Plasma stability in a tokamak with $q \approx 1$ and forces acting on the conducting wall during disruption

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External kink mode instability of the tokamak plasma in the process of disruption and the sideways forces acting on the conducting wall due to the eddy currents are investigated. We analyze the stability of the equilibrium configuration obtained in simulations of the disruption in ITER by the DINA code with account of runaway electrons (RE) affecting the current profile [1]. The configuration of interest is the plasma with minor radius of 1 m and almost circular shape with a large current (> 5 MA) and the safety factor of $q \approx 1$. Being close enough to the vacuum vessel wall at its top, it is found stable against the ideal kink mode $n = 1$. Using the stability code KINX [2], the conditions for wall stabilization (stability gaps) at the Alfvén timescale are determined varying the current profile and q at the plasma edge. The structure of the resistive wall modes (RWM), including the plasma displacement, the RWM growth rates and the currents induced in the wall are calculated in the thin wall approximation. The sideways force acting on the wall is determined as the Lorentz force from the surface current in the wall and the equilibrium field, as in [3].

1. Introduction Sideways or the lateral force, presumably generated by a kink mode is considered a reason of the significant sideways vessel displacements observed during some disruptions in the Joint European Torus (JET) tokamak. The force itself was estimated up to 4 MN in JET and expected to be a factor of 20 larger in the International Thermonuclear Experimental Reactor (ITER) tokamak which substantially exceeds the admissible upper level in ITER estimated as 48 MN [4]. The large sideways force in tokamaks is often attributed to the asymmetric vertical displacements and halo currents. The scenarios with huge sideways forces developing at the very start of a disruption, when the plasma just becomes deformed, but remains isolated from the wall are described by the analytical models [5-7] with a kink mode as a sole driver (without halo currents) of the force. Here the latter concept is numerically investigated for the inertia-less RWM.

2. Limiting conformal wall position and stability gaps: $n = 1$ kink mode. The ITER disruption scenario is considered for plasma after the thermal quench with account of the RE current generation as calculated with the DINA code [1]. The plasma displaced close to the top of the vacuum vessel (figure 1a) was further cut off from the separatrix and moved even closer to the inner shell of ITER vacuum vessel in order to get stronger stabilization from the conducting wall. The profiles for this almost circular low-beta plasma (further referenced as “peaked”) and the analyzed configuration itself are shown in figures 1b and 1c. In this case the external $n = 1$ kink mode can be stabilized by the “one-sided” ideally conducting wall despite low safety factor $q \approx 1$. To assess the wall stabilization sensitivity to the equilibrium parameters, let us first consider such a plasma, but with the wall conformal to its boundary. In figure 2a the limiting positions a_w/a (the ratio of wall to plasma minor radii) of the conformal wall are shown for the peaked (figure 1b) and flat (constant inside plasma) current density profiles versus q_{edge} at the plasma edge (either the total plasma current I_p or toroidal magnetic field B is adjusted to give a specific q_{edge}). Except the values just below q_{edge} =1 (with $a_w / a \to 1$) and at q_{edge} >1.5 (for which multiple resonant surfaces q = 1 appear in the plasma for the peaked current profile and internal kink modes go unstable), the external kink mode can be stabilized by an ideally conducting wall at a reasonable distance from the plasma a_w/a = 1.3 for 1<q_{edge}<1.4. Figure 2b shows the stability gaps in the q_{edge} axis for the one-sided wall stabilization. Despite marginal conformal wall positions farther from the plasma for the flat current profile (seemingly more stable), a wider stability gap 1< q_{edge}<1.5 is found for the peaked current (though with some region of weak ideal instability inside) as compared to 1< q_{edge}<1.15 for the flat current.

3. Sideways force in ITER due to n=1 RWM. The sideways force is a natural consequence of the eddy currents in the wall induced by the n = 1 mode growth. In figure 2c the RWM growth rates computed by the KINX-RWM code [2] are shown for the one-sided wall stabilization (figure 1c). The sideways force in the direction $X = R\cos\varphi$ is calculated as $\mathbf{F}\cdot\nabla X = \int_{S_w} \delta\mathbf{j}_s \times \mathbf{B}_0 \cdot \nabla X\, dS$, where $\delta\mathbf{j}_s$ is the induced surface current in the inner shell of ITER vacuum vessel S_w, $\mathbf{B}_0$ is the equilibrium magnetic field, and integration is performed over the wall surface. With surface current $\delta\mathbf{j}_s = \sum_n \delta\mathbf{j}_s^n e^{in\varphi}$ for axisymmetric configuration one gets the complex quantity $F_c = \pi\int_{L_w} \delta\mathbf{j}_s^1 \times \mathbf{B}_0 \cdot \nabla R\; Rdl$ (neglecting the equilibrium field projected on the normal to the wall as compared to the toroidal field) and the force $F_\varphi = \mathrm{Re}(e^{i\varphi}F_c)$ acting in the horizontal direction defined by the toroidal angle φ. The module of F_c (corresponding to the maximal force) normalized by the maximal magnetic field perturbation normal to the plasma boundary b_p, $F = |F_c / b_p|$ and the normalized force F_t from the interaction of the induced surface current with only the toroidal equilibrium field versus q_{edge} are presented in figure 3a. Here q_{edge} varies with plasma current at fixed vacuum toroidal field 5.3 T in the ITER vacuum vessel center. With the one-sided RWM, in contrast to the conformal wall RWM as in [3,7] (represented here by the growth rates and normalized forces in figure 2c and figure 3a for the flat current profile), the sideways force is almost completely determined by the interaction of the surface current with the toroidal field. Note that F_t can be somewhat higher than the total force F for the one-sided RWM. The calculated F monotonically increases with the RWM growth rate and saturates at $\gamma_{RWM} \to \infty$. A simple simulation-based estimate of the sideways force with the ITER wall can be obtained assuming the normal magnetic field perturbation at the plasma boundary $b_p = 0.1B_p$, i.e. 10% of the averaged equilibrium poloidal field $B_p = \mu_0 I_p / L_p$. It gives F_t equal to 2.15 MN and 1.45 MN for the peaked and flat current cases respectively. The RWM structure shown in figure 3b is dominated by the resonant $m = 1$ poloidal harmonic inside the $q = 1$ surface for the peaked current. For the flat current the coupling of the dominating $m = 2$ surface wave to the $m = 1$ harmonic is the main feature of the RWM structure (figure 3c). This coupling is strongest at the no-wall limit $\gamma_{RWM} \to 0$.

4. Discussion. The presented external $n = 1$ kink mode stability calculations demonstrate that after the thermal quench in ITER the plasma strongly reduced in size and displaced upward almost touching the wall can be stable assuming ideal wall conductivity despite low safety factor $q \approx 1$ giving rise to the $n = 1$ RWM with one-sided wall stabilization. The sideways force calculated for the plasma shown in Fig. 1c monotonically increases with the γ_{RWM} and saturates when approaching the ideal wall limit $\gamma_{RWM} \to \infty$. We note that for the edge safety factor q_{edge}>1 the m=1 poloidal harmonic do couple to the m=2 surface wave both in the peaked and flat current density cases. The reasons for that are different: for the peaked current with the $q = 1$ surface inside plasma it happens mostly due to the toroidal kink [8] mode structure, but for the flat current the enhanced poloidal harmonic coupling is caused by the requirement of zero force acting on plasma in the inertia-less approximation. Let us note that due to nontrivial contribution of the poloidal harmonics $m \geq 2$ to the sideways force the presented results essentially differ from those in [3] where the perturbations are coupled harmonics $(m,n) = (1,1)$ and (1,–1) that leads also to different sideways force dependence on γ_{RWM}. For the configurations considered here the equivalent presence of $(m,n) = (1,1)$ and (–1,1) harmonics dominant in the RWM structure would correspond to less realistic case with very low $q_{edge} < 0.25$ (one-sided wall) with the strongest coupling due to the plasma elongation at $\gamma_{RWM} \to 0$. Both the monotonic force behavior with γ_{RWM} and the mode structure features remain the same also for the stabilization with a conformal wall. Further study is needed to clarify the relation between these numerical results and theoretical statements in [3,9]. Despite the difference in the mode structure for $q_{edge} > 1$ the resulting force is about one order of magnitude smaller compared to the existing scaling in accordance with [3]. It means that the dangerous level of the force could be reached at much larger kink-like perturbations, and the RWM induced wall force can hardly be an explanation for the 4 MN disruption force in JET. This may be attributed to the absence of the halo/Hiro currents while the plasma is separated from the wall by the vacuum gap. We can conclude, as in [3], that a large sideways force should be searched for either at the next stages of disruptions with plasma/wall contact or using realistic 3D wall electromagnetic models.

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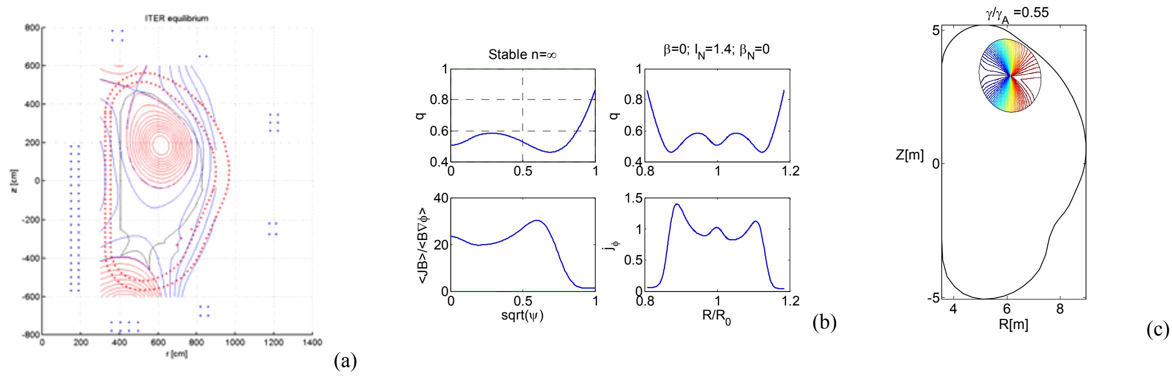

Figure 1. a) Equilibrium from DINA disruption modelling: level lines of the poloidal flux function; b) Profiles of safety factor q and parallel current density for the artificially cut-off plasma (see on the right) with zero beta and I_p = 8.6 MA; c) Position of the cut-off plasma near the ITER vacuum vessel, level lines of plasma normal displacement are shown for unstable ideal mode n=1.

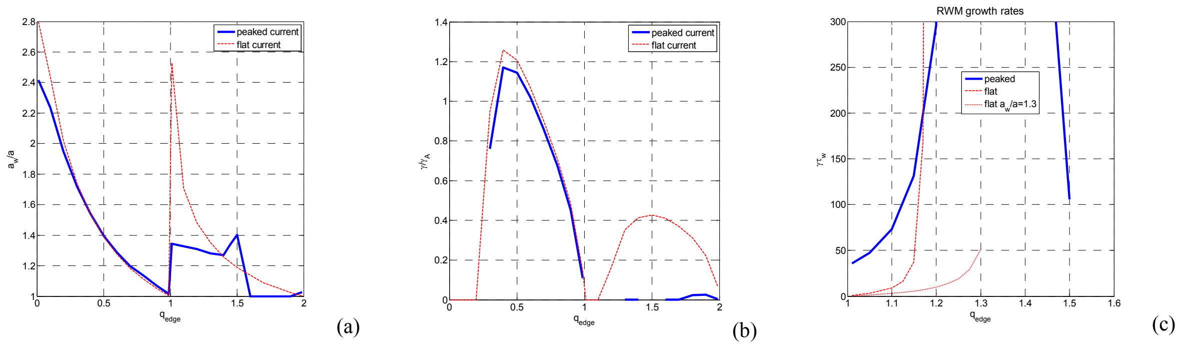

Figure 2. a) Limiting conformal wall position vs safety factor at the plasma edge; b) Ideal MHD growth rates for the one-sided wall stabilization; c) RWM growth rates normalized by resistive wall time $\tau_w = 0.25 s$.

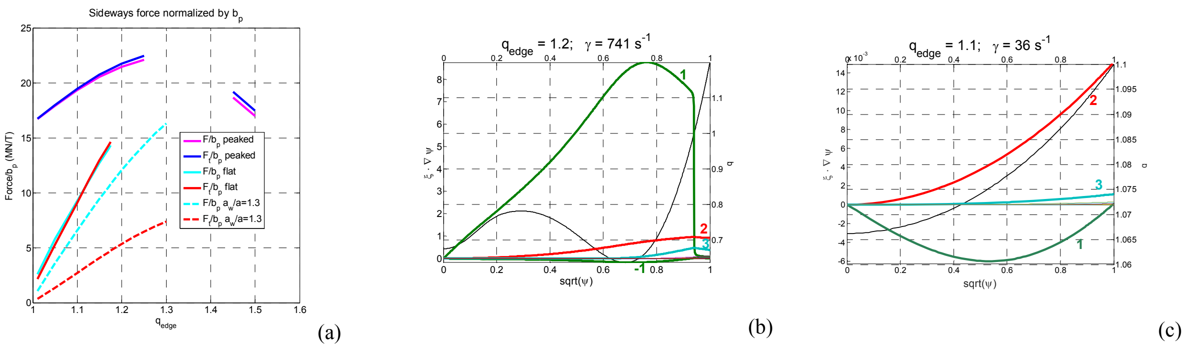

Figure 3. a) Sideways force normalized by the plasma normal magnetic field perturbation: F – full force, F_t – force from toroidal equilibrium field B=5.3T; b) Poloidal harmonics of n=1 RWM plasma displacement in the straight field line coordinates for peaked current, q profile is shown by black line; c) Poloidal harmonics of n=1 RWM plasma displacement for flat current.