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Models and scalings for the disruption forces in large tokamaks

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Abstract. The study is devoted to theoretical analysis of the models for calculating the disruption forces in tokamaks. It is motivated by the necessity of reliable predictions for ITER. The task includes the evaluation of the existing models, resolution of the conflicts between them, elimination of contradictions by proper improvements, elaboration of recommendations for dedicated studies. A better quality of the modelling and higher accuracy are the ultimate theoretical goals.

Impact. The disruption forces may strongly restrict the operational range in tokamaks. This can be illustrated by the JET tokamak normally operated with plasma current up to about 3 MA, though originally the discharges with current up to 4.8 MA were considered possible (with the elliptical cross section and toroidal field up to 34.5 kG) and even 6 MA has been mentioned [1] as the design plasma current in JET. For ITER with expected 15 MA current, 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.

Novelty. In recent years, there was a steady progress in developing a better physics 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 poloidal current induced in the wall, the kink-mode coupling, plasma position in the vacuum vessel must be the elements essentially affecting the disruption forces. These and related predictions along with earlier less sophisticated concepts and results are analyzed here.

Quality. The key question is the quality of the proofs behind them. 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 presented approach is careful in this aspect and provides a universal basis for comparison of the existing models. The study is focused on the problems important for the ITER scenarios.

The addressed problems. In terms of mathematics, the main goal must be the calculation of **jxB** or some integrals of this force density in the vacuum vessel wall, where **B** is the magnetic induction and **j** is the current density. The plasma enters this purely electromagnetic task as a distributed current with evolving distribution. The main complications arise from the related changes of the plasma shape and position to guarantee the force balance for the plasma. Because of small plasma mass and relatively slow development of disruptions the plasma must remain force-free at each time step, while the disruption force on the wall can exceed the inertial force by 6-8 orders of magnitude [2, 3]. Proper description of the plasma reaction becomes a necessary part in the task.

This is a developing area, and several points require clarification. Among them is the effect of the plasma position and the poloidal current on the disruption force. Recent theories show [4, 5] that each of them can strongly affect the force, but some studies [6] ignore them.

Another disputable subject is the kink mode structure: should it be a single harmonic $m/n = 1/1$ [7] or a pair of coupled modes (1/1) and (1/−1) [8] to satisfy the force-free condition for the plasma and simultaneously produce a significant sideways force on the wall?

The sideways force itself is a mystery which makes difficult extrapolations from JET to ITER. It becomes clear that so-called Noll's formula cannot be used for that: it is a product of oversimplified modelling with a result [9] 25 times larger than a similar estimate [8], but with a more refined plasma model.

Various models attribute the sideways force to different stages of the discharge, starting from the pre-disruption kink mode and ending by halo currents and other events after the plasma-wall contact. A pure sideways force can appear due to $n = 1$ perturbation only, but theory also predicts that a large integral radial force can develop in an axially symmetric configuration during TQ or CQ. Then a question is which of the two forces can be more dangerous? Also, is it possible to distinguish the difference between them in experiment? Was the JET damaged by a pure sideways force or a combined action of several forces?

The model. The study is mainly based on the Maxwell equations and, therefore, is general. The induced currents in the vacuum vessel wall are described by the standard Ohm's law. A particular attention is paid to the plasma-wall electromagnetic coupling under constraints imposed by the force balance for the plasma.

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