PRESENT UNDERSTANDING OF ELECTROMAGNETIC BEHAVIOUR DURING DISRUPTIONS IN JET

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Disruptions in JET cause generally vertical displacement events (VDEs) and vertical forces at the torus. In various disruptions large amplitude locked kink modes were observed which led to lateral displacements of the torus. The toroidal asymmetry of the plasma was investigated on the basis of magnetic measurements.

1. INTRODUCTION

The JET divertor configuration is up/down asymmetric. Large perturbations can cause VDEs due to saturation of the vertical stabilisation. The resulting vertical force can produce significant vessel displacements and stresses [1].

In many disruptions the vessel forces and displacements are toroidally non-uniform. Peaking factors (local/average) of the vertical support forces of up to 1.8 have been reported [2]. Of particular concern is the global sideways displacement of the torus observed in some disruptions. The largest one recorded so far was 5.6 mm in the VDE of pulse 34078 (3.5 MA). Previous damage at vacuum seals of valves between the torus and neutral beam injectors has been ascribed to such sideways movements. The mechanical aspects of asymmetric forces is discussed in [3]. The plasma asymmetry is the main subject of this paper.

2. GLOBAL VDE BEHAVIOUR

In the worst type of a VDE the plasma reaches a large displacement before the start of the current quench, for example about 1m in the pulse 34078. A simulation of this pulse with the MAXFEA code suggests that the main contribution to the vertical force is due to halo currents. PF coil and vessel eddy current forces are not sufficient to provide a force balance at the plasma. The measured poloidal halo current I_H is about 0.6 MA, derived from the top/bottom difference of the toroidal magnetic field. The halo current force is $F_H \approx I_H{\cdot}B_T{\cdot}w$, where w is the radial width of halo current recirculation in the torus. With $B_T = 2.7$ T and an estimated width in the range 1 to 1.5 m one expects $F_H \approx 2$ MN while the simulation gives $F_H \approx F_{total} \approx 3$ MN. The reaction force measured at the vertical ports is ≈ 1.8 MN. The consistency among these values is fair considering uncertainties of measurements, of estimates of w, and of simulations.

3. TOROIDAL ASYMMETRY

3.1 Example Pulse 38070

The upward VDE of this pulse (fig.1a) gave a vertical force of 1.5 MN at the vessel supports (fig.1b) with strong toroidal non-uniformity (fig.2) and led to a 5.5 mm sideways displacement of the torus in direction octant 5 ⇒ 1 (fig.1c).

The asymmetry of the halo is evident from the difference of the halo current evaluated from magnetic signals at opposite octants (fig.1d), and also from the toroidal distribution of halo currents measured directly from shunts at a subset of the array of mushroom tiles located at the upper outboard part of the torus. The mushroom tile currents exhibit large variations in amplitude and time. This suggests that the halo region is sweeping across the tiles with a non-uniform current density. The net asymmety can be seen from fig.3 which shows a strong peaking of time integrated currents around octant 6. The scaled current intercepted by all mushroom tiles is included in fig.1d. Initially these tiles appear to intercept the whole halo since all three signals shown are then about equal.

The toroidal asymmetry of the plasma is evident from the differences of the vertical and radial plasma current moments at opposite octants shown in fig.4.

These differences indicate a tilt of the plasma about a radial axis through octants 1 and 5 with amplitude

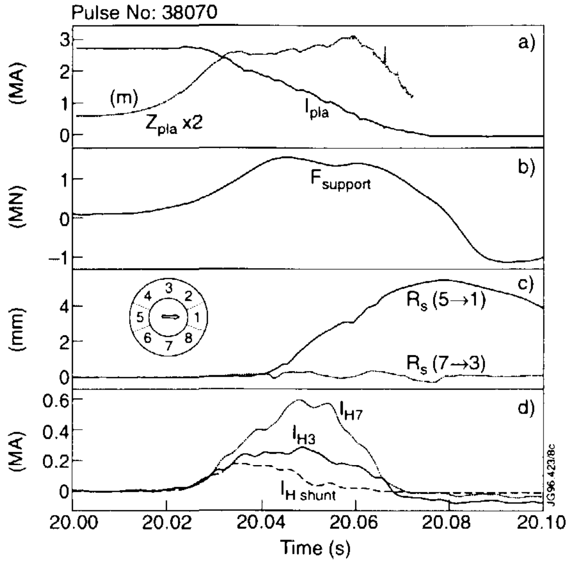

Fig.1: Experimental data for pulse 38070. R_S ⇒ torus sideways displacement in directions octant 5 ⇒ 1 and 7⇒ 3. I_H ⇒ halo current fromoctants 3,7. I_{Hshunt} ⇒ halo current scaled from mushroom tile currents.

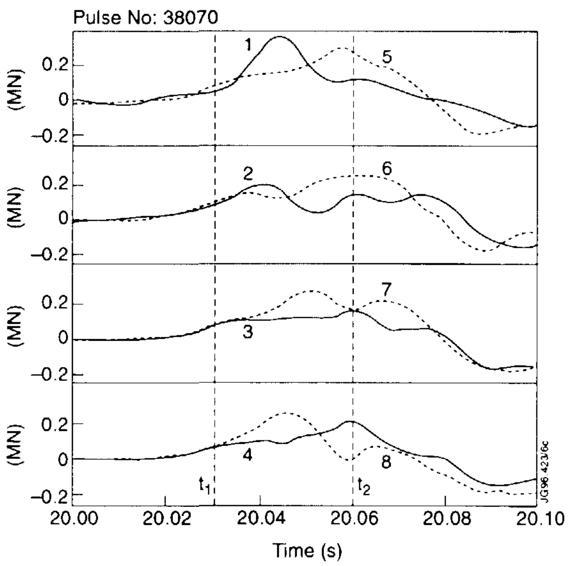

Fig.2: Increment of vessel vertical support forces at octants 1-8 caused by VDE of pulse 38070. t_1 - t_2 is the interval where the plasma current moments are asymmetric at opposite octants.

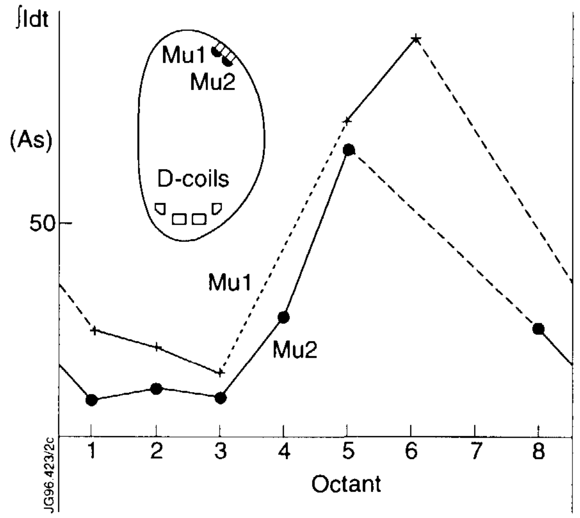

Fig.3: Toroidal distribution of integrated mushroom tile currents.

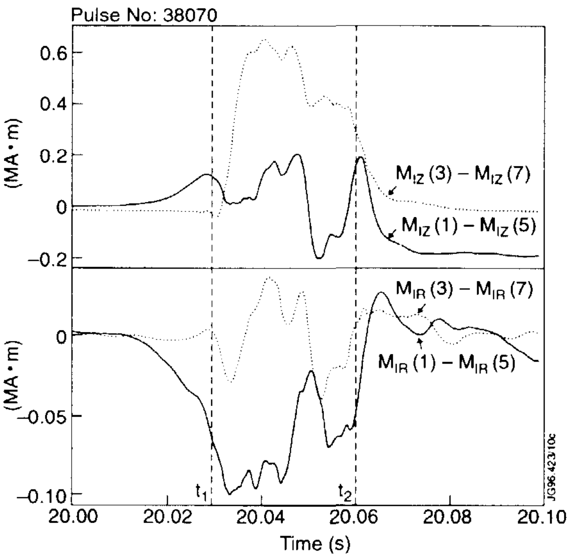

Fig.4: Differences of the vertical and radial plasma current moments between opposite octants.

δZmax ≈ ± 0.15m (at I_p ≈ 2 MA) and a small sideways shift of about 0.02 m along this axis in direction of octant 1. In octant 7 the plasma is closer to top of the vessel than in octant 3. The toroidal asymmetry of the halo current (fig.1d) and that of local halo currents flowing into the mushroom tiles (fig.3) is as expected from these plasma displacements. The toroidal asymmetry of vertical vessel support forces (fig.2) shows also a consistent correlation: force integrals are larger at octants 6,7,8 than at octants 2,3,4. In this and in a number of other pulses, the plasma mode was locked in one position so that torus displacements could escalate. In other VDEs with asymmetric plasma behaviour the mode appeared to move so that inertia prevented larger sideways torus displacements.

3.2 Simplified Model

The plasma is taken as a current ring tilted about a radial axis by an angle $\Delta Z/R$ and shifted along this axis by ΔR as indicated by current moment measurements, where ΔZ, ΔR are plasma displacement amplitudes from a ring with radius R. The displacement is rigid, the displacement vector projected on a poloidal plane describes an ellipse. A pure m=1/n=1 kink mode would correspond to $\Delta Z = \Delta R$. The destabilising forces acting on the ring may be decomposed into those arising from the toroidal field B_T and from the gradient $\partial B_R/\partial z = \partial B_Z/\partial R$ of the equilibrium field. They must be balanced locally and globally by asymmetric repelling eddy and halo current forces between the plasma and the torus. The observed asymmetry of halo currents suggests that it plays a major role in the force balance. The model gives the global force F_X along the tilt axis, the tilt moment M_X and, included here for comparison, the global vertical destabilising force F_Z at the plasma:

$$F_X = (\pi/2)\cdot[-\Delta M_{IZ} B_T + \Delta M_{IR} R(\partial B_Z/\partial R)] \quad (1)$$
$$\approx (+2.4 - 0.03)\ \text{MN} \quad \approx +2.4\ \text{MN}$$

$$M_X = (\pi R/2)\cdot[-\Delta M_{IR} B_T - \Delta M_{IZ} R(\partial B_R/\partial z) \quad (2)$$
$$\approx (-1.0 - 0.6)\ \text{MN·m} \approx -1.6\ \text{MN·m}$$

$$F_Z = 2\pi R\cdot I_p\cdot(Z_p - Z_{po})\cdot(\partial B_R/\partial z) \approx +3.4\ \text{M} \quad (3)$$

Values, taken from fig.4 and averaged over 30ms, are: $\Delta M_{IZ} \approx 0.5$ MA·m, $\Delta M_{IR} \approx -0.08$ MA·m. Furthermore $B_T = -3$T at R = 2.7 m, and the estimated field gradient required for the original plasma shape is about + 0.1 T/m. The estimated horizontal impulse (2.4MN)·(30ms) is consistent with the dynamic behaviour of the vessel [3], characterised by a measured torus displacement of 5.5 mm , a reaction force at the vessel supports of 0.6 MN, and an observed almost critical damping. The estimated tilt moment acting on the torus is also in rough agreement with the reaction moment implied by the asymmetry of vertical support forces (fig.2).

3.3 Conditions for Torus Sideways Displacement

It can be expected that large displacements are only possible when

(a) the plasma displacement is large before the current quench,
(b) the plasma boundary q-value decreases to about one, to permit kink instability
(c) the mode is locked, not shifting phase or rotating as in Alcator C-mod [4].

The expected relation of sideways displacements with the minimum boundary q-value is shown in fig.5 using $q^* = 5B_T a^2/I_p R_I$ as an approximation. Larger displacements are only seen when $q^* \leq 1.3$. However, low q* does not always give a large displacement as indicated in fig.5. This may be partly due to changes of the toroidal position of the kink mode giving changes in direction of the force at the torus, and also to the fact that the mode amplitude often remained small.

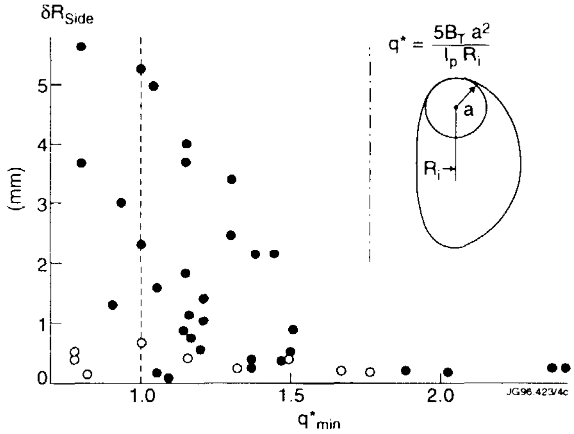

Fig.5: Statistics of sideways torus displacements plotted versus minimum q. Open circles are downward VDEs.*

3.4 Role of Plasma Configuration and In-Vessel Structures

The fig. 6 shows that sideways displacements are small when the initial triangularity is high. An inspection of displaced plasma shapes indicates that large sideways displacements can result when the plasma touches simultaneously structures at some poloidal distance in the upper part of the vessel, such as saddle coil sections, mushroom tiles and the upper dump plate. It appears that the shaping field applied for high triangularity reduces the poloidal extension of the attachment.

It is also suspected that the discreteness of the plasma facing structures in the upper part of the torus encourages a non-uniform development of halo currents intercepting these elements. A toroidal non-uniformity of the halo region could enhance the escalation of the kink mode.

Downward VDEs never produced sideways displacements of the torus exceeding 1 mm, even in cases where the conditions (a) and (b) mentioned above are well satisfied. In all downward VDEs and during the critical phase of high current the plasma/wall contact is poloidally localised at the top of the outer divertor target. This supports the hypothesis that a large poloidal extent of plasma/wall contact is a condition for the generation of a large sideways impulse at the torus.

In the search for causes of sideways displacements it was also noted that upward VDEs with high beta prior to the VDE gave smaller displacements than VDEs with low initial beta, as illustrated in fig.7. With high beta the impurity influx and the speed of current quench are found to be enhanced. The absence of larger sideways displacements may be partly attributed to the relative short duration of the current quench and consequently of large plasma asymmetries.

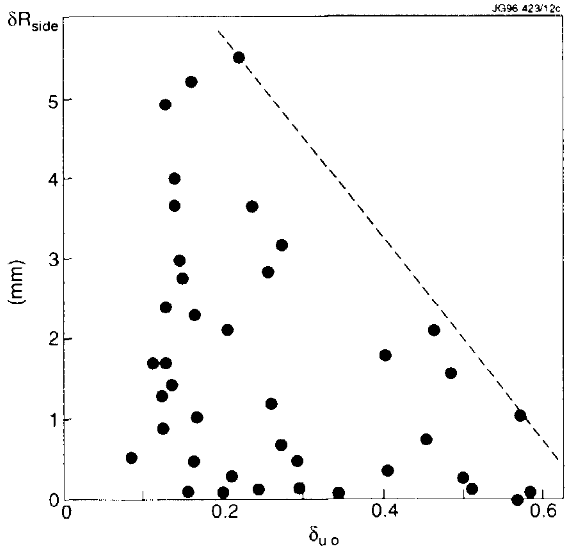

Fig.6: Sideways torus shifts in upward VDEs plotted versus initial upper triangularity δ_{uo}

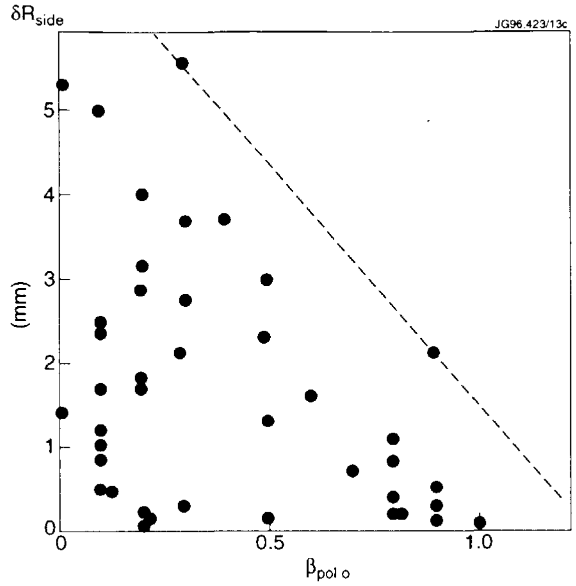

Fig.7: Sideways torus displacements in upward VDEs plotted versus initial poloidal beta.

4. CONCLUSIONS

- A large sideways force at the torus in one direction can occur in VDEs with large vertical plasma displacement at large current. It is caused by a locked m=1/n=1 kink mode which can arise when the plasma boundary q-value becomes ≈ 1.
- It is suspected that the choice of a first wall shape giving only a relatively small poloidal extent of plasma contact during VDEs would reduce the danger of creating sideways displacements of the torus.
- Neither are large asymmetric forces expected when the current decreases before the vertical plasma displacement becomes large. In JET this cannot be enforced.

References

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