Some evidence has been obtained of precursor activity to ELM's in both edge magnetic and density reflectometer signals. This activity consists of fluctuations with frequencies in the range 60–100kHz, implying that the mode numbers involved are rather high. Steady–state H–modes in which plasma parameters are held constant by ELM activity have been produced at 2MA/2.3T, with a maximum duration of 18s being achieved. At 2MA the limit to the duration of the H–mode was set by technical, rather than plasma–related, limitations. This regime was established by combining strong gas puffing ($\sim$50mbls^{-1}) using NBI and off–axis ICRH. Energy confinement of these H–modes is high, typically corresponding to twice the Goldston L–mode prediction.

Recent theories of the H–mode postulate that the L–to–H transition is due to shear in the edge poloidal velocity driven by a radial electric field gradient. A new active charge exchange diagnostic for the measurement of edge ion temperatures and poloidal rotation has permitted this question to be investigated in JET for the first time. Initial measurements have shown that the poloidal rotation velocity in the plasma edge does increase gradually during the period of the H–mode transition, reaching values $\sim 2\times10^4$ms^{-1}. However, there is no rapid jump at the transition as has been reported from other tokamaks.

4.3 MHD Stability. Experiments in JET have improved our understanding of the conditions under which disruptions occur and of plasma behaviour in the pre–disruptive phase. Recently, greater emphasis has been given to the development of techniques for avoidance of disruptions, or for the minimization of their consequences. A substantial advance has been made in this respect through improvements to the Plasma Fault Protection System (PFPS). Early detection of the the 'locked' (i.e. non–rotating) m=2, n=1 mode which is invariably a precursor to major disruptions has enabled measures to be taken (reduction of plasma current, plasma elongation and of heating power) to minimize the impact of the resultant disruption on the torus.

This has been of particular value in overcoming the problems resulting from vertical instabilities which follow major disruptions. Analysis has shown that these arise from loss of vertical stability in elongated plasmas at the energy quench and that their consequences are aggravated by the slow post–disruptive current decay observed since the introduction of beryllium into JET. Such instabilities lead to substantial forces on the vacuum vessel (several hundred tonnes) and have resulted in damage to internal components. By using detection of the occurrence of a 'locked' n=1 mode to trigger a rapid (few hundred milliseconds) reduction of the PFX amplifier current (the dominant source of the destabilizing force) to zero, it has been possible to postpone the loss of vertical stability until much later in the current decay with a consequent reduction in forces by an order of magnitude.

Although several aspects of major disruptions remain problematic, in the main, the causes of disruptions on JET have been well documented and are largely understood. One exception has been the disruption caused by the growth of a large amplitude n=1 'locked' mode as the internal separatrix (X–point) is formed. This mode becomes more persistent at low–q and appears to have a low–density threshold. More detailed experiments have now confirmed these observations and have identified the most likely cause of the growth of the mode as external error fields arising from details of the construction of the poloidal field coils. The principal source of these error fields appears to be the vertical field coils and it has been shown that the threshold density depends on the coil configuration, the helicity of the internal magnetic field (the pessimal arrangement occurs when the helicity of the tokamak magnetic field matches that of the calculated error field) and the edge safety factor. The occurrence of the mode does not, as had previously been thought, depend on the existence of an X–point, nor even of a plasma more elongated than the natural elongation in JET ($\kappa \sim 1.4$). In the worst cases, it is not possible to establish plasmas with $q_\psi < 3$ since the low density limit due to these 'error field' modes overlaps with the high density limit.

Studies of the sawtooth have continued, both to try to elucidate the nature of the instability and to investigate means of sawtooth stabilization. Q–profile measurements in circular plasmas have been performed to minimize the systematic errors which increase the uncertainty of such polarimetric measurements in elongated plasmas. The results have confirmed earlier conclusions that q(0) remains below unity in sawtoothing discharges and that it decreases well below unity during 'monster' sawteeth. These experiments will also permit a comparison with measurements made by a new technique, the Motional Stark Effect (MSE), which makes use of spectral splitting of line emission from injected neutral beam atoms which arises from the Lorentz electric field which the atomic electrons of the injected neutrals experience as they cross the magnetic field.

Evidence of the importance of local modifications of the current profile has been obtained from the first demonstration of fast wave current drive using the ICRF system antennas as a phased array. This technique yields little net current drive, but substantial anti–parallel currents on either side of the ICRF resonance are predicted. By varying the phase of the antenna array so as to reverse the relative directions of the predicted anti–parallel currents and by locating the resonance on the inboard and outboard q=1 radii in turn, it was possible to show that, when a flattening of the current profile about q=1 was predicted, sawteeth could be stabilized for periods of up to 2s. When an increase in the gradient of the current profile at q=1 was predicted, rapid small amplitude sawteeth were observed, indicating a destabilization of the sawtooth instability. Similar experiments were performed with the ICRF resonance located at the q=2 surface in an attempt to stabilize m=2 activity. Some evidence of stabilization of m=2 modes was observed, but further analysis is required to determine unambiguously whether the effect is due to local heating or local current drive.

5. Plasma Performance

5.1 High Performance Discharges. The performance of JET plasmas was extended in several ways. Uprating of the capability of the shaping amplifier from 40 to 50kA permitted improved X–point configurations to be established at 3 and 4MA and 5MA double null X–point plasmas to be established for the first time. Extensive experiments were performed at plasma currents in the range 3–4.5MA, in sawtoothing and sawtooth–free discharges, over a wide range of plasma densities and at combined heating powers of up to 25MW. In many cases, the performance of these discharges was limited by impurity influxes, though this could be influenced by varying the X–point to target distance, by judicious use of gas–puffing and by exploiting both X–point targets. The highest stored energy obtained to date, 12.7MJ, was obtained in a 4MA sawtooth–free plasma with 21MW of heating power. One of the most significant results was that, at high densities, fusion yield was independent of the type of heating used (NBI or ICRF). Furthermore, no significant difference in performance between sawtoothing and sawtooth–free discharges was observed, indicating that sawteeth do not play a major role in the confinement properties of these plasmas.

Considerable efforts were made to increase the fusion yield of plasmas in preparation for the PTE. Both single null (SNX) and double null (DNX) plasmas were investigated using NBI and, for the first time, combined NBI and ICRF heating. Studies focussed on hot–ion H–mode plasmas in the range 3–4MA as experience had shown that, in the present JET configuration, these plasmas produced the highest neutron yield and offered the best prospects for further development to higher performance.

Progress was made in several directions. In the DNX configuration, ICRF power in the range 3–5MW was successfully coupled into hot ion H–modes produced by NBI power in the range 12–16MW. The increased electron temperature resulting from ICRF heating led to a higher neutron yield for a given NBI power, although no increase in total fusion yield was obtained. In the SNX configuration, the majority of experiments utilized the configuration in which the ∇B ion drift was away from the X–point, as previous experiments had shown that the more optimal power distribution between the inner and outer X–point strike zones yielded a longer delay until the impurity influx which terminates the high performance phase in this regime. Optimization of 3MA/2.8T discharges in this configuration yielded the highest neutron yield obtained to date, $4.3\times10^{16}s^{-1}$, which corresponded to an $n_d(0)\tau_E T_i(0) = 9.2\times10^{20}$keVsm^{-3} and a projected $Q_{DT} = 1.1$.

5.2 High–β_t Experiments. Previous experiments in JET at high values of β_t have been rather limited, although values of $\beta_t \sim 5\%$ had been obtained. A more systematic investigation of the β–limit has been performed in which the performance of sawtoothing and sawtooth–free discharges has been compared to elucidate the role played by the q=1 surface and its associated instabilities in determining the limiting β_t. In addition, hot ion H–modes have been established in sawtoothing and sawtooth–free plasmas to investigate the influence of β–limiting processes on the performance of this regime.

The highest β_t values were obtained in 1.5–2MA DNX plasmas in which typical Troyon factors, $\beta_t/(I_p/aB_t)$, in the range 2.2–2.6 were obtained with a highest β_t value of 5.4%, corresponding to a Troyon factor of 3.1. As in earlier experiments, no evidence of a disruptive limit was observed, but several discharges exhibited β–limiting behaviour. In general, β_t was limited by ELM activity, often accompanied by large amplitude mhd modes with n=1, 2, 3. In a few cases, evidence of limiting behaviour was observed before ELM activity began. Further analysis is required to understand the cause of this behaviour.

6. Next Step Physics

6.1 Current Drive Experiments. The design of Next Step devices in predicated upon the exploitation of a variety of current drive schemes. Two principal techniques for bulk current drive have been explored: lower hybrid current drive (LHCD) and bootstrap current. While the LHCD system has been employed in a variety of experiments, including the 1 minute limiter pulse and the 7MA programme (see later), the emphasis in recent experiments has been the optimization of synergistic effects between ICRF and LHCD to optimize current drive efficiency and the demonstration of 100% current drive at the highest possible current.

Studies have shown that synergistic effects are optimized in plasmas with low electron density and peaked density and temperature profiles, which result in a large fast electron population in the inner half of the plasma. Under these conditions, overall current drive efficiencies (corrected downwards for direct current drive by TTMP damping of the ICRF waves) of up to $0.4\times10^{20}\mathrm{Am^{-2}W^{-1}}$ have been achieved and 100% current drive has been attained at plasma currents of up to 1.5MA. The enhanced current drive efficiency is thought to be due to TTMP damping of the fast waves on the fast electrons, resulting in their acceleration to energies of several hundred keV. This is supported by observations of bremsstrahlung spectra with characteristic energies above 100keV in LHCD experiments with ICRF heating, whereas the characteristic energy in full current drive plasmas without ICRF is ~40keV.

In many JET H–modes, bootstrap current fractions of 25% are typical. Previously no attempt had been made to optimize this figure nor to address the issue of whether significant bootstrap current can be obtained in ICRF heated plasmas with no central particle source. In low current (1–1.5MA) ICRF heated H–mode plasmas with $\beta_p \sim 2$, bootstrap current fractions of up to 70% were achieved and sawteeth were stabilized, presumably as a result of current profile broadening. In addition, these plasmas exhibited high thermal energy confinement, significantly (up to a factor of 1.7) above that predicted by the JET–DIIID scaling.

6.2 AC Tokamak Operation. Operation of the tokamak as an AC device offers an alternative route to quasi–continuous operation without the overheads entailed in external current drive systems. The feasibility of such a scheme has previously been demonstrated on very small tokamaks at plasma currents of up to 4kA. Recent changes in the poloidal field circuit at JET have permitted this question to be investigated at significantly higher current, up to 2MA, and a systematic study of the parameters which determine the reliability of the second breakdown has been performed.

Reliable operation and additional heating of a two–cycle plasma was established at 2MA and plasma parameters were found to be very similar in the two cycles. It was not possible to demonstrate a smooth transition between the two cycles with zero dwell time, but dwell times as small as 50ms and as long as 6s were achieved without difficulty. Indeed, the second plasma could be established following disruptions at up to 400kA in the tail of the first. Extensive studies were also made of the optimum control of the current ramp–down, which has provided an understanding of the constraints on aperture and safety factor control necessary for successful termination of the first, and initiation of the second, cycle.

6.3 Toroidal Field Ripple Experiment. Establishing the acceptable amplitude of toroidal field ripple for a tokamak reactor is fundamental to the design of a Next Step tokamak. By operating JET with 16 (rather than 32) toroidal field coils, it was possible to compare plasma performance with theoretical predictions, particularly in relation to fast particle confinement. Experiments were performed in both L and H–modes using ICRF and NBI heating in plasma configurations with 16 and 32 coils in the TF set. In the former case the edge toroidal field ripple was ~15%, while in the latter less than 1%.

Analysis of the results of this experiment is still preliminary, but the degradation of plasma confinement appears to be broadly as expected. In particular, in L–mode plasmas with 16 coils, central ion heating due to NBI was reduced relative to plasmas with 32 coils and the efficiency of ICRF heating fell significantly as the minority ion resonance was moved to larger major radius. Both effects led to a significant degradation of energy confinement with 16 coils compared to the 32 coil case. In addition, the reduction of fast particle confinement due to the enhanced ripple, as measured either by triton burnup measurements or neutral particle analysis, was in line with expectations. A striking difference in H–mode behaviour between the 16 and 32 coil cases was also observed. Whereas, with 32 coils, ELM–free H–modes with high energy confinement could be achieved readily at NBI powers of 3MW, only ELMy H–modes could be obtained with 16 coils, even at NBI powers as high as 12MW. The energy and particle confinement of these H–modes was significantly poorer than in the 32 coil plasmas.

7. Limiter Experiments

7.1 One Minute Pulse. The duration of JET limiter pulses is usually greater than that required to reach steady–state with respect to energy, and even particle, confinement, but it is generally short with respect to the resistive diffusion timescale and the timescale necessary for particle interactions with the limiter to approach steady–state. To explore the consequences of such long pulse operation, a one minute plasma at 2MA/1.9T was developed, utilizing ICRF heating and LHCD to minimize volt–second consumption.

While the plasma approached a quasi–steady–state with respect to magnetic diffusion (the central region being modulated by sawtooth activity) after ~10s, the plasma–wall interaction changed gradually throughout the pulse. It was found that the external gas requirements of the discharge fell to zero over a period of order 30s (which varied with the additional heating power), after which the density rose slowly. Z_{eff} measurements indicated that the rise in density was due primarily to increased deuterium recycling rather than increased impurity influxes. This behaviour was confirmed by observations of the decay of density following pellet injection and indicates a change in the recycling properties of the limiter with increasing temperature.

7.2 7MA Experiments. Although 7MA plasmas were produced several years ago, recent improvements in the design of the vessel protection tiles and the advances made in disruption control during the present programme have increased the margin of safety for high current operation and have allowed more extensive experimentation at 7MA than had previously been possible. Significant progress has been made as a result. The flat–top duration of 7MA plasmas has been extended to 9s, by employing LHCD and additional heating to reduce flux consumption, and additional heating experiments have been carried out at total powers of up to 28MW. Energy confinement of these discharges is good, with total stored energies of up to 12MJ being achieved (not far short of the highest H–mode value of 12.7MJ).

8. Conclusions

Recent JET experiments have encompassed several objectives: demonstration of improved performance in several plasma regimes; enhancement of fusion yield; improvement of our understanding of the fundamental physics which determines plasma behaviour; and exploration of a number of issues central to the design of a Next Step tokamak. Significant progress has been achieved in many areas. In addition, the foundation has been laid for a successful transition to the new phase of the JET project which will exploit the Pumped Divertor to address the key questions relating to the control of heat and particle exhaust and of impurity influxes.

We would like to acknowledge the contributions made to this work by many members of the JET Experimental and Operating teams, whose dedication has been central to the achievement of the results described here.

ANNEX

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