32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-2.073 (2005)

Free Boundary Simulations of ITER Discharges

N. Humphry-Baker, M. Windridge, J.B. Lister, V.N. Dokuka[1], R.R. Khayrutdinov[1], S.H. Kim, V.E. Lukash[2]

Centre de Recherches en Physique des Plasmas,

Association EURATOM-Confédération Suisse, EPFL, 1015 Lausanne, Switzerland

[1]TRINITI, Moscow Region, Russia

[2]RRC Kurchatov, Moscow, Russia

Introduction We use the DINA-CH free-boundary equilibrium evolution code to explore the effect of different Poloidal Field (PF) control strategies during a plasma VDE in ITER, which requires integrated modelling of the vacuum vessel, PF coils and control system, with flux and energy transport. The importance of choosing correct coil voltage strategies was verified in early TCV discharges, in which the acoustic footprint of a Vertical Displacement Event (VDE) varied according to the way in which the feedback behaved during the disruption.

During a strong plasma disturbance, the plasma position and shape change suddenly and require strong feedback to bring the equilibrium back to its nominal configuration. During this time, the plasma movement and the PF coil voltages induce changes in the vessel current and changes to the PF pattern. The PF crossed with the toroidal vessel current produces a poloidally structured force distribution in the vacuum vessel as well as total radial and vertical forces. Given adequate power supply voltages, the plasma position can be restored. If the power supply voltages saturate, then control can be lost and the plasma position is never recovered, leading to a VDE which usually terminates when q=1 at the plasma boundary.

We first derive the local forces on the vacuum vessel and inspect their origins. We then determine whether the PF coil control strategy makes a significant difference in ITER at all, and we find that it does, confirming the TCV result. We restrict our analysis to a rapid loss of plasma energy in a thermal quench and use an approximate plasma transport model, assuming that the electromagnetic response should not depend on detailed energy transport.

Calculation and properties of the forces To determine suitable control strategies to reduce induced $\vec{J}\times\vec{B}$ forces on the vacuum vessel we examine the sources of the forces and their relative importance. The vessel and passive stabilisers are modelled in DINA-CH as 131 filaments; the plasma current is modelled on a 65x33 grid structure; there are 11 PF coils; the result is a system of 2287 current filaments embedded in the PF generated by the currents themselves. We consider the local fields at each filament $B_j^* = \mathrm{sum}(G_{ij}^* I_i)$ where G_{ij}^* is the Green's function. The vertical force on each filament is then $F_j^z = 2\pi R_j B_j I_j$ where R_j is the filament radius. Evaluating the forces for each filament as a function of time we isolated the contributions to the forces on the vessel from the PF coils and the plasma current separately. Fields due to currents in the vessel also give rise to local $\vec{J} \times \vec{B}$ forces in the vessel itself, however the total vertical force was verified to be zero.

The overall forces near the end of a VDE (Fig.1 left) were analysed in terms of their origins. Writing the force as a combination of the initial values before the event, B_0 and I_0, and the change in these quantities during the event, δB and δI, yields $F_z = 2\pi R\,(B_0 + \delta B)(I_0 + \delta I)$ and the force can therefore be split into four components (B is now the radial field):

$$F_{z_{00}} = 2\pi R(B_0 I_0) \qquad F_{z_{10}} = 2\pi R(\delta B I_0) \qquad F_{z_{01}} = 2\pi R(B_0 \delta I) \qquad F_{z_{11}} = 2\pi R(\delta B \delta I)$$

The first two are negligible, since the vessel current is negligible before a disturbance. Figure 1 shows the third and fourth contributions which are of similar magnitude. Since δB is generated by the control system during the VDE, it is already clear that the control system has a large impact on the final force.

The forces on the PF coils by the plasma, the vessel and the other PF coils were calculated, but the dynamic forces were very small compared with the pre-existing static forces, as expected.

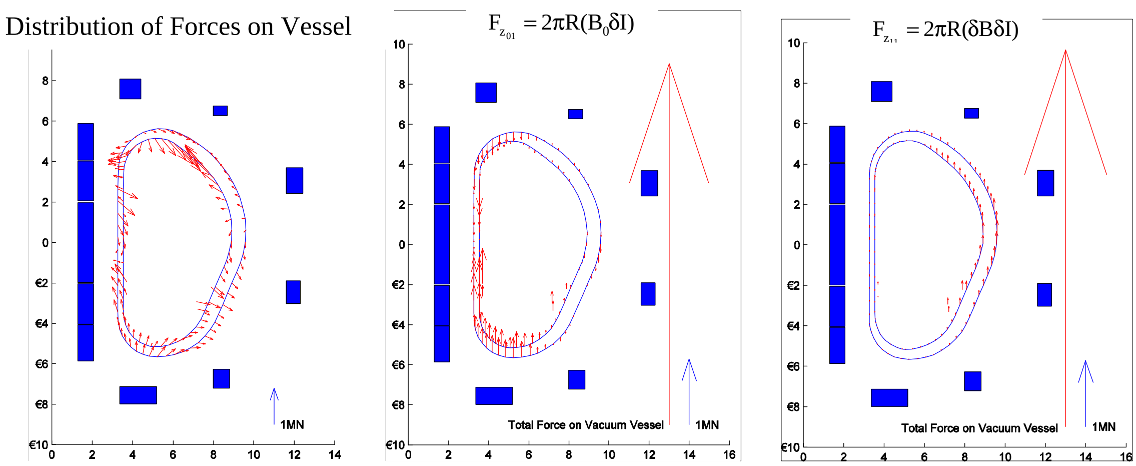

Fig.1 *left) the total forces towards the end of the VDE; centre) the forces due to B_0 ; right) the forces due to δB. The vertical arrow is the total vertical force.*

Knowing the force distribution facilitates the implementation of control strategies targeting certain areas, by imposing "slow" shaping voltages on the closest PF coils to a given part of the vessel to change the local magnetic field and thereby modify the local forces.

Test of different strategies The forces on the vessel were evaluated for four strengths of thermal quench:

- very slow cooling (>10'000 ms), with no loss of control,
- a slow thermal quench (~1'100 ms), with a small vertical disturbance and no loss of control,
- a medium thermal quench (~350 ms), with a large vertical disturbance and loss of control,
- a very fast thermal quench (~80 ms), also lost by the controller.

The loss of β_p was obtained by locally removing energy from the plasma as n^2T^2, varying the gain to obtain the different thermal quench strengths. In the first PF strategy, the controller worked normally for the full simulation. In the second strategy, the fast vertical feedback and the slow shape feedback were cut when the thermal quenches began. The third and fourth strategies positively or negatively saturated the fast vertical feedback shortly after the thermal quenches had started, with the slow shape feedback still working. We thereby obtained 16 different simulations from which to study the effect of the controller on the vessel forces. Figure 2 shows the forces for the fastest quench for the four strategies.

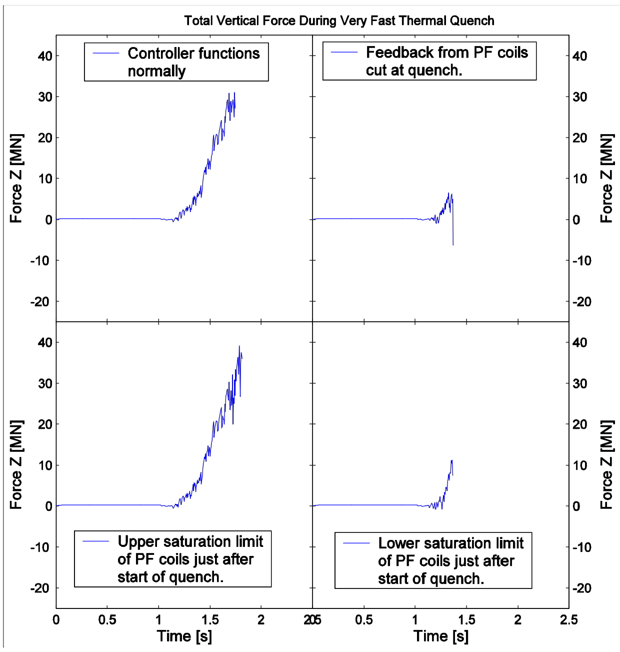

Fig.2 *Forces for the four PF control strategies*

The estimates of the total vertical forces were noisy once the VDE had started. The plasma current distribution was also very noisy, as well as the passive currents in the vacuum vessel. We believe that the noise originates from the plasma current distribution evolution as the passive currents have a more structured form than that of the plasma currents.

The first observation is that changing the control has a large effect on the vertical force either by reducing it (sometimes ten-fold) or increasing it. The smallest forces occur when the controller is able to keep hold of the plasma, since there is no or very little plasma movement in these simulations, thus no currents are induced in the vacuum vessel. The forces remain under 1MN. In the simulations resulting in a VDE, the forces are much greater, the largest one reaching 40MN. The medium thermal quench produces a larger force than the very fast thermal quench because the plasma current induces larger currents in the vessel. The PF coils also induce currents in the vessel, increasing the force. In the second strategy the VDE is an upward movement, except for the slow cooling simulation type. The fast quench has the least force because it is the shortest VDE, therefore the induced currents and fields cannot increase to large values. The no disturbance plasma vessel force becomes negative because the plasma is driven to the bottom of the vacuum vessel, inducing currents in the opposite direction. Most of the forces in the third strategy are negative because the voltages applied to the positioning coils push the plasma towards the bottom of the vessel. Depending on the direction of the currents induced in the vessel, the forces due to the PF coil currents on the vessel can cancel out the forces due to the plasma current. The negatively saturated coils in the fourth strategy project the plasma upward. Because of this, the plasmas in the medium and very fast thermal quenches disrupt rapidly, thus their forces are not great. Whereas, for the other two quench rates, the VDE is slower, allowing the forces to grow.

It is clear that if the controller is able to control the plasma working as normal then it is best to leave it as such. But once a VDE becomes inevitable, then modifying the controller has positive effects on the peak forces.

Action of the “slow” shaping coils The PF voltages on the coils which are not driven by the fast supply were individually positively and negatively saturated as we did for the fast coils. The forces were locally reduced or inverted for most of the coil saturations, although it is not necessarily the forces on the filaments closest to the saturated coil, which are modified. This implies we must develop a fully-coupled model to find the optimal strategy.

Discussion We have demonstrated that during the VDE associated with a thermal quench, the vessel forces are strongly dependent on the PF voltage strategy. Cutting the feedback voltage immediately reduces the forces and offers a realistic option in the case of supply malfunction. Even if the maximum design forces have to be handled, the number of events corresponding to this design criterion should be significantly reduced. Given normal PF supply functioning, we have shown that the shaping supplies must also be controlled during the VDE and that the forces can be kept very low compared with the worst case assumptions of 90MN during a VDE disruption. This work will be extended to the current quench to confirm that these conclusions are not simply valid during the thermal quench.

This work was partly supported by the Fonds National Suisse de la Recherche Scientifique.