Theoretical and numerical studies on electromagnetic disruption forces

V. D. Pustovitov[1], G. Rubinacci[2], F.Villone[3]

[1] *National Research Centre Kurchatov Institute, pl. Kurchatova 1, Moscow 123182, Russia*

[2] *CREATE, DIETI, Università degli Studi Federico II di Napoli, Italy*

[3] *CREATE, DIEI, Università degli Studi di Cassino e del Lazio Meridionale, Italy*

Introduction

Disruptions are a key problem for future tokamaks like ITER [1], because the accompanying electromagnetic forces may be a threat even for the integrity of devices. These forces are due to the interaction of eddy and halo currents induced in the structures during a disruption and the strong magnetic field present in the tokamak. This paper summarizes recent results of our theoretical and numerical studies on this subject.

The starting point of our analysis is one of the findings of [2]: the total global electromagnetic force acting on a perfect conductor circumventing the toroidal plasma must be zero, if we disregard the plasma inertia (i.e. describe the plasma by equilibrium equation at each time instant during a disruption). Since a significant total disruption-induced current can circulate in such perfect conductors (up to several MA in ITER), a strong local electromagnetic force density occurs; however, these local forces must sum up to zero, so that the overall global force vanishes. This paper derives a number of important consequences of this general result. First of all, we verify the aforementioned theoretical finding with simulations carried out with the CarMa0NL code [3]. Secondly, we show that the arising of a net force on the vacuum vessel is due exclusively to the penetration of magnetic field outside the vessel itself. Then, we confirm that a representation of the plasma in terms of simple current filaments may be completely inadequate to determine the total force on the vessel, because a description compliant with the equilibrium constraint is required. Finally, the results obtained suggest a possible scheme for mitigating the global force acting on the vessel during a disruption, resorting to a highly conducting "disruption force damper" (DFD) circumventing the vessel.

Formulation

The force on the wall $\mathbf{F}_w$ during a disruption can be computed as [2]:

$$\mathbf{u}\cdot\mathbf{F}_w = \frac{1}{\mu_0}\oint_{wall+}\left\{(\mathbf{B}\cdot\mathbf{u})\mathbf{B} - \frac{\mathbf{B}^2}{2}\mathbf{u}\right\}\cdot d\mathbf{S} - \mathbf{u}\cdot\mathbf{F}_p\,, \qquad (1)$$

where $\mathbf{u}$ is any constant vector, $\mathbf{F}_p$ is the net force on the plasma and $wall+$ is any surface enclosing the wall, such that poloidal and toroidal field coils remain outside. When $\mathbf{u}=\mathbf{e}_z$ is a unit vector along the vertical axis, this is the vertical force F_z. Before the disruption, when $\mathbf{B}=\mathbf{B}_0$ and $\mathbf{j}=0$ in the wall, we have $\mathbf{F}_w=0$. It follows from (1) that large $\mathbf{F}_w$ can appear when $\delta\mathbf{B}\equiv\mathbf{B}-\mathbf{B}_0$ at the outer side of the wall is large enough. For a given plasma evolution during the disruption, the amplitude of $\delta\mathbf{B}$ on the outer side of the wall will depend on the wall resistivity. In particular, if the wall is perfectly conducting, so that $\delta\mathbf{B}=0$ behind the wall, (1) states that the integral force on the wall must be equal and oppositely directed to the force on the plasma: $\mathbf{F}_w=-\mathbf{F}_p$. The latter is always very small in tokamaks [2], since the plasma motions during disruptions are slow with respect to Alfvén time.

This theoretical finding is verified numerically with the aid of the CarMa0NL code [3], which solves evolutionary equilibrium equations inside the plasma, coupled to eddy currents model in surrounding 3D volumetric conductors. The electromagnetic interaction between the plasma and the conductors is decoupled via a suitable surface *S* in the plasma-wall vacuum gap; this way, the most suitable formulation can be used in each of the two regions.

Inside *S*, MHD force balance equation is solved, precisely supposing that the plasma mass can be neglected. Consequently, the plasma evolves instantaneously (i.e. with no inertia) through equilibrium states – the so-called evolutionary equilibrium approach. This is fully coherent with the aforementioned assumption of negligible $\mathbf{F}_p$ in the plasma and hence the code can be used to verify the expectation of $\mathbf{F}_w=0$ on a perfectly conducting wall.

Outside *S*, we use an integral formulation, assuming as primary unknown the current density in the wall; no thin-wall approximation is made. The solenoidality of the current density is guaranteed by using the electric vector potential, represented in terms of edge elements. The Ohm's law in the wall is imposed in weak form, expressing the electric field in terms of the magnetic vector potential and of the scalar electric potential through Biot-Savart integral. The effect of plasma currents on the 3D conductors is taken into account with an equivalent surface current on *S*, producing the same magnetic field as the plasma outside *S*, plus the toroidal flux variation due to the plasma evolution. Once the current density in the wall is found, the force is computed by numerically carrying out the integral $\mathbf{F}_w\equiv\int_{wall}\mathbf{j}\times\mathbf{B}dV$.

Results

We perform calculations for a tokamak with ITER parameters (Fig. 1), for a configuration with a plasma current of 15 MA. To stress the basic phenomenology, only the inner shell of the vessel is considered as conducting wall around the plasma.

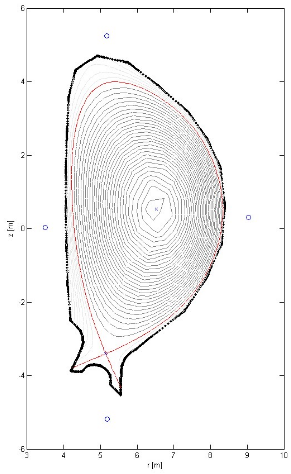

Fig. 1. Reference plasma configuration

A Major Disruption event is analyzed. The plasma pressure (quantified here by the poloidal beta β_P) drops instantaneously to a very low value (Thermal Quench, TQ). After that, the toroidal plasma current starts to decrease (Current Quench, CQ) linearly in time, reaching zero in 36 ms – in fact, it is forced abruptly to zero at the instant when halo currents start to contribute to equilibrium configuration, because these are not included in the present simulation. The plasma reacts to these perturbations with an upward Vertical Displacement Event (VDE).

We consider four values of the vessel resistivity: the nominal one (η_0 = 8E-7 Ωm), two values 10 and 100 times smaller and one value 10 times larger; for each, the plasma evolution is simulated with CarMa0NL and the corresponding global vertical force on the vessel is computed. The results in Fig. 2 show that, at smaller wall resistivity, the diffusion of the magnetic perturbation through the wall becomes weaker and maximum of the global force on the wall gets decreases, coherently with theoretical expectations. Conversely, the force starts to increase only when the magnetic field better penetrates outside the vessel.

Figure 2 reports a rather counterintuitive result: for a perfectly conducting wall, the current induced in the vessel may be higher than in other cases, but the global force acting on the vessel nevertheless approaches zero. This happens because high local force densities sum up to zero in the case of perfectly conducting wall, while this does not happen in other cases.

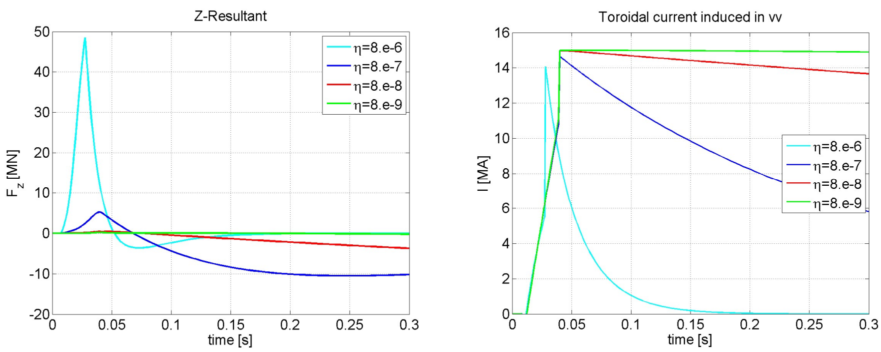

Fig. 2. Total current induced in the wall and global vertical force on the wall

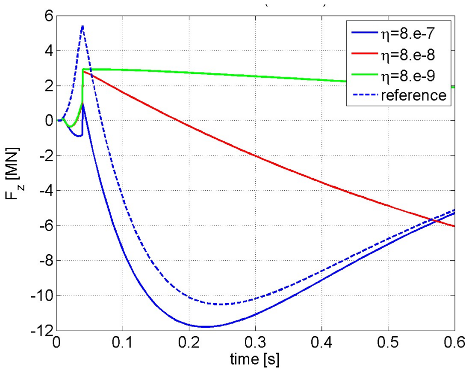

Fig. 3. Force on the wall for a filamentary plasma

These results confirm, in particular, that the CarMa0NL code correctly recovers the integral condition $\mathbf{F}_p = \mathbf{0}$ on the plasma. Conversely, if a simplified description of the plasma is used without balancing of the forces, this might not be true anymore. A particularly significant example is the widely used approximation of a plasma as a set of current-carrying filaments. If the constraint of zero total force acting on the full set of such filaments is not imposed, the calculated force on the perfect wall must be wrong of the same amount. To demonstrate this, we consider the case of one fixed toroidal filament placed in the centroid of the initial plasma configuration, carrying a time-varying current exactly equal to the one of the disruptive plasma described above. The results are reported in Fig. 3: in the case of perfectly conducting vessel, the force after the current quench is not zero as with a plasma in equilibrium, but is equal to about 3 MN; this is exactly the force acting on the filament, which is not in equilibrium.

Using the same reasoning as above, if one circumvents the vessel with a perfectly conducting shell (Disruption Force Damper, DFD), we can predict that the sum of the global forces on the vessel and on the DFD is zero. Moreover, thanks to magnetic coupling, the DFD "drains" most of the current initially flowing in the vessel, as soon as the magnetic field penetrates through the vessel, because it has a much smaller resistivity. The overall expected effect is a "transfer" of net force from the vessel to the DFD, which can save the vessel from damage, possibly even "sacrificing" the DFD in case of violent disruptions (Fig. 4) [4].

[1] Hender T et al, *Nucl. Fusion* **47** (2007) S128

[2] Pustovitov V D, *Nucl. Fusion* **55** (2015) 1130302

[3] Villone F et al., *Plasma Phys. Control. Fusion* **55** (2013) 09500

[4] Pustovitov V D , Rubinacci G, Villone F, submitted for publication

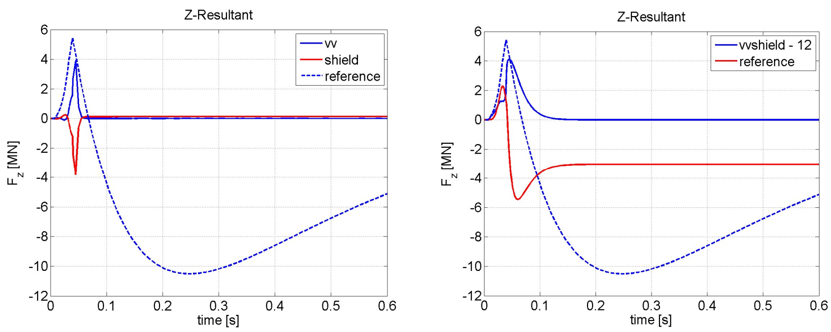

Fig. 4. Force on wall and DFD for a continuous (left) and a filamentary (right) DFD