ENGINEERING ANALYSIS OF JET OPERATION

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ABSTRACT

Since 1994 the JET experiment has been operated with a divertor, with currents up to 6MA. Disruptions are generally accompanied by vertical plasma displacements giving rise to vertical forces at the torus. Vertical force swings up to 5MN were recorded at vessel support. The forces are toroidally non-uniform, with peaking factors up to 1.8. Global sideways displacements of the torus, up to about 5mm, were also recorded in a number of disruptions. They are interpreted as consequence of a large amplitude m=1, n=1 kink mode. Disruptions led to damage of some components inside and also outside the vessel, such as internal saddle coils, and Beryllium evaporator heads.

I. INTRODUCTION

Until 1992 the JET experiment was operated without a divertor. Based on an extensive analysis it was then possible to allow operation at plasma currents up to 7 MA in the limiter mode and up to about 6 MA in the X-point mode operation [1] while the original design value for extended performance was 4.8 MA. The operation limits were to a large extent determined by the forces and stresses arising at the vacuum vessel and the mechanical shell during vertical displacement events (VDEs) and disruptions, as reported previously [2]. Vertical forces up to 3.7 MN acting on the vessel supports were observed. It was concluded that, at the moment of its maximum, the vertical force is primarily caused by halo currents re-circulating in the vessel [3].

For the assessment of operation limits it was originally assumed that the halo currents and the associated forces are approximately uniform along the toroidal direction, as suggested by observations at the DIII-D Tokamak [4]. However, local measurements of intercepted halo currents [5] and measurements of forces at the vessel supports indicated the presence of large fluctuations and toroidal variations of the halo current density and the presence of substantial toroidal non-uniformities of the global vertical forces acting on the JET vessel was highlighted in May 1994. Large asymmetries of halo currents were also reported from JT-60U [6] and Alcator C-mod [7]. These findings indicate that non-uniformity of disruption forces may be an important issue of Tokamak design.

Since 1994 JET has been in operation with a pumped divertor [8]. Many new components had been installed inside the vessel, notably four divertor field coils, divertor target plates, cryo pump, and also eight saddle shaped coils intended for the control of MHD instabilities. The plasma size is reduced so that the plasma current is limited to about 6 MA. Most experiments were carried out at $I_p < 4$ MA. New problems have been encountered during the divertor operation:

- The vertical position is more difficult to stabilise, mainly due to the smaller plasma size and the resulting reduction of passive stabilisation by wall currents, but also due to the fact that larger equilibrium field gradients are needed for the desired divertor configurations.

- The magnetic configuration with single X-point is strongly up/down asymmetric. As a consequence, rapid disturbances like giant ELMs and giant sawtooth relaxations led often to loss of stabilisation so that the plasma moved vertically by typically 1m before disrupting. This kind of VDE can cause particularly large dynamic vertical forces at the torus. Forces up to about 8 MN had been anticipated during divertor design for an upward VDE of a strongly elongated 6 MA plasma [9]

- Strong asymmetries of disruption forces and resulting vessel displacements have been observed. Various upward VDEs caused significant global sideways displacements of the torus. This phenomenon occurred to a lesser extent also during the previous operation without divertor but its importance was not realised then.

- The new in-vessel components are exposed to eddy and halo current loads, arising from fast plasma current variations during the energy quench and the current quench and from VDEs. In some cases these loads were higher than expected and caused damage to some of these components. The non-uniformity of halo currents may have enhanced local forces.

II. FORCES ON THE VACUUM VESSEL AND DISPLACEMENTS DUE TO DISRUPTIONS

A. Measurements

The vessel movements are caused by vertical and horizontal forces applied to the vacuum vessel walls, in-vessel components and divertor coils. To analyse the effects and nature of disruptions JET has a set of sensors (see Fig. 1)

a) Displacement resistance transducers attached to the main vertical ports (MVP) measure radial displacements and those attached to the intermediate vertical ports (IVP) measure vertical movements.

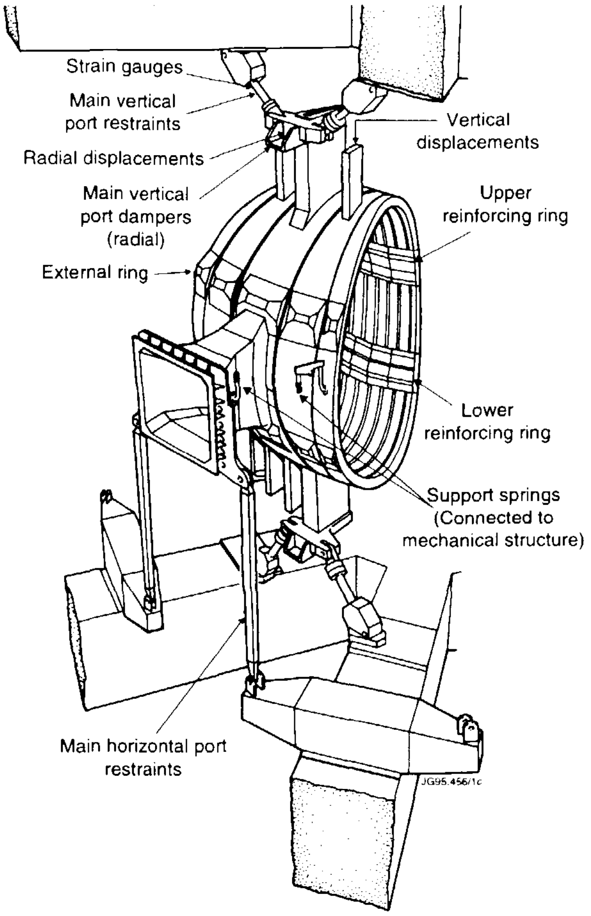

Fig. 1: Vessel Measurements and constraints

b) Strain gauges on the restraining struts at all main vessel ports at the top and bottom of the vessel measure the vertical forces applied by the vessel to the iron magnetic circuit.

c) The value of the plasma current and the displacement of its centroid are detected by measuring the tangential and radial field around the poloidal contour of the plasma. The tangential field is measured by 16 poloidally oriented pickup coils located along the inside wall of the vessel at two opposite octants (3 and 7). The radial field is deduced by "saddle loop" coils applied on the external wall of the vessel. These measurements are corrected for the contribution from divertor coil currents.

d) A number of poloidally and toroidally distributed shunts on the earthing connections of certain in-vessel components, including "mushroom" tiles, measure halo currents collected from the plasma.

Displacements and forces at supports are monitored to establish safe operating regimes.

B. *Axisymmetric effects and trends of global parameters*

All disruptions in JET, and often other types of large amplitude perturbations, produce vertical plasma displacements. In most cases the vertical stabilisation is completely lost due to saturation of a stabilising circuit. This is as would be expected because a rapid plasma current quench, which could typically be in the region of 100 MA/s, induces currents in the components surrounding the plasma (PF coils, divertor coils, vessel) which produce a transient vertical force at the plasma due to the up-down asymmetry of the single divertor configuration. To compensate this effect the radial field amplifier should supply peak voltage far in excess of its design parameters. Similarly it is impossible to maintain the radial plasma position when there is a rapid drop of plasma current. This current quench is in turn enhanced by the loss of position control and by the resulting plasma-wall interaction.

The most severe VDEs are those where the vertical instability arises before the current quench. The current moment $I_p \delta Z_p$ can then reach large values causing large global vertical forces at the torus and large halo currents affecting in-vessel components. The reasons for instability before a current quench are not clear. It is suspected that large amplitude perturbations such as giant ELMs, minor disruptions, L-H mode transitions or disruption precursors cause, in some cases, an inappropriate response of the vertical stabilising circuit. Further investigations are aimed at improving the stabilising circuit and the reliability of the magnetic measurements which are affected by noise and screening effects.

Pulse 34078, which, with plasma current 3.5 MA, resulted in a vertical instability, has been taken as an example because it shows both the trend of the global axisymmetric parameters and also the largest recorded sideways displacement of the vessel. The typical trends of the plasma current I_p, the displacements of its centroid and the total vertical force measured at the vessel supports are shown in figs. 2a, 2b and 2c respectively. This total force does not directly represent the electromagnetic forces acting on the vessel, but indicates the effect of these through the dynamic response of the vessel, ie, the inertial and constraint spring effect.

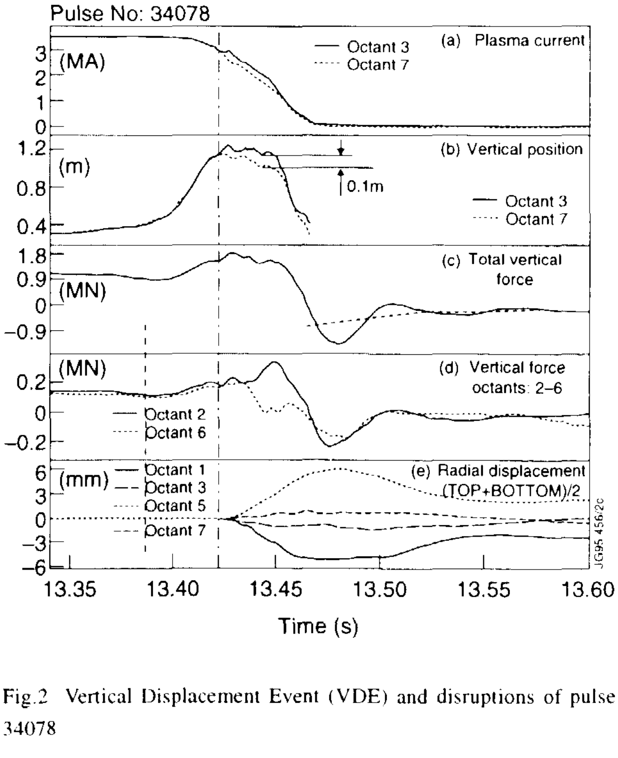

Fig.2 Vertical Displacement Event (VDE) and disruptions of pulse 34078

The vertical force at the torus consists of three contributions:

- forces on the four divertor coils; disruptions generally cause a substantial increase of the divertor currents and force variations. (see Table I)
- forces due to induced toroidal currents in the vessel
- forces due to halo currents intercepted by in-vessel elements, these currents circulate through "earthing" connections in the vessel, and also directly in the divertor target. Induced currents are due to plasma current change and the velocity of displacement whereas halo currents depend on the distance between plasma boundary and wall. Owing to their different origins the two types of forces tend not to peak at the same time. Both induced and halo currents create forces which tend to oppose plasma displacements.

Table I

Computed vertical forces and currents in divertor coils before and after the current quench of a 5 MA "SLIM" plasma

Coil	I(kA)		F_z(MN) (+ upwards)			
	Before	After	Before		After	
D1	15.6	37	-0.1	total	-2.5	total
D2	19.3	29	+0.8	+5.2	+0.8	+5.2
D3	26.7	40	+1.8		+2.1	
D4	28.6	53	+2.7		~0	

Fig.2c shows the evolution of the total vertical force at the vessel supports. In this pulse the vertical stabilisation was lost before the disruption. One recognises the presence of upward forces before the disruption caused by the divertor currents and of an additional transient upward force in the case of an upward VDE. The subsequent evolution of forces at the supports is due to magnetic forces acting on the divertor coils indicated by broken lines superimposed on the pulse dynamic response of the vessel indicated by a fundamental oscillation at ≈15 Hz. This mode is also apparent from the plot of the average difference of radial displacement of the upper and lower MVPs in an axisymmetric instability (fig. 3). It appears as a rolling/rocking motion excited by a twisting moment due to the fact that the resultant of the vertical forces, applied for a duration of the order of 10ms, is not in line with the reaction force at the MVP restraints (fig. 4).

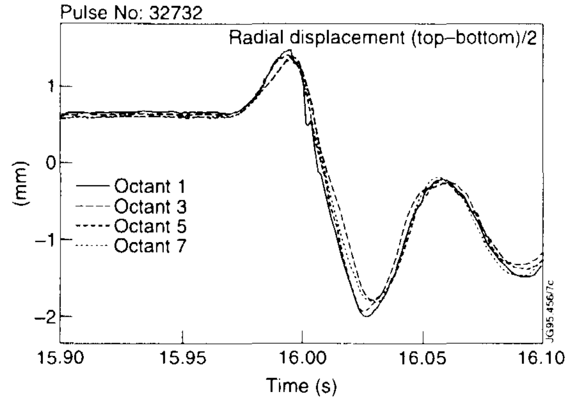

Fig. 3: Radial differential MVP (rolling motion) displacements caused by upward VDE of 3MA plasma

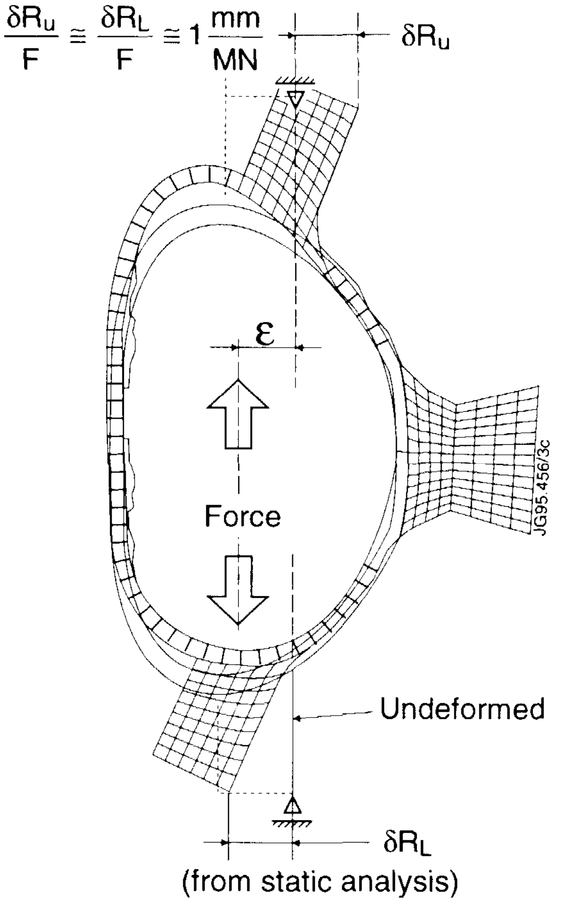

Fig. 4: "Rolling" motion

C. *Non-axisymmetric effects*

Fig. 2d presents the evolution of vertical support forces at opposite octants (2 and 6) for the upward VDE of pulse 34078. There are substantial differences of force amplitudes and of phases. One notes, in particular, that the peak force at octant 2 is accompanied by a minimum at the opposite octant 6. Similar behaviour is shown in other disruptions. Reasons for these asymmetries could be either the asymmetry of the vessel restraints such as the large neutral beam injector boxes at the horizontal ports of octants 4 and 8, or the asymmetry of the electromagnetic forces. However, since in various pulses it has been noticed that the distribution of the asymmetries varies, ie, the max. peak force does not always occur in the same octant as one would expect if the non-axisymmetric distribution of forces depended on mechanical asymmetries, one deduces that it is the distribution of magnetic forces which is non-axisymmetric, presumably because of non-symmetric induced or halo currents.

Fig. 2e shows the average radial movement of the top and bottom MVPs on the instrumented octants. Note that the ports on octant 5 move outwards and those on octant 1 move inwards with respect to the central axis of the machine. The movement of octants 3 and 7 are much smaller. From the vector sums of the average octant displacements it appears the whole vessel moved approx. 5.6mm in the direction between octants 5 and 6.

The MVP restraints have been mainly designed to resist vertical loads and they are free to move radially. They do not allow movement of the extremities of the ports in the toroidal direction; therefore they resist sideways movement of the vessel. The maximum resultant sideways reaction force amounting to 0.55 MN is reached at time 53.46 (corresponding to the time of the maximum sideways movement of the vessel). The natural frequency of the sideways movement appears from fig. 2e in the region of 3 Hz and is in good agreement with the figure that can be derived from the vector resultant of the toroidal stiffness of the MVPs and the global inertia of the vessel (~240t).

Considering this low natural frequency the horizontal electromagnetic force which is applied to the vessel for only 10-20ms must have been much greater than 0.55MN and can be estimated, using the dynamic response of the bulk of the vessel, in the region between 1 and 2MN.

The plasma configuration is an approximate lower current analogue of a prospective 5MA high performance plasma, exhibiting high flux expansion around the target area by using currents in all four divertor coils. The safety factor q95 is about 2.5. It is important to investigate whether large sideways vessel displacements are a feature of this configuration or if they occur also in VDEs of other plasmas.

In pulse 34078 the VDE was most probably caused by a fast rotating n=2 helical plasma mode (~5kHz) with large amplitude, which started 0.6s before the VDE after a giant sawtooth. The feedback signal is not compensated for pick-up of this mode. The mode therefore caused frequent switching of the Fast Radial Field Amplifier to maximum level (~10 kV) and premature disabling of some FRFA units, whereupon the vertical stabilisation deteriorated and was lost around 53.3s.

Fig. 2b shows the movement of the current centroid position derived at octants 3 and 7. Up to a vertical displacement of about 0.8m the agreement of signals from the two octants is very good, but from 53.42s, when the plasma is close to the vessel wall, the central centroid in octant 3 is about 0.1m higher than in octant 7. If we interpret this as a mode m-1, n-1, equivalent to a tilting of the plasma the resulting force acting on the plasma due to the interaction with the toroidal magnetic field would be about 1.1MN in the direction octant 1 ⟶5. Since each plasma element is in a quasi stationary equilibrium this force would have to be balanced by other toroidally asymmetric forces such as induced or halo current forces generated in the vessel which could explain the observed sideways movement.

It should be noted from fig.2e that the sideways movement of the vessel starts at the same time $t \approx 53.42$s as the departure of the vertical plasma position from toroidal symmetry. A detailed analysis shows that at this moment also the toroidal distribution of the vertical forces measured at opposite vertical ports (fig. 2d) starts to become non-uniform. A correlation between the horizontal force and the asymmetries of the plasma vertical position appears likely from the observation that in two disruptions exhibiting a reversal of the sideways motion 1 ⟶5 and 5 ⟶1) the difference between vertical forces at the octants 90° from the direction of motion (octants 3 and 7) is also reversing.

At present there is no direct measurement available of the total poloidal component of the halo current. Some indication of the halo current is obtained from mushroom tile currents (shunt measurements). These intercepted halo currents are generally very erratic and not toroidally uniform in all cases. However a particularly marked departure from axisymmetry is clear when the sideways forces are produced [10].

Sideways movements with significant amplitude (>1mm) have not been observed in downward VDEs up to now. This could be due to noticeably faster disappearance of the current, and hence the force, which might be ascribed to the lower time constant due to a tighter coupling between plasma and divertor coils.

III. STRUCTURAL CONSEQUENCES OF DISRUPTIONS

Disruptions, particularly when the plasma is in proximity of the vessel wall, may cause damage to in-vessel components. Asymmetric VDEs in particular give concern because they can cause higher local stresses due to the peak factor. Sideways movements may endanger the constraints of the vessel, most notably the connections to the Neutral Injectors which, due to their large masses, behave as fixed constraints. Modes higher than the fundamental (~14Hz) can be excited and an analysis is needed to quantify their effect.

A. *Analysis of stresses induced by sideways motions of the vessel*

The vessel is restrained in toroidal direction by the struts connected to the MVPs, and by the Neutral Injectors (NIs), through the rotary valve cases. Its F.E. model has been obtained by mirroring and rotating the existing half-octant model and includes 120,000 d.o.fs.

A load of 0.55MN, measured in pulse 34078 as a resultant of the load differences detected in adjacent legs, was applied to the inboard side of the model. The average static deflections and the natural frequency calculated were in reasonable agreement with the one measured as the resultant of the radial movements of the MVPs. The model, thus validated, indicates max. stresses at the root of the MVPs of approx. 92MPa, to which we have to add stresses due to axsymmetrical displacements.

The stresses at the MHP connections to the NIs are evaluated separately in two cases (fig. 5):

a) sideways motions parallel to the NI front flange
b) sideways motion normal to case a).

In case a) the clamps linking the rotary valve to the NIs and to the vessel behave as two elastic hinges, which give an elastic restoring force on each port of approx.

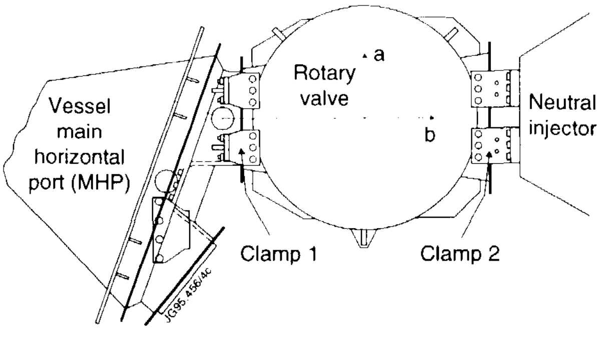

Fig. 5: Connection between MHP and Neutral Injector (plan view)

10kN/mm. This acts in parallel to the reaction from the restraints and gives negligible stress in the vessel structure for low frequencies.
In case b) the clamps are rigid and the forces derive from the inertial loads of the NIs (masses of ~80t free to move radially) and are limited only by the elasticity of the vessel port sector. F.E. analysis shows a max. stress of 140MPa for the max. vessel displacement seen. A full modal analysis is being done and new instrumentation will be installed during the present shutdown to detect radial and tangential motions of the MHPs to reveal any higher vibration modes which are potentially dangerous for peripheral parts such as windows.

B. *Analysis of stresses induced in divertor coils*

In an upward VDE of the worst configuration identified, 5MA SLIM plasma, the current in divertor coil no.4 may reach 53kA, due to the induction effect caused by the plasma current quench. This gives rise to centripetal forces and potential buckling particularly because of the large diameter of the coil. This effect has been studied in detail to establish the safety margin, considering errors of circularity as manufactured, the effect on their stiffness of their composite structure with copper and epoxy layers, and their response to the impulsive electromagnetic forces.

Since the contribution to deflection of the equivalent shear module was found to be negligible, the stiffness product E.I. can be safely assumed as that of the copper only. The coils are considered to have some initial ellipticity, assumed conservatively to be a radial deviation of 6mm. This is amplified by the impulsive load, a function of the dynamic response to this mode, and causes an impact on the tangential restraints which in the worst combination does not exceed 40MPa.

Thermal shear stresses in toroidal direction were evaluated and found to be below 10MPA, with max. differential temperature between adjacent turns of 20°C. They may be combined with a primary vertical shear stress of 10MPa.

C. *Stresses in TF coils*

Following disruptions at 6MA with FAT plasma the stresses in the TF coils have been recalculated with the prospective increase of B_{tor} to 4T at 78kA from the nominal 3.45T at 67kA. This was done with FE Abaqus code. The stresses are due to "in plane" loads, ie, tension and bending caused by D-shape errors, and "out of plane" loads, ie, torsion and transversal forces. The max. shear stress of 9.5MPa in operation is reduced to 6.7MPa at disruption, by the effect of induced current in the divertor. These occur at the centre of the cross section and are given by the vector sum of the in plane and out of plane shear stresses, in proximity of the inner cylinder grooves.

The side supporting teeth of the ring and collar of the mechanical structure were also a point of concern and have been re-evaluated. The max. side load acting on the teeth was calculated as 750kN, compared to the allowable value of 830kN.

D. *In-vessel components damaged during 1994-5 operations*

D1. *Saddle Coils (fig. 6)*

The saddle coils, installed during 1992-3 shutdown were designed to mitigate disruptions and control non-axisymmetric modes. The coils, when not yet operational, were temporarily short-circuited and grounded outside the vessel so as to limit internal induced voltages and the risk of breakdown. In September 1994 the upper saddle coils were found damaged. In octants 2,4,6 and 8 the L-shaped bars which are the transition between toroidal and poloidal sections had been distorted. Looking from the centre of the machine, the right hand busbars were bent towards the tokamak central axis and the left hand busbars were bent towards the plasma. The terminals of the crossover bars at the inner wall side were also bent and one of the ceramic insulating balls of the end support had been pushed out. From the damage it was assessed that a current of at least 14kA had passed through the conductor while the nominal operating value was 3kA.

Observed measurements of the induced current in the lower saddle coils at the plasma energy quench show large current spikes of 1-2ms duration in a direction consistent with the permanent deformations. Similar spikes are also seen in the induced voltages in the upper saddle coils reconstructed from magnetic measurements. These are however not quite large enough to explain quantitatively the effects seen, considering the dynamic amplification factors, unless they are attenuated for fast events or by electronic saturation. Halo currents and arcing may have contributed.

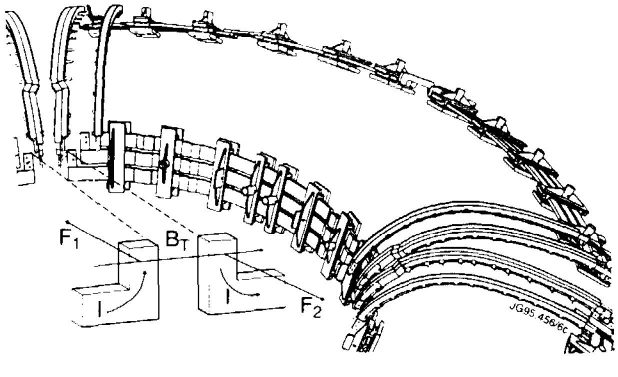

Fig. 6: Upper saddle coils (Partial view)

As a remedial action the upper saddle coils have been disabled and resistors have been placed in the crowbar circuits of the lower saddle coils to limit the induced current. The L-shaped bars in Inconel 600 have been replaced by stronger versions in Inconel 625 and the flexible links between toroidal and poloidal sections have been made stronger.

D2. Beryllium Evaporator Heads (fig. 7)
Four Be evaporator heads are inserted into the vacuum vessel for Be evaporation at the equatorial plane of octants, 1,3,5 and 7, using a pneumatic system and retracted during plasma operation. Previous to the divertor installation the Be heads were parked behind the inner vessel wall. For divertor operation the evaporation position of the Be heads was changed to give better coverage of the divertor. Consequently the retracted position was changed to about 400mm within the vacuum vessel, exposing the head to a larger poloidal field change.

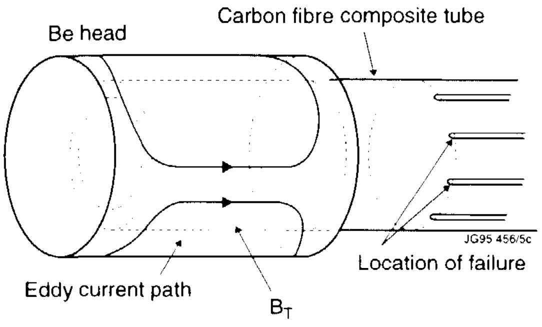

Fig. 7: Beryllium evaporater head

In November 1994 one of the evaporators broke and another was found severely damaged. The fracture location was at the end of some slots in the carbon fibre composite (CFC) tube which supports the Be head. The support cylinders of the damaged heads were made of an inferior grade CFC and had lower mechanical strength than the others. The damage is believed to have been caused during pulse 32275 by induced currents in the Be heads due to a poloidal field change in the region of 50T/s extrapolated from measurements on pickup coils on the vessel wall. The twisting moment caused by the interaction with the toroidal field is estimated at 400Nm, taking into consideration the magnetic damping and dynamic effects. Mechanical tests on the correct grade CFC tubes gave a failure twisting moment of 350Nm.

The weaker CFC tubes have been replaced and the retracted position of the Be heads is now behind the inner vessel wall. A modified version will be installed during the Mk II shutdown incorporating the following improvements: shorter slots, increased thickness of the CFC tube at the position where it failed and slots in the Be heads to reduce the induced current.

IV. CONCLUSIONS

Rather violent vertical disruptions have occurred during the latest series of operating campaigns with consequent damage to structural components. These events are particularly difficult to analyse when the plasma is in close proximity to the vessel wall. Sharp field variations at the boundary are difficult to measure and predict. Disruptive modes are frequently non-axisymmetric and understanding them presents many difficulties. More comprehensive and precise instrumentation with better signal to noise ratio is needed and efforts will be made in this direction during the present shutdown

With the divertor configurations in H-mode experimented in JET during recent operations with I_p ~3MA the peak factor, ie, the ratio between maximum and average vertical force per octant was up to 1.8 and the ratio between the max. horizontal force and max. vertical force attained values of around 0.5. However these data are only indicative and cannot be extrapolated to obtain design specifications at full current or in other configurations. Much more systematic and comprehensive testing and analysis are needed.

During disruptions the stresses in the vessel structure and coils were not particularly severe. A vessel survey showed no permanent deformations. It could be argued that the inherent flexibility of the vessel is not a drawback if it absorbs impulsive forces inertially and oscillations are limited by suitable damping.

The damage to in-vessel components has been analysed and remedial action taken. This consists of redesign of details and reinforcement, or where this is not possible issue of operating instructions which ensure the electromagnetic load is within acceptable limits. Components which protrude from the vessel wall in proximity of the plasma are inevitably at risk and are to be avoided.

Use of a smooth first wall and of a plasma configuration which is easy to stabilise appears a necessary strategy in view of a fusion reactor. The possibility of having non-axisymmetric disruption forces and net sideways forces at the torus of a fusion reactor suggests that a better understanding of such phenomena is needed to find ways of avoidance, or to foresee adequate safety margins for non-axisymmetric forces.

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