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Analytical approach to calculation of disruption-induced vertical force on the tokamak wall

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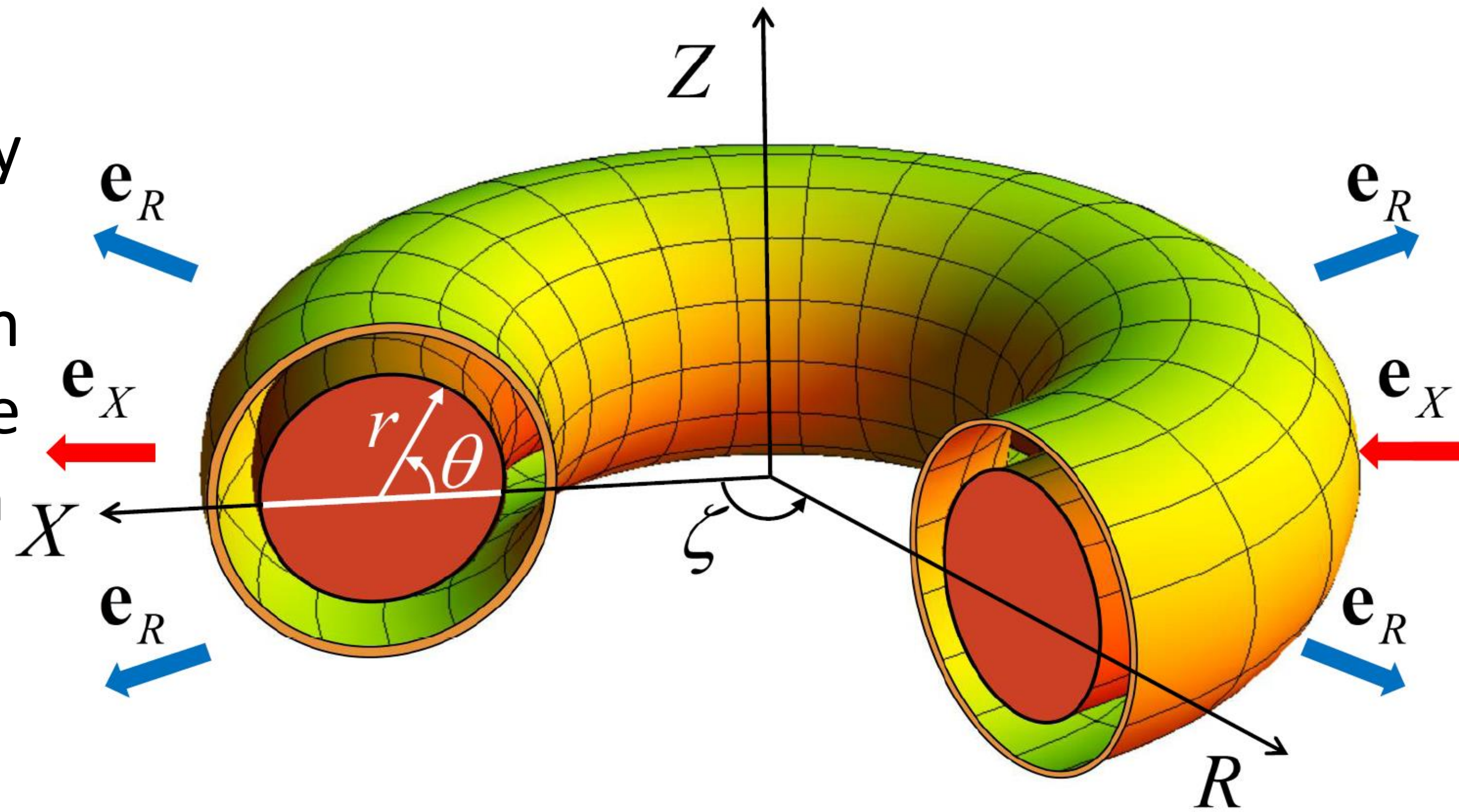
Abstract. Integral vertical disruption force acting on the tokamak vacuum vessel wall is analytically calculated starting from the Maxwell equations and the Ohm's law for the wall. It is confirmed, in particular, that the toroidal current density in the plasma fully determines the plasma contribution into the forced. For the wall current description, two modes with different decay rates are used. The force is examined with emphasis on the post-disruption stage.



Introduction

Despite a long history of research, there are still unresolved questions and even conflicts between theoretical concepts. One was inspired by a formula for proposed in [4] and recently criticized in [5]. Another one is related to the role of the halo currents. The wide-spread opinion is that “the forces associated with halo currents are a major contributor to the vertical force acting on the torus vessel during a disruption” [6]. However, in a stark contrast, it was stated that the total vertical force is largely unaffected when the amount of halo current changes [2]. Being solidly supported by reliable 2D calculations and analytical arguments for the forces due to wall halo currents and toroidal currents in the open field line region, this deserves a closer inspection.

The main subject is the vertical force on the wall

$$F_z^w = \mathbf{e}_z \cdot \int_w \mathbf{j} \times \mathbf{B} dV$$

The derivations here start from the Maxwell equations. At the first stage, these are based on the properties:

After these transformations, the general result (justified in Sec. 2)

- axial symmetry
- the current lines are closed inside the full system plasma + wall (*w+ = pl + w*)
- the toroidal currents do not produce an integral force on themselves.

After transformations

$$F_z^w + F_z^{pl} = -\int_{w+} j_\zeta B_r^c dV \qquad (1)$$

The subscript *c* means the coils

Reduction of (1)

In a tokamak, the external poloidal magnetic field can be represented as

$$\mathbf{B}_p^c = \mathbf{B}_\perp^c + \mathbf{B}_q^c + \ldots$$

uniform vertical + quadrupole

$$2\pi\mathbf{B}_p^c = \nabla\psi^c \times \nabla\zeta$$ with $$\psi^c = \psi_0^c + \pi r^2 B_\perp^c + \psi_q^c + \ldots$$

$$\psi_q^c = C_q[(z - z_q)^2 - (r - R_q)^2]$$

With such substitutions,

$$F_z^w + F_z^{pl} = \int_{w+} j_\zeta \frac{\partial\psi^c}{\partial z} dS_\perp = 2C_q(M_{IZ}^{pl} + M_{IZ}^w)$$

where

$$M_{IZ}^\alpha \equiv \int_\alpha j_\zeta (z - z_q)\frac{r^2}{R_w^2} dS_\perp$$

are the “current moments”. α is either *pl* or *w*

The vertical shift: $$\int_{plasma} (z - \xi_z) j_\zeta dS_\perp = 0$$

Then $$\int_{pl} (z - z_q) j_\zeta dS_\perp = J(\xi_z - z_q)$$

Similarly $$\int_{w} (z - z_q) j_\zeta dS_\perp = J_s^w b_w - J_w z_q$$

Here J is the plasma current, J_w is the net current in the wall, $J_s^w b_w$ is from $z j_\zeta$

The final general result – only toroidal currents

$$F_z^w + F_z^{pl} = 2C_q[J(\xi_z - z_q) - J_w z_q + J_s^w b_w]$$

This purely electromagnetic relation is derived it without constraints on the plasma dynamics, plasma and wall shapes. The wall contribution is described by two terms, which evolve differently after the end of discharge:

$$J_w = J_w^0 e^{-t/\tau_0} \qquad J_s^w = J_s^w(0) e^{-t/\tau_1}$$

with $\eta \equiv \frac{\tau_0}{\tau_1} = 2\left(\ln \frac{8R_w}{b_w} - 2\right)$ and $\tau_1 = \tau_w / 2$, $\tau_w \equiv \mu_0 \sigma b_w d_w$

This makes the post-disruption force $F_z^w = C_w f_w(t)$ with

$$f_w(T) = e^{-T} - \alpha e^{-\eta T}$$

and $T \equiv t / \tau_0$

The post-disruption force, due to wall currents only

$$F_z^w = 2C_q[J_s^w b_w - J_w z_q] \Longleftrightarrow j_\zeta^w = j_0^w + j_s^w \sin u$$

This force must be zero in the ideal-wall limit, if the disruption was fast enough, see (Nucl. Fusion **55** (2015) 113032). Then after the disruption

$$F_z^{iw} = C_{iw}(e^{-T} - e^{-\eta T})$$

The time dependence is determined by the single quantity η.

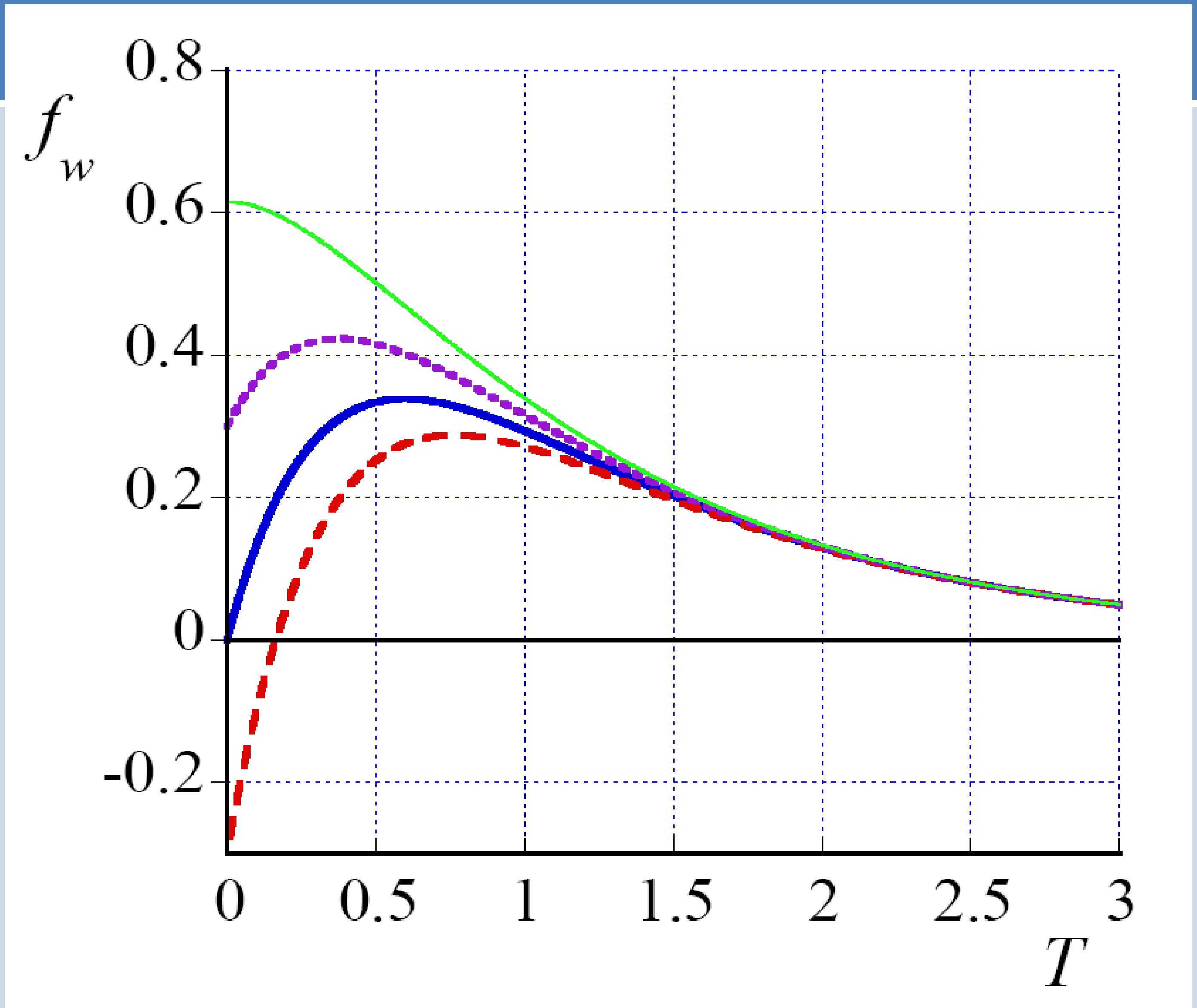
The initial values, just after the rapid event, are fully defined. After that the force will evolve and can reach a large level. The process is determined by the wall resistivity. Two measurable quantities are needed, if the preceding disruption was not an "ideal-wall" event.

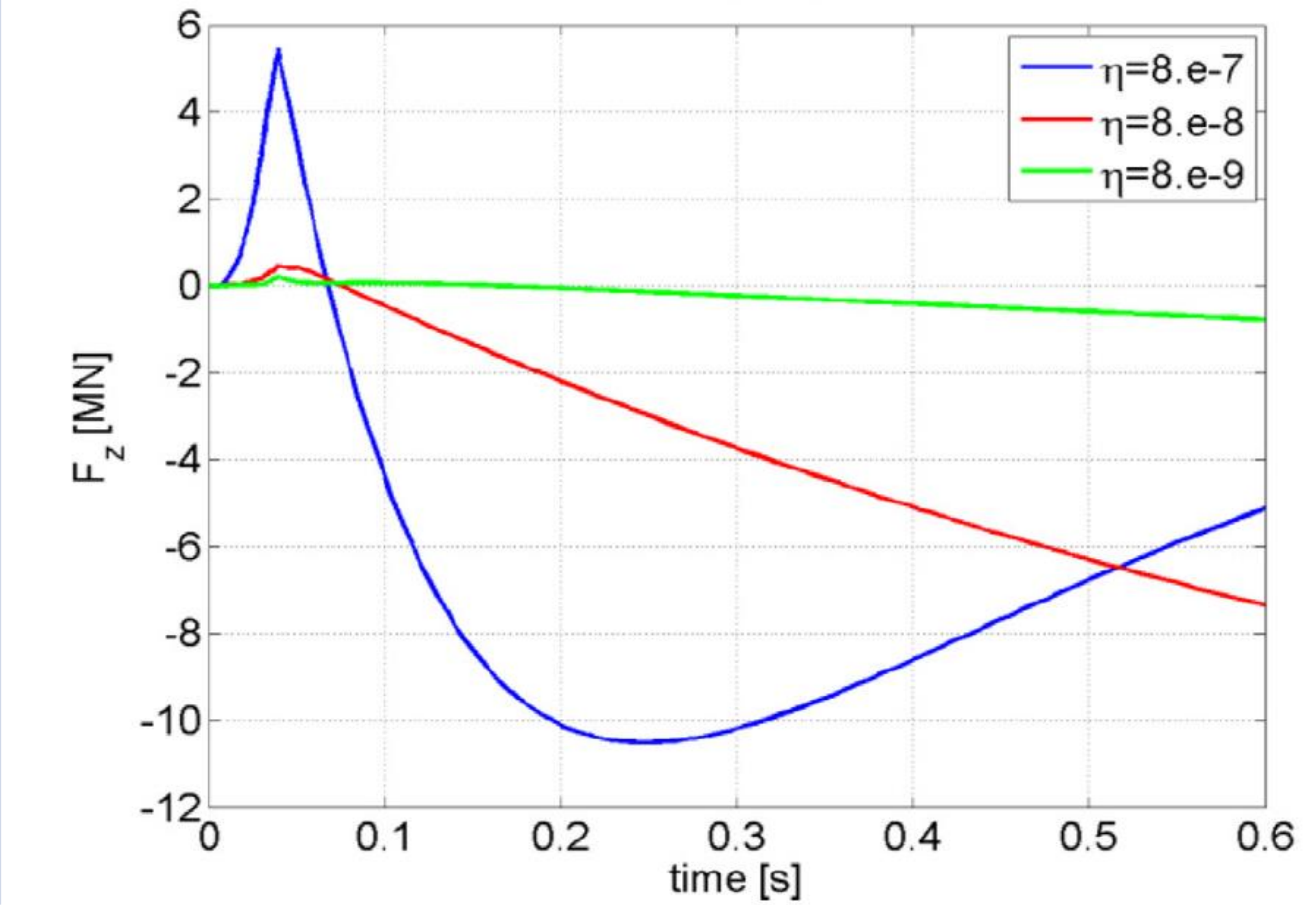
The post-disruption force has been observed in numerical calculations. We confirm that this force can be large.

Analytics versus CarMa0NL computations

Our analytical result: from top to bottom α = 1/2.6, 0.7, 1, 1.3

V.D. Pustovitov, G. Rubinacci and F. Villone 2017 Nucl. Fusion 57 126038





Summary

- With or without halo current, the vertical force on the wall is fully determined by interaction of the toroidal current in the system plasma + wall with poloidal field external to this system. In agreement with (Clauser et al. 2019 Nucl. Fusion 59 126037)
- A significant growth of the vertical force on VV is possible after the end of disruption
- The time scales are determined by the wall parameters
- At least two differently evolving modes are needed for description of the wall current
- Our result is essentially different from that in (Miyamoto 2011 Plasma Phys. Control. Fusion 53 082001)