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JET Contributions to the ITER Physics Research and Development Programme (1996)

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TASK NO: **1.1**

TASK TITLE: **Vessel Sideways Displacements**

ORGANIZATION: **JET**

CONTACT: **V. Riccardo**

In JET there are disruptions leading to a net asymmetric radial displacement of the vessel. This kind of event happens only when the disruption is upward, if the plasma reaches the top of the vessel with almost full current, the safety factor at the boundary becomes close to a critical value (near to 1) and the asymmetric mode locks for a time long enough for the impulse to build up.

When sideways vessel displacements are recorded also asymmetries in the plasma position and current, and more generally in the magnetic probes around the vessel and the halo current measurements, are present. Usually the plasma tilts about and shifts along the direction that will be the one in which the torus will move. The amplitude of the tilt is larger (about 5 times) than the one of the shift, at least from the available measurements.

Downwards disruptions, even if the critical safety factor is reached do not show magnetic asymmetries as large as those of the upwards ones, and their sideways displacements are always negligible. Before divertor coils had been installed inside the vessel, the largest, and comparable to the largest recorded during divertor operation, sideways displacement had been recorded for a downwards disruption.

A link with plasma parameters before the disruption has been sought, so far without any satisfactory result. It seems that high β plasmas are less likely to give sideways motion, since the current quench in these cases is faster; anyway it has to be said that JET usually operates at low β (between 0.1 and 0.4) and so it is easier for an asymmetric disruption to have low β: the data base can be biased. In the same way the trend in the plasma elongation, which shows a peak about JET most popular elongation, 1.7, does not necessarily mean that there is an upper boundary increasing with the elongation, proportional to the growth rate and so leading to healthier displaced plasmas, and another upper boundary, decreasing with the elongation, proportional to the velocity of the disruption, so that the impulse has a small time to grow.

Considering the tilt only and replacing the plasma with a current ring, the sideways force due to the plasma asymmetry is then proportional to the product of the toroidal field with the difference of the vertical current moments in the sections normal to the direction of the vessel displacement. So that for the worst cases, when the asymmetry in the plasma vertical position is the largest possible, the sideways displacement scales with the product of the plasma current with the toroidal field.

The largest sideways displacement recorded so far is 6.9mm, in a 3.5MA/2.8T spontaneous disruption. In that pulse the vertical force swing on the MVP dampers was 3200kN, while on the same supports the horizontal force was 700kN and on the lateral restraints it was 800kN. Usually the worst conditions for the sideways motion are reached in induced VDEs, when the plasma is kicked up. Few spontaneous disruptions fall close to the upper boundary, which is 0.7 10^{-9} $mA^{-1}T^{-1}$. The sideways force is reacted by the vessel supports (on the MVP dampers, about 100MN/m, and on the lateral restraints on the MHPs, about 110MN/m) and by the TF coils through the magnetic damping effect, whose damping factor is about $5MNm^{-1}s^{-1}$. Lateral restraints have recently been fitted to oppose sideways displacements. Due to problems in accessing the vessel the efficiency of the restraint system is limited.

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TASK NO: **1.1**

TASK TITLE: **Disruption Database**

ORGANIZATION: **JET**

CONTACT: **M. Johnson, A. Tanga**

A disruption database containing the JET contribution to the IDDB was created and a copy of this database was sent to N. Fujisawa (Physics Integration Unit ITER). The database contains most of the parameters requested by ITER for the IDDB. A descriptor for the database is shown below.

Description: Contains data requested by ITER for the IDDB update.

Data types:

PULSE: Pulse Number

IPLAS: Plasma current before disrution

"At time of Ip quennch minus 200ms"

DIPDT: dIp/dt mean value from strt of Ip quench until Ip has decayed by 60%

PCONF: Plasma confinement type i.e limiter x-point or unknown

MG2LI: Internal inductance before thermal quench.

'"At time of Ip quench minus 200ms"

ELONG: Plasma vertical elongation.

'"At time of Ip quench minus 200ms"

NOTE: IPFX is ramped down on disruption precursors hence the value
at time of Ip quench may be less than given by ELONG

AMNIR: Plasma minor radius

"At time of Ip quench minus 200ms".

MG3WP: Plasma stored energy.

'"At time of Ip quench minus 200ms"

NEVAL: Volume averaged density

'"At time of Ip quench minus 200ms"

ZEFHZ: Zeff (Vbrem horizontal)

'"At time of Ip quench minus 200ms"

TEMEG: Electron Temperature on magnetic axis.

'"At time of Ip quench minus 200ms"

GASTP: Gas Type

IPSPK: delta–Ip/Ip(0)

BEPL1: Beta poloidal

'"At time of Ip quench minus 200ms"

BEPL2: Beta poloidal

'"At time of Ip minus"

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TASK NO: **2.1, 2.2**

TASK TITLE: **Detached Plasma Data**

ORGANIZATION: **JET**

CONTACT: **G. Vlases**

Explanatory Note: The work described in this report was carried out in the Mk IIA divertor, which began physics operation in June 1996. In October 1996, conductance of the bypass leakage paths was reduced by 70%; the configuration subsequent to this change is called Mk IIAP. The heaviest emphasis on the Mk IIA campaign was on the effect of divertor geometry and triangularity on steady state ELMy H-modes. The period March-July 1997 is dedicated to DTE1, to be followed by a short programme, still in Mk IIA, to complete urgent ITER physics studies. The Mk IIGB (Gas Box) will be installed late in 1997.

2.1 Detached Plasma Data

2.1.1 Detachment in Mk IIA is similar to that in Mk I (see JET Report P(97)03). In Type I ELMy H-mode operation, with intrinsic impurities only, the divertor plasma is detached on the inner leg and attached on the outer leg between ELMs under most conditions, and always attached during an ELM.

2.1.2 Radiating Species. Carbon is the principal radiator in non-seeded operation. With beam fueling only, f_{rad} is only about 0.15, rising to 0.45 for heavy D_2 puffing. With seeding, the seeded impurity dominates the radiation, and values of f_{rad} to 0.7 and 0.6 were achieved in Mk IIA and Mk IIAP respectively.

2.1.3 Modelling. Much progress has been made in modelling both attached and detached plasmas, using a coupled fluid-monte carlo hierarchy (EDGE2D/NIMBUS). In addition, a coupled core/edge/divertor code system has been developed and is being used to model pulses.

2.1.4 Detachment Mechanism. Recombination plays an important role and is needed in the modelling to describe I_{sat} reduction.

2.1.5 Influence grad B drift direction. Not studied in Mk IIA.

2.1.6 Helium Exhaust. Not yet studied in Mk IIA.

2.2 Detachment Window. Results on the detachment window were very similar to those reported for Mk I. ELMy H-modes with intrinsic impurities only were generally slightly detached on inside target only. With Neon and Nitrogen seeding it was possible to obtain fully detachment, but with poor confinement, reverting to near L-mode conditions at high radiated power fractions and density near Greenwald.

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TASK NO: **2.3, 2.4, 2.5**

TASK TITLE: **Detach window, Radiating Divertor, Impurity**

ORGANIZATION: **JET**

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

2.3 Highly Radiating (Seeded) pulses. Results are very similar to Mk I. At high radiated power fraction, the radiation zone moves to the X point. Nitrogen radiates more in the X-point and divertor than does Neon. Effect of geometry is very small. High radiated power fraction always accompanied by confinement degradation. Maximum radiated power fraction achievable decreases as divertor closure increases; it is thought that this is a result of increasing divertor CX losses.

2.4 SOL Impurity Flows.

2.4.1 In trace Neon injection experiments, the dominant parameter controlling decay time was the neutral flux into the cryopump, Φ_p. For fixed Φ_p, the decay time was shorter for top D_2 puffing than divertor D_2 puffing. The decay time in Mk IIA was much shorter than in Mk I.

2.4.2 Pellet Injection. Injection of 3mm pellets at up to 5 Hz gave no measurable differences from gas puffing.

2.4.3 Effect of Detachment. In non-seeded Type I ELMy H-mode pulses, detachment was slight and no effect on intrinsic impurity content was seen. With N_2 seeding at high radiating power, the core density of nitrogen increased when the X-point MARFE formed.

2.4.4 Shielding Mechanisms. DIVIMP modelling shows largest contributor to core C concentration to be arising from private flux region (mainly chemical sputtering) and inner wall. Wetted area of divertor tiles produce much larger sources of carbon, but influx very well shielded. These results supported qualitatively by EDGE2D modelling.

2.5 Density Limit

2.5.1 Scaling. The density limit in ELMy H-modes manifests itself as a gradual decrease of confinement to L-mode values. The highest density attained with NI fueling pulse gas puffing was about 0.85 n_{gw}, with good confinement (H_{93}≈1) up to 0.8 n_{gw}. Seeded ELMy H-modes had similar density limits, but poorer confinement. The L-mode density limit at low power (e.g. 2-3 MW NI) in Mk IIA was only about 50% of that in Mk I. This results from higher C sources in Mk IIA for given core plasma density and SOL power flux, which is believed to arise from the narrower divertor plus enhanced chemical sputtering at the higher tile operating temperatures of Mk IIA.

2.5.2 Edge Density Limit? NI fueled discharges are somewhat more peaked than RF heated pulses, but the peaking reduces as the density limit is approached by gas puffing.

2.5.3 Density Limit Theory. While at JET, K. Borrass developed a SOL-based density limit model which describes the observations reasonably well.

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TASK NO: **2.6, 2.7, 2.9, 2.11, 2.12, 2.14, 2.17**

TASK TITLE: **Divertor Physics**

ORGANIZATION: **JET**

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

2.6 SOL Similarity Studies. The scaling of energy confinement in a series of N_2 seeded discharges with high f_{rad} (>50%) was studied using plasma which were dimensionally similar except for a variation in ρ^* and ν^*. It was determined that the scaling was not gyrobohm, as is obtained in ELMy H-modes at low radiated power, and in fact was close to Bohm-like. Future experiments are planned.

2.7 SOL Width Studies. A database of SOL widths in JET has been assembled and is being analysed to determine its scaling.

2.9 Erosion Studies. One module of Mk II A was removed part way through the campaign for detailed analysis. Results indicated very heavy net deposition in the cool corners of the divertor and pumping channels.

2.11 Wall Impurity Sources. DIVIMP modelling indicates that the lower inner wall is an important impurity source. Comparison with experimental measurements of the wall fluxes is in progress.

2.12 Tolerable ELMs

2.12.1 ELM Size. Type I ELMs in JET vary in size from 2% to 8% of the plasma energy content in NI heated pulses. The energy loss time scale is 100 µsec. The ELM size decreases approximately as $f_{elm}^{0.5}$. The fraction of the ELM energy which reaches the target, and the deposition zones, are being analyzed. The freq. depends primarily on triangularity, gas puff rate, and power flux through the edge. In comparable RF produced H-modes, the ELMs are about an order of magnitude more frequent, and correspondingly smaller, with confinement at least as good as in NI H-modes.

2.12.2 Type I ELMs always “burn through” to the target. Type III not yet analyzed.

2.12.3 JET has put most of its Mk I ELM data in the ITER database, and is now preparing to transmit the data from Mk IIA and MkIIAP.

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.

2.17 SOL Width Mechanism. Theoretical work is continuing, and the SOL width database is being analyzed for comparison with theory.

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TASK NO: **2.20, 2.21, 2.22**

TASK TITLE: **Divertor Physics**

ORGANIZATION: **JET**

CONTACT: **G. Vlases, L. Horton**

2.20 Divertor Geometry

2.20.1 Confinement with D_2 Puffing. Confinement degrades was gas puffing, but good core confinement is maintained up to densities of about 0.8 n_{gw}. The best confinement vs. density tradeoff was found in Mk IIAP, the most closed configuration. Vertical and horizontal target performance was similar. Triangularity had a strong effect on ELM frequency, which in turn affects density and Z_{eff}.

2.20.2 Confinement with Impurity Seeding. Confinement degrades rapidly with increasing f_{rad} (and increasing $n_{e,\ edge}$). Values of Z_{eff}, when scaled to ITER, may be marginally acceptable.

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.

2.21.2 Neutral Compression. Upstream neutral pressure in Mk II AP was systematically lower (about 40% in ELMy H-modes) than in Mk IIA, with very similar divertor neutral pressures. Despite this, the confinement quality was not improved. The best correlation was between confinement and divertor neutral pressure, rather than midplane neutral pressure.

2.21.3 ELMs and Geometry. CCD cameras and soft x-ray cameras both show that some of the energy of NI Type I ELMs is deposited on various limiting surfaces outside the divertor, and on the upper (baffle) sections of the divertor. Quantitative estimates are in progress. The divertor sides for horizontal target operation are typically on the “2cm midplane flux surface”.

2.21.4 Pumping vs. Geometry. The pumping rate varies slowly as the strike point is moved from the dome, to the corner, and then on to the vertical plates, with a maximum variation of a factor of 2. This slow variation has been modeled with EDGE2D and results from the trapping of neutrals in the corners of the divertor near the pumping ports.

2.21.5 Impurities and Geometry. There is little effect of divertor geometry on core carbon concentration [C]. This results partly from the fact that the main chamber walls contribute substantially to the core [C]. With recycling impurities, it is possible to influence the core concentration through the divertor/magnetic equilibrium configuration.

2.22 Model Validation Code development and application to the interpretation of experiments is a major activity at JET. The principal tools are EDGE2D/NIMBUS (with or without the coupled core code JETTO) and DIVIMP.

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TASK NO: **3.2**

TASK TITLE: **ITER Demonstration Discharges**

ORGANIZATION: **JET**

CONTACT: **N. Zornig, T. Jones**

JET has improved its real-time power control system (RTPC), resulting in :

- More diagnostic signals available in real time.
- More accurate delivery of power reference waveforms by the heating systems.
- Possibility of varying the density in real time under RTPC as a function of one or more of the available diagnostic signals.

The RTPC is now widely used at JET and with respect to the simulation of burning plasma dynamics a set of demonstration experiments was carried out in which the route to an ignited plasma was simulated. In these experiments the expected values for the alpha and additional power in an ITER plasma [1] were scaled down by a suitable factor to match the JET heating sources, preserving the same ratio of alpha power over additional heating power, i.e. around 5 approaching the ignited state. Another requirement for these experiments is that the ratio of density in the ignited state over the initial value is preserved, being around 3.

The additional power was given by NBI heating and the simulated alpha heating (P_α^{sim}), being proportional to W^2_{dia} , by ICRH. This proportionality factor is related to the ITER confinement margin, and two demonstration experiments have been performed using this scheme with different proportionality factors. In the first experiment this factor was chosen so that no ignition was achieved. In the second experiment a thermal runaway was demonstrated. Both the density and additional heating power were pre-programmed according to the data given in [1]. By starting with a low density the L-H transition can be achieved at relative low power. The fusion power is then increased by gradually increasing the density.

Future burn-simulation experiments are under consideration: Vary the speed of the density ramp and the proportionality factor, relating W^2_{dia} and P_α^{sim} ; vary the additional heating power to change the path to the ignited state; control the fusion power output in the sub-ignited state using the additional heating power or density as actuator.

References:

[1] G. Janeschitz et al, “Status of ITER”, Plasma Physics and Controlled Nuclear Fusion, 37 (1995), A19-A35.

[2] N. Zornig et al., “Experimental results using the JET real time power control system”, contributed paper to 19th Symposium on Fusion Technology, Lisbon, 1996.

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TASK NO: **4.1, 4.2, 4.3, 6.1**

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

ORGANIZATION: **JET**

CONTACT: **J. Cordey, K. Thomsen, D.Start, E. Righi, W. Kerner**

During 1996 in an effort to confirm the ITERH93-P scaling which is being used to predict the performance of ITER, extensive scans in the dimensionless Larmor radius variable ρ^*, dimensionless collisionality ν^* and β have been made.

The variation of ITERH93-P with ρ^* and ν^* has been confirmed but the strong degradation with β of the scaling expression is not seen.

The dependence of the MHD β limit on the collisionality in ELMy H-modes has also been examined. For the geometry and collisionality of ITER the β limit (β_{nth} =3) is found to be well in excess of the requirement in ITER (β_{nth} = 2.2).

Studies of the H-mode power threshold have been continued during 1996. The threshold in the Mark IIA divertor has been found to be very similar to that of Mark I and also changing the triangularity and other geometrical features has been found to have very little effect on the threshold.

Studies of both confinement and the power threshold will be continued in the D-T phase of JET during 1997 to assess whether changing the isotope effects the scaling.

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TASK NO: **4.4, 4.7, 4.9**

TASK TITLE: **Energy and Particle Transport Model Testing**

ORGANIZATION: **JET**

CONTACT: **A. Taroni**

Work has been carried out to test the validity of the mixed Bohm/gyro-Bohm model developed at JET [1] against experimental results from several Tokamaks available in the ITER profile data base [2]. The results obtained show that the model allows a fairly accurate simulations of L-modes and Elmy H-modes in the data base if temperature boundary conditions consistent with the experimental ones are prescribed. Therefore the model can provide a useful guide for interpretation and prediction of results in Tokamaks including ITER. However the predictive capability of the model is at present limited by uncertainties on transport modelling in the boundary region.

The inclusion of a neoclassical transport barrier inside the separatrix has been shown to give a good description of the evolution of Elm-free H-modes in JET. This is first step towards a better modelling of the boundary region. Work is in progress to include a semi-empirical model of Elm activity.

A further step in this direction has been performed by linking the core transport codes JETTO and SANCO (for main plasma and impurities), to the multi-species boundary transport code EDG2D/NIMBUS.

This new tool has been shown to allow transport studies that take into account consistently the effect of the SOL and divertor region on confinement in the plasma core and vice versa. Such a tool can now be used for predictions of ITER performance with various assumptions on transport models in the core and in the boundary region.

[1] M. Erba et al., Development of a Non Local Model for Tokamak Heat Transport in L-mode, H-mode and Transient Regimes. JET Report JET-P(96)10, to appear in Plasma Physics and Controlled Fusion.

[2] J. Connor et al., Validation of 1-D Transport and Sawtooth Models for ITER, 16th IAEA Fusion Energy Conference, Montreal, Canada, 7-11 October 1996, IAEA-CN-64/EP-21.

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TASK NO: **5.1**

TASK TITLE: **TF Ripple**

ORGANIZATION: **JET**

CONTACT: **B. Tubbing**

The report on the work on Toroidal Field Ripple Effects is essentially unchanged from that made in 1995. The general conclusions were:

The losses of fast particles (> few 100keV) are in agreement with the predictions on the basis of stochastic diffusion theory. This conclusion is based on the Triton burn-up results from the second JET Ripple experiment, together with the ICRH minority particle results from the first experiment.

The losses of plasma energy in discharges with Neutral Beam Injection are larger than predicted. In addition, the losses of toroidal rotation frequency exceed the expectations. Further investigations have focused on the question of the link between losses of particles in the energy range of a few tens of keV to 100keV and the rotation. The rotation may make an additional contribution to the ripple losses due to resonant effects. This is currently being investigated with a modification of the Orbit Following Monte Carlo code DRIFT.

The H-mode threshold is not significantly changed by the ripple. At the level of 2% ripple at the plasma edge, the H-mode threshold was found to be somewhat reduced.

It was observed that ripple increases the sensitivity to locked modes due to error fields for NBI rotation driven plasmas, while for ohmic plasmas it reduces the sensitivity.

Relevant publications:

Tubbing, B.J.D. and JET Team, in EuroPhysics Conference Abstracts (Proc. 22'nd Eur. Conf. Bournemouth, 1995), 19C, Part 4, European Physical Society, Geneva (1995) 1.

An overview of both the JET ripple experiments has been delayed due to the analysis of the plasma rotation effects, but is expected to be submitted in the near future.

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TASK NO: 5.3

TASK TITLE: Studies of TAE Modes in JET

ORGANIZATION: JET

CONTACT: A. Fasoli, S. Sharapov, C. Gormezano, J. Lister (CRPP), W. Kerner

As indicated in a previous report containing the description of work for this Task, the experimental effort within the JET / CRPP collaboration on the physics of Alfvèn Eigenmodes proceeds along three main avenues.

First, the spectrum of Alfven Eigenmodes (AE), both in terms of frequencies and damping rates, is investigated in the frequency range 30-500 kHz using an external exciter connected to the JET saddle coils. An AE damping rate database for comparison with theoretical models has been established and is being filled with more reactor relevant plasma conditions. In 1996 a new AE resonance tracking scheme, based on real time mode detection and digital control of the frequency, has been implemented. This allows one to follow the evolution of a single AE throughout several seconds within a discharge, hence measuring the dynamic evolution of the mode damping rate. In addition to the damping, it is possible to obtain quantitative information on the fast particle drive and its variations during the additional heating phase of a JET discharge. The analysis of the evolution of the measured effective damping rate of the driven mode, difference between the total damping and the fast particle drive, both before and after the creation of fast particles and for toroidal Fourier components with opposite mode numbers, yields information on the mode marginal stability. In specific conditions this technique allows a direct evaluation of the critical fast particle pressures and pressure gradients for instability, and/or of the minimum unstable toroidal mode number. These studies have been performed so far in limiter plasmas with fast ions produced by ICRH and non-resonant NBI, with $v_{||}<v_A/3$. The experimental results agree with the predictions of the CASTOR-K code that the NBI produced fast ions play a stabilising role for AE of low toroidal mode numbers ($n<3$) and only AE with $n>\sim 8$-10 can be driven unstable. The same kind of experiments will be undertaken in D-T plasmas to help determining the alpha particle drive and possibly the related AE marginal stability limit for an ITER-like scenario.

Secondly, direct measurements of the electromagnetic fluctuations in the AE frequency range reveal the appearance of high-n unstable modes ($n>8$) driven by the fast particles created by NBI and ICRH in JET high performance plasmas. Particularly, in the NBI case, broad band activity in the TAE frequency range is observed when the second order fast particle-wave resonance $v_{||}=v_A/3$ is satisfied. These unstable modes seem to affect the overall fusion performance in JET, possibly via modification of the beam power deposition profile, which is the main source of plasma heating.

The third method for studying AE is based upon the non-linear interaction of two fast waves in the ICRF frequency range. AE can be excited by the beating of the two ICRH waves. The excitation takes place in the plasma core, at the ICRH resonant layer, is not limited by the antenna geometry to low toroidal mode numbers and can yield relatively large amplitude modes due to the high power available in the JET ICRH plant. This method, which has been demonstrated experimentally at JET, is therefore suitable for assessing the effect of AE on fast particle orbits. Optimisation studies indicate that the most efficient configuration for AE excitation encompasses two adjacent RF modules with dipole phasing, corresponding to a high ICRH absorption per pass.

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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**

During the 1996/97 JET Experimental Campaign a number of issues relevant to the transition to H-mode have been studied. Heating systems (namely NBI and ICRF) have been compared and found to be substantially identical as far as H-mode power threshold is concerned, although toroidal rotation with ICRH is a factor two-three lower than that measured during NBI H-modes.

Different magnetic configurations (Standard Fat, Super Fat and Gas Box, all with the strike zones on the horizontal target plates) have been found to be equivalent, although in Super Fat and Gas Box configurations identification of the L-H transition is more difficult.

Experiments with different phasing of the ICRF antennas have also been carried out. Results show that if a dipole-like phasing is used ($0\pi0\pi$, $0\pi\pi0$ or $\pi/2$) the H-mode transition occurs at the expected power, while with monopole-like phasing ($00\pi\pi$) the threshold power is increased by about 30% due to the decreased heating efficiency. No H-mode was observed in pure monopole (0000) phasing.

High density H-modes have also been studied to confirm the non-linear scaling of the threshold power with density observed in 1995 JET data.

The global scaling of the loss power with the main plasma parameters is substantially unchanged from Mk0 (no Pumped Divertor) to MkI and MkIIa (with and without plugging of the by-pass leaks).

Particular emphasis has been given to studying the conditions that lead to the H-L transition using both NBI and ICRF heating. The conclusion is that no hysteresis can be observed in JET H-modes. In particular, in the case of ICRF heated plasmas the evolution of the discharge from L-mode to the H-L transition has been followed through the evolution of the edge electron density and temperature, measured at the top of the T_e pedestal. The plasma goes back to L-mode when the critical temperature for the transition to ELMy H-mode is crossed again.

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TASK NO: **6.5**

TASK TITLE: **Error Field Induced Locked Modes in JET**

ORGANIZATION: **JET**

CONTACT: **B. Tubbing**

Locked modes have been produced in a series of experiments by applying external static error fields using the in vessel JET saddle coils. For these experiments a single null ohmic target plasma was used with plasma current Ip=1.5 MA, minor radius a=0.95 m and ITER relevant shape. In all the experiments a steady state was reached and then the saddle coils current was ramped up at a maximum rate of 1.25 kA/s. The penetration thresholds have been studied as a function of the electron density and edge safety factor q_{95}. The mode penetration was measured by ex-vessel saddle loops, the density is measured as the line average of the central line of sight of the FIR interferometer, q_{95} and the position and shape of the q=2 surface are reconstructed using EFIT. The resonant magnetic fields $\left|\tilde{B}_{2,1}\right|$ are calculated using the vacuum code COSC: for a plasma with q_{95}=3.3, the 2/1 error field on the q=2 surface is $2.26\times10^{-7}\,T\,/\,A$. An overall number of 32 discharges has been analysed.

Natural error field. The penetration thresholds have been measured, in similar conditions (q_{95}=3.3, B_φ=1.5T, I_p=1.5MA, $n_e = 1.4\times10^{19}m^{-3}$), with four different saddle coils phases: ++, -+, —, +- corresponding to a maximum radial field pointing to the bottom of the vessel and at toroidal angles 45°, 135°, 225°, 315° respectively. Since the thresholds must be the same if the contribution of the natural error field is taken into account, it is possible to measure the natural field and its phase in this way. The natural error field has been found to be maximum at a toroidal angle of 278° and have amplitude $\left|\tilde{B}_{nat2,1}\right| = 8.90\times10^{-4}\,T$ corresponding to a relative amplitude of $\left|\tilde{B}_{nat2,1}\right|/B_\varphi = 5.9\times10^{-5}$.

Slow ramp pulse. The penetration thresholds for two pulses with similar plasma conditions and different ramp rates (1250 A/s and 375 A/s) were compared and it is found that the thresholds differed by about 100 A.

Electron density and q_{95} scaling. Having made corrections for the natural error field and for the ramp rate, a two parameter scaling law was built for the penetration threshold as a function of the electron density and q_{95}. The electron density ranges between $5.3\times10^{18}m^{-3}$ and $1.70\times10^{19}m^{-3}$; q_{95} ranges between 2.03 and 5.41 . If only the subset of 28 shots with q_{95}<3.8 is taken into consideration, we find a very good linear scaling of penetration thresholds vs. electron density. If, on the other hand, all 32 discharges are taken into consideration, another good linear scaling is found of thresholds vs. density and q_{95}. The scaling law can be written as:

$$\left|\tilde{B}_{2,1}\right|/B_\varphi = \left(1.08 \pm 0.10\times10^{-23}\right)n_e\left(m^{-3}\right) - \left(1.31 \pm 0.36\times10^{-5}\right)q_{95} + \left(4.2 \pm 1.5\times10^{-5}\right).$$

Implications for ITER. Scaling towards ITER is usually done for a plasma with q95=3 and Greenwald parameter $n_e\pi a^2/I_p = 2\times10^{13}m^{-1}A^{-1}$ which corresponds, in our case, to an electron density $n_e = 1.06\times10^{19}m^{-3}$. Substituting these numbers into equation (1) we obtain a penetration threshold scaled to ITER: $\left|\tilde{B}_{2,1}\right|/B_\varphi = 1.17 \pm 0.12\times10^{-4}$.

Relevant Publications. SANTAGIUSTINA A. et al. , 6th ITER Expert Group Meeting on Disruptions, Control, MHD; 1997 Moscow.

ITER PHYSICS R&D PROGRAMME

TASK NO: **6.8**

TASK TITLE: **Plasma Rotation**

ORGANIZATION: **JET**

CONTACT: **N.C. Hawkes**

The JET poloidal rotation diagnostic makes measurements at the edge of the plasma of the flow velocity of impurity ions excited by charge exchange with the heating beams. The viewing geometry allows the separation of the flow into poloidal and toroidal components. With the correct plasma configuration very high spatial resolution (better than 1 cm) is possible.

Measurements were made on JET in dedicated discharges with an optimised equilibrium. In these discharges a CD_4 puff was added to increase the signal level from the carbon charge exchange line. A prelude phase of low power neutral beam injection was used to give a period of charge exchange measurements during the initial L-mode.

In all cases the H-mode transition was accompanied by ELMs. In most transitions these ELMs persisted for several hundred milliseconds and in these cases the plasma pressure profiles had already steepened by the time the transition was complete. However, in a limited number of cases the transition ELMs persisted for less than 50 ms (fast transitions) and the pressure profiles remained close to the L-mode profiles until after the transition.

In the fast transition cases the signal intensity in the outermost (largest major radius) chords showed a sudden drop at the time of the drop in H_α intensity. This is evidence of the sudden increase in impurity confinement that contains the fully stripped carbon ions within the plasma, while they are lost rapidly from outside the confinement region. The signal intensities from chords with smaller major radius show instead a ramp up of intensity with time following the transition.

Over the entire profile the change in poloidal flow speed at transition is small. There is some evidence for a change at the level of 5 $km.s^{-1}$ on the outermost chord at the transition [1]. (After the transition, transients are occasionally observed as well as gradual changes to the measured velocities in the outermost chord. This chord has a very low signal level and it is not certain that these drifts are not artifacts arising from the growing toroidal rotation.)

In most H-mode theories, the shear in the perpendicular $\mathbf{E}\times\mathbf{B}$ flow is supposed to suppress the turbulence responsible for the enhanced transport of L-mode. The relevant parameter in the measurements is therefore the gradient of radial electric field, E'_r. This parameter has contributions from both the pressure gradient and poloidal and toroidal flow velocities, and tends to be somewhat noisy. In the situation where the H-mode transition is slow, the pressure profiles become steep before the transition is complete, giving a high value of E'_r of at least 2.5×10^6 $V.m^{-2}$ which does not change during the transition. In the case of a fast transition the pressure gradients have not developed before the transition and the value of E'_r is much lower, at about 2×10^5 $V.m^{-2}$.

Whilst the lower value of E'_r is smaller than that obtained from measurements on smaller tokamak, there is reason to suppose that the critical shear velocity for turbulence suppression should be dependent on the size of the plasma, either major or minor radius. Crude arguments imply that the small value of E'_r measured on JET could be consistent with the larger values measured on DIII-D and COMPASS when the size scaling is taken into consideration.

Future effort is aimed at reducing the errors in the velocity measurements to address this issue.

[1] N.C. Hawkes et al., Plasma Phys. Control. Fusion **38** (1996) 1261.

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TASK NO: **6.7, 6.9**

TASK TITLE: **Halo Current**

ORGANIZATION: **JET**

CONTACT: **P. Andrew**

In JET, the total poloidal halo current during disruptions is measured to be up to 20% of the initial plasma current, I_p. This is based on the measured change in toroidal field between top and bottom of the vessel at 2 opposite toroidal positions. Halo current deduced from current shunts in each octant of the vessel only give up to 15% of the initial I_p, but this is consistent if the shunted tiles only intercept a fraction of the halo. The shunts do, however, measure that any toroidal asymmetries are predominantly n=1, justifying the above measurement of total halo current based on magnetic sensors at only 2 toroidal positions.

It was observed that at a given I_p, there was a large spread in the measured halo current, filling the space between 0 and 20% I_p. It was found that the difference between large and small halo currents was closely related to the magnitude of the plasma current vertical moment. For example, when the current quench precedes the vertical displacement the moment, $I_p\Delta z$, only reaches a modest value, and the observed halo current is small. Large moments arise when a large vertical displacement is achieved (eg. 1m) before significant current decay; in these cases large halo currents are observed.

When the halo current is measured to be significantly different in opposite octants, the plasma current moment in those octants is also observed to differ in the same sense. A more complete picture of the toroidal asymmetry is given by the current shunts. The halo current is composed mainly of n=0 and n=1 components. The n=1 component is usually stationary, but sometimes jumps from one octant to another. Genuine rotation of the plasma has not been observed.

There is a close correlation between toroidally asymmetric halo current, and net sideways displacement of the vacuum vessel during disruptions. Although neither the halo current nor sideways movement are systematically oriented toroidally, the phase difference between them is. If the peak halo current is observed in the north-most sector of the torus, the sideways movement is south-west $\pm\ 45^0$. This phase difference agrees qualitatively with a model where an n=1, m=1 displacement of the plasma is combined with the n=0 vertical displacement.

Finally, the issue had been raised whether the degree of toroidal asymmetry is smaller when the total halo current is larger at a given plasma current. This would imply an upper bound to the halo current density. However, it was found that the peaking factor reached up to 1.6, independent of the total halo current. The peaking factor is defined as the maximum to average halo current estimated using the 2 toroidally opposed magnetic measurements.

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TASK NO: **6.7, 6.9**

TASK TITLE: **Plasma Equilibrium/Shape Control**

ORGANIZATION: **JET**

CONTACT: **M. Garribba, B. Tubbing**

A plasma equilibrium controller of the LQR type has been designed at JET. A summary report can be found in "JET Contributions to ITER on the NET Article 7 Contract NET94/870, Volume II, p.1-12". The report contains a summary of the decoupling controller work carried out for JET and an attempt to obtain an equivalent result with an LQR algorithm. Simulations are presented for the controller and experimental test will be carried out as soon as it is compatible with the JET operation.