Parametric dependence analysis of disruption forces in tokamaks

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1. Introduction

Disruptions are among the fundamental issues to be tackled in future tokamaks [1]. With rapid transfer of the magnetic energy, they generate significant (eddy and halo) currents in the conducting structures. Interaction of these currents with the strong magnetic field present in the tokamaks is expected to produce substantial electromagnetic forces and torques, which might challenge even the integrity of the device elements. Consequently, theoretical and experimental studies on disruption modelling, prediction, avoidance and mitigation are currently in progress. In this paper, we investigate the dependence of the disruption-induced global electromagnetic forces on various parameters (resistive wall time, plasma current quench time, vertical instability growth rate and stability margin). This is a highly debatable area with contradictory indications and huge scatter of the results [2-5].

The paper is organized as follows. Section 2 illustrates briefly the modelling tool used in the present paper, while Sections 3 and 4 presents some results. Finally, Section 5 draws the conclusions.

2. Modelling tool

The modelling tool that we use is the CarMa0NL code [6], solving evolutionary axisymmetric equilibrium equations in the plasma, coupled to 3D volumetric conductors described by the eddy currents equations. This code is used here to provide predictions for ITER-relevant geometry and range of parameters, since it has been recently proven adequate to such studies [7]. Indeed, the CarMa0NL results have been found consistent with the counterintuitive, but theoretically founded property [8] that the total global electromagnetic force acting on a perfect conductor circumventing the toroidal plasma must be zero, neglecting plasma inertia. The simulations in [7] has reproduced this property despite circulation of significant total current in such ideal wall (up to several MA in ITER) and strong local electromagnetic force density. Moreover, the results obtained suggested the proposal of an electromagnetic disruption force damper [7], able to “drain” global force from the conducting wall.

3. Force dependence on the current quench time

An ITER 15 MA equilibrium configuration is considered, surrounded by a simplified version of the structures (only the inner shell of the vessel, with nominal resistivity). The Thermal Quench (TQ) is simulated as an instantaneous drop of β_p from nominal value to 0. The Current Quench (CQ) is supposed to be exponential in time, with a toroidal plasma current evolving as $I_p = I_{p0}\exp(-t/\tau_{CQ})$, with I_{p0} = 15 MA and for various values of τ_{CQ}. The plasma evolution is computed until convergence achieved on the Grad-Shafranov solution; the plasma current is forced instantaneously to zero after the last converged configuration.

The event is triggered by the TQ, which is the same in all cases. The subsequent plasma trajectory depends on τ_{CQ}: in the limit $\tau_{CQ} \to 0$ it is determined by the plasma current decay, while in the limit $\tau_{CQ} \to +\infty$ it is determined by a pure Vertical Displacement Event (VDE) triggered by the TQ at constant plasma current. Consequently, the current density pattern in the structures (with fixed parameters) is different in the two limiting cases.

The global vertical force F_z (Fig. 1) is computed as the volume integral over the wall of the electromagnetic force density **J** x **B**. During the CQ, for $\tau_{CQ} \to 0$, the wall reacts as a perfect conductor, so that the global force on the wall approaches zero, as predicted in [7-8]. Conversely, the global force increases for increasing τ_{CQ}, approaching a maximum for $\tau_{CQ} \to +\infty$. In this limit, there is no variation of the plasma current; the force is only due to the VDE triggered by the TQ. It is interesting to note that vertical displacement of the plasma of comparable amplitude produce completely different global forces acting on the structure, due to substantially different current density patterns induced in the structures.

After the end of the CQ, the transient is purely electromagnetic: the current density in the wall decays due to wall resistivity.

4. Force dependence on resistive wall time

Six different walls are considered, all with the same geometry of the ITER inner shell, but at increasing minor radius, hence with an increasing distance from the plasma. The VDE is triggered by a beta drop of identical amplitude in all cases; the plasma current is held constant. The growth rate has been computed with a linearized version of the CarMa0NL code around the initial configuration; the product $\gamma\tau_w$ is related to the stability margin m_s [9].

The plasma evolution has been computed until the plasma hits the wall; after that, the plasma current is brought instantaneously to zero. The plasma trajectory in the poloidal plane is very similar in all cases; the only difference is in the time scale of the evolution. The final plasma configuration, when the plasma hits the wall, is very similar, but the current density pattern is appreciably different, due to the substantial difference in the time scale.

The global vertical force has a similar qualitative behaviour in all cases (Fig. 2). During the VDE, the force increases exponentially, then it experiences a sharp transition to negative values after the plasma current is forced to zero from the nominal value of 15 MA. Quantitatively, the maximum (positive) value of the force F_{zmax}, experienced at the end of the VDE, depends significantly over the quantity $\gamma\tau_w$, i.e. over the stability margin m_s. The dependence of the maximum force on $\gamma\tau_w$ is monotonically decreasing in the range explored (Table 1). This result is consistent with the predictions of [3] in the limit $\gamma\tau_w \rightarrow +\infty$, while it does not show the trend [3] $F_{zmax} \rightarrow 0$ for $\gamma\tau_w \rightarrow 0$. A possible explanation is that the maximum in F_{zmax} is attained at an even lower value of $\gamma\tau_w$ than that obtained in our study.

Conversely, the minimum (negative) value of the force is practically the same in all cases; it depends mainly on the purely electromagnetic transient occurring when the plasma current is forced to zero from the nominal value of 15 MA. The current in the wall decreases according to the wall time constant, regardless of what happened before the quench itself.

5. Conclusions

A thorough analysis of the dependence of global forces acting on conducting structures following a disruption has been carried out with CarMa0NL code. The results confirm theoretical expectations that indeed the maximum value of this force depends both on the time scale of the CQ (for fixed structures) and on the product $\gamma\tau_w$ (or equivalently on the stability margin). Further studies will be addressed at extending the range of validations and at including halo currents in the analysis.

References

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Case	Displacement	τ_w [s]	γ [s^{-1}]	$\gamma\tau_w$	$1/m_s$	m_s	F_{zmax} [MN]
01	-40cm	0.149	5.616	0.837	0.725	1.380	5.38
02	-20cm	0.152	7.259	1.103	0.961	1.041	4.76
03	0cm	0.155	9.725	1.507	1.318	0.759	3.95
04	+20cm	0.159	13.813	2.196	1.912	0.523	3.29
05	+40cm	0.162	21.851	3.540	3.077	0.325	2.24
06	+60cm	0.168	44.600	7.493	6.369	0.157	1.16

Table. 1. Dependence of the global vertical force on stability margin

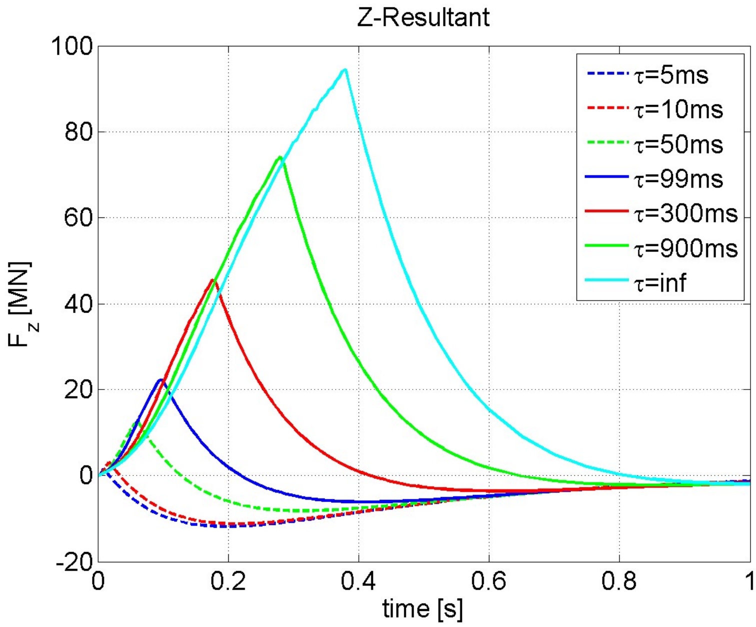

Fig. 1. Time dependence of the global vertical force for various values of τ_{CQ} time

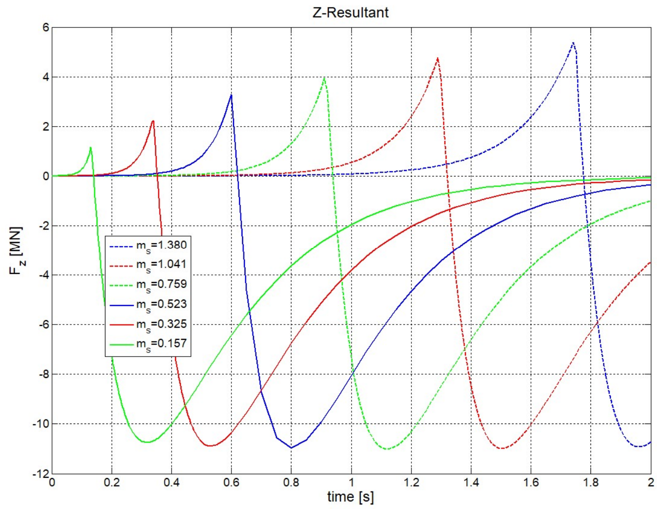

Fig. 2. Time dependence of the global vertical force for various values of stability margin