Models and scalings for the disruption forces in large tokamaks

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ABSTRACT

- In recent years, there was a steady progress in developing a better basis for calculating the forces, which gave rise to new trends and ideas.
- It was discovered, in particular, that the wall resistivity, penetration of the magnetic perturbation through the wall, the kink-mode coupling, the mode rotation must be the elements essentially affecting the disruption forces. These and related predictions along with earlier concepts and results are analyzed here. The key question is the quality of the proofs behind them.
- The study is focused on the problems important for the ITER scenarios.

BACKGROUND

- Disruption forces may strongly restrict the operational range in tokamaks.
- For ITER, the most pessimistic scalings give the sideways force above the tolerable level, but a great scatter in theoretical predictions (about two orders of magnitude) shows that the problem still remains open.
- There are several different approaches to calculating the disruption forces, with a number of various (often implicit) simplifying assumptions. Their evaluation, elimination of wrong elements and contradictions, formulation of the general basis are the main theoretical challenges.

METHODS / IMPLEMENTATION

THE MODEL

A convenient base for analysis, comparison, revision and conclusions is the approach built starting from the most reliable and universal part for all cases of interest, i.e. the Maxwell equations and the Ohm's law for the wall. The plasma enters the task through the boundary conditions, which makes them the critical element responsible for proper incorporation of the plasma physics. The main goal is the calculation of **f** = **j** × **B** or integrals of **f** in the vacuum vessel wall, where **B** is the magnetic field and **j** the current density.

GENERAL RELATIONS

$$\mu_0 \mathbf{c}\cdot(\mathbf{F}_w + \mathbf{F}_{pl}) = \int_{w+} \left[(\mathbf{c}\cdot\mathbf{B})\mathbf{B} - \frac{\mathbf{B}^2}{2}\mathbf{c} \right]\cdot d\mathbf{S}_{w+}$$

Here $\mathbf{F}_w$ and $\mathbf{F}_{pl}$ are the integral electromagnetic forces on the wall and plasma, respectively, **c** is a constant vector, integration is performed over the toroidal volume bounded by the surface covering the wall from outside. Since $\mathbf{F}_{pl} = 0$, this gives the force on the wall. Substitution $\mathbf{B} = \mathbf{B}_{ax} + \mathbf{b}$, where $\mathbf{B}_{ax}$ is the axisymmetric part of **B,** turns this into $F = F^{BB} + F^{Bb} + F^{bb}$ with

$$\mu_0 F^{BB} = \int_{w+} \left[(\mathbf{c}\cdot\mathbf{B}_{ax})\mathbf{B}_{ax} - \frac{\mathbf{B}_{ax}^2}{2}\mathbf{c} \right]\cdot d\mathbf{S}_{w+}$$

(≠ for the vertical force only) and

(≠ for the sideways force only)

$$\mu_0 F^{Bb} = \int_{w+} [(\mathbf{c}\cdot\mathbf{B}_{ax})\mathbf{b} + (\mathbf{c}\cdot\mathbf{b})\mathbf{B}_{ax} - (\mathbf{b}\cdot\mathbf{B}_{ax})\mathbf{c}]\cdot d\mathbf{S}_{w+}$$

GENERAL PROPERTIES

- These relations are valid when the integration surface is axially symmetric (it can be always selected as such behind the wall, where **j** = 0) , while the plasma and wall can be 3D. The halo current is automatically accounted for.
- An important consequence is that only slow plasma evolution can lead to a large integral force on the wall. Slow means that the plasma-produced perturbations can effectively penetrate through the wall.
- The maximal force on the wall must be produced by the events (TQ, CQ, VDEs, halo, RWMs) with a characteristic time scale of the resistive time of the wall. Also, the holes in the wall assist the outward penetration of **B**.

MODELS FOR THE SIDEWAYS FORCE

ANALYTICAL RESULTS FOR A 'CIRCULAR' TOKAMAK

$$\mu_0 F_\alpha^{Bb} = r_w R_0 \int_\alpha [B_{0\theta} b_r \sin\theta\cos\zeta - B_0 b_r \sin\zeta + (\mathbf{B}_0\cdot\mathbf{b})\cos\theta\sin\zeta] d\theta d\zeta$$

A nonzero contribution is produced by $b_r = b_r^{1,1}\sin(\theta-\zeta) + b_r^{1,-1}\sin(\theta+\zeta)$

Then $F_\alpha^{Bb} = C_1^\alpha b_r^{1,1}(r_w) + C_{-1}^\alpha b_r^{1,-1}(r_w)$, applicable to either plasma or wall.

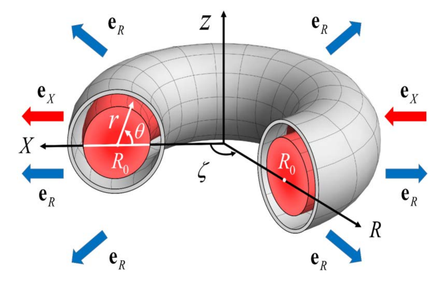
- The coefficients are different for α = *in* and *out* because of the wall currents
- Two harmonics allow to satisfy $F_{in}^{Bb} = F_x^{pl} = 0$ at any growth rate γ. This makes the modes (1, 1) and (1, –1) coupled by a linear relation.
- In contrast, with only one harmonic of b_r , a zero force on the plasma requires unrealistic γ.

THE MODELS WITHOUT $F_x^{pl} = 0$

Such are those with a plasma replaced by a current ring or with a single-mode perturbation. The Noll's formula is a product of such modeling. When such models give a sideways force of a few MN for JET, it actually contains a tremendous non-compensated force on the plasma.

The predictions of such inconsistent models are misleading.

SCALINGS FOR THE SIDEWAYS FORCE

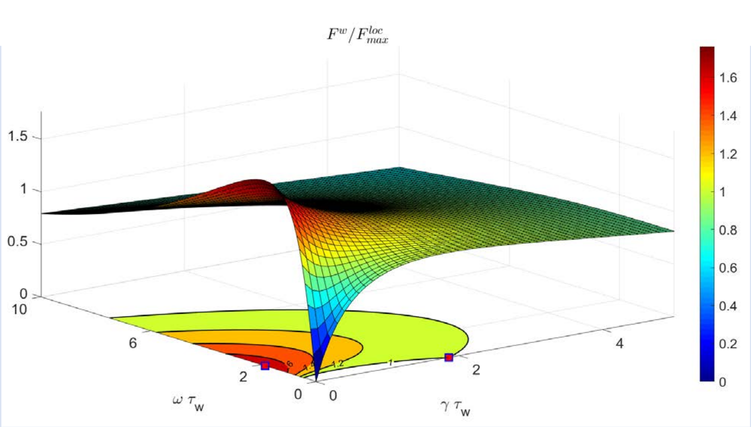


- The Noll's formula $F_x = \pi J B_0 \delta z_p$ relating the sideways force to the kink-like tilt of the plasma should be replaced by

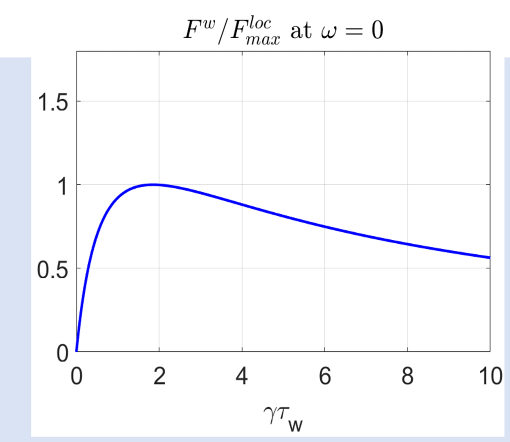
$$F^w = 4\pi^2 R_0 r_{pl} \left(\frac{r_{pl}}{r_w}\right)^2 \frac{B_J^2}{\mu_0} \frac{b_{11}(r_{pl})}{B_J} f(\gamma,\omega)$$

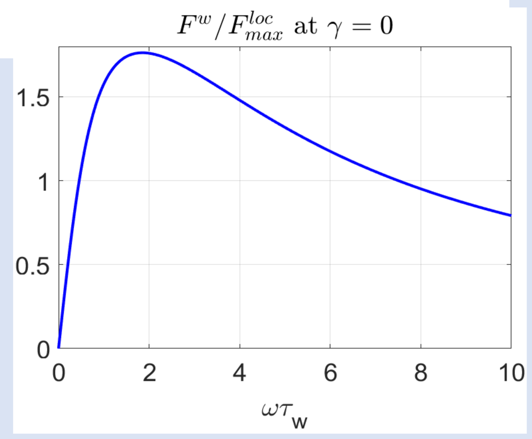
where f < 0.5. The latter gives a force an order of magnitude smaller.

- This formula also gives the rotating sideways force. With or without rotation, the maximal force is produced by slow RWM-like modes.



Normalized amplitude of the rotating sideways force. The figures are produced by Prof. G. Rubinacci





The normalized sideways force produced by the locked (left) and purely rotating (right) kink modes, as functions of the growth rate and mode rotation frequency, respectively.

CONCLUSION

- The proposed force relations are based on the Maxwell equations and only one integral constraint on the plasma, $\mathbf{F}_{pl} = 0$.
- They are therefore applicable in a general case, with plasma evolving, unstable, not necessarily ideal, anisotropic, rotating.
- The sideways force rotating with low frequency is a new theoretically predicted danger because of possible resonances.

REFERENCES

Pustovitov V. D., Rubinacci G., Villone F., On the computation of the disruption forces in tokamaks, Nucl. Fusion **57** (2017) 126038.
Pustovitov V. D., Rubinacci G., Villone F., Sideways force due to coupled rotating kink modes in tokamaks, Nucl. Fusion **61** (2021) 036018.