5th Asia-Pacific Conference on Plasma Physics, 26 Sept-1Oct, 2021, Remote e-conference

# Disruption induced electromagnetic loads in tokamaks

V.D. Pustovitov
National Research Centre 'Kurchatov Institute', Moscow, Russian Federation
e-mail (speaker): Pustovitov_VD@nrcki.ru

The disruptions, either spontaneous or intentionally triggered by some intervention from outside, lead to rapid redistribution of the magnetic energy in tokamaks. The currents excited in the vacuum vessel wall interact with the externally applied magnetic field, which results in large pulsed electromagnetic loads on the wall. During the current quench the released energy is proportional to the initial current squared. Then the related force in ITER with 15 MA is expected to be 25 times larger than that in JET with 3 MA. The most pessimistic estimates predict the sideways force about 80 MN, with momentary value significantly exceeding the design guidance. That is why the problem attracts attention, though the scale of danger was tolerable in smaller machines.

To prevent a damage from such forces, a strategy based on a firm knowledge is needed, but the existing approaches give too large scatter in the predictions. Still unresolved are the questions on the origin of the sideways force in JET and on the most dangerous sequence of events. The list of the reasons potentially responsible for large disruption forces include the kink modes, both locked and rotating, thermal quench, current quench, vertical displacement events, halo currents. Their role is discussed here in the review of recent advances in theory.

The main uncertainty in the task is the plasma dynamics. However, in the disruption events, the plasma inertia is almost negligible. Therefore, only the force-free motions are allowed during the disruptions. This is certainly valid for global evolution because the wall reaction suppresses the fast displacements of the plasma. Such "wall stabilization" is weakened by the resistive decay of the eddy currents. As a consequence, incorporation of the resistive dissipation in the wall in the model becomes a necessity.

This was proved to be especially important in calculation of the integral forces on the wall. Such a force on the perfectly conducting toroidal wall must be zero [1] at any plasma evolution because the magnetic perturbation generated inside cannot penetrate outside the ideal wall. The models that do not satisfy this direct consequence of the Maxwell equations should be rejected. Strong dependence of the disruption forces on $\gamma\tau$ with asymptotic decay to zero in the ideal wall limit (at $\gamma\tau\to\infty$), where $\gamma$ is the growth rate and $\tau$ is the resistive wall time, is confirmed in numerical calculations [2–4].

The wall resistivity and the force-free plasma constraint have been incorporated into the model of the sideways force generation by the kink modes [5]. The result demonstrated that two coupled modes are needed to produce such a force on the wall. The previously developed models with a single mode are shown to greatly violate the plasma force balance. It was demonstrated that the scalings based on the Noll's formula and predicting a tremendous force in ITER [6] greatly overestimate this force. From theoretical viewpoint this means that the problem should be reconsidered. More optimistic results for ITER are expected.

Recently it was shown theoretically that the rotating kink modes can produce the rotating sideways force on the tokamak wall [7]. This force must be maximal at $\omega\tau$ of order unity, where $\omega$ is the rotational frequency of the mode. The faster modes produce a smaller force, but before the mode locking the dangerous range of $\omega\tau$ must be inevitably crossed. The amplitude of the rotating force is predicted as not too large (less than 10 MN in ITER), but the dynamical amplification in the case of mechanical resonance can be a problem. It is known that, for ITER, the dynamic amplification of structural forces that would occur if the rotating modes resonated with the vessel at the 8 Hz fundamental mechanical vessel frequency is a concern [8]. The analysis in [7] reveals the physics behind this threat.

The vertical force on the wall is another issue. It is generally believed [9] that "the forces associated with halo currents are a major contributor to the vertical force acting on the torus vessel". The same is confirmed in [10].

In contrast to that, it was shown recently in 2D calculations that the total vertical force is largely unaffected when the amount of halo current changes [11]. The main question here is which of the two contradicting positions is correct. The answer is needed for optimization of the discharge scenarios to minimize the negative consequences of the disruptions, including those produced intentionally by the disruption mitigation systems [10]. The analysis is performed on the basis of the approach described and tested in [1–4].

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