Sideways forces on the wall during early disruption phase in tokamak

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The sideways forces acting on the conducting wall due to the $n = 1$ kink instability are investigated. During the early phase of the disruption the plasma is considered to be isolated from the wall and halo currents do not appear. The plasma with minor radius of 1 m and almost circular shape with a large current (> 5 MA) and the safety factor of $q \approx 1$ close enough to the top of the ITER vacuum vessel is considered, so that the ideal $n = 1$ kink mode is wall stabilized [1], but instead the resistive wall mode (RWM) develops. RWM growth rates, plasma displacement structure and the $n = 1$ surface currents induced in the wall are calculated with the KINX stability code [2]. Sideways forces acting on the wall are determined as the Ampere force from the perturbed surface currents and the equilibrium magnetic field.

In [1] sideways forces produced by the equilibrium toroidal field and RWM induced currents in the wall were found to reach maximum in the ideal wall limit $\gamma\tau_w \to \infty$ ($\tau_w = \mu_0 \sigma d_w a_w$ is resistive time of the wall with thickness d_w, minor radius a_w and conductivity σ). But for the considered inertia-less plasma model [3] the total sideways force in the ideal wall limit must be zero due to contribution from the equilibrium poloidal field or taking into account the force on the conductors inside the wall (the only possibility to make the equilibrium poloidal field at the wall vanish).

The magnitudes of the sideways force for ITER early disruption plasmas are computed for free-boundary equilibria obtained with the SPIDER code [4] under plasma current variation. For inertia-less plasma the total force on the wall reaches its maximum for low values of RWM growth rate $\gamma\tau_w \sim 1$ and vanishes for $\gamma\tau_w \to \infty$ in accordance with [3]. This asymptotic behaviour is attained for any inertia-less RWM perturbation once the consistent equilibrium field is used.

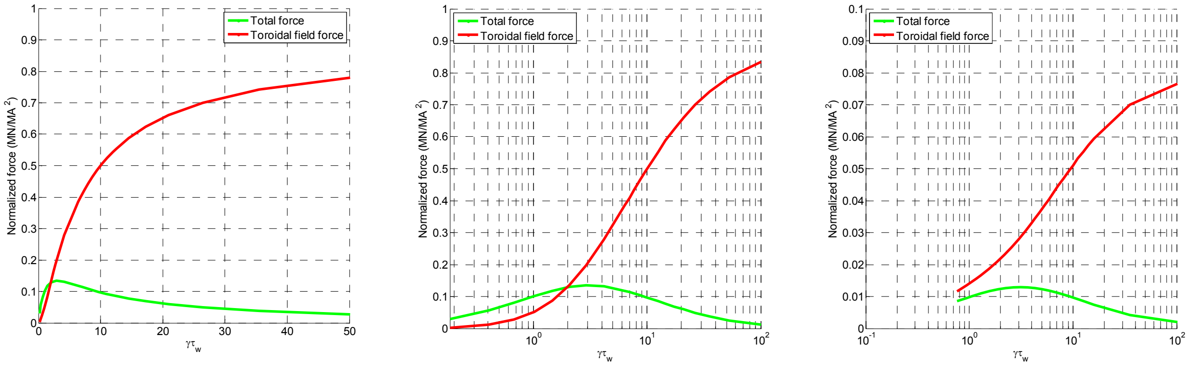
1. Sideways force in large aspect ratio approximation: $q < 1$. In 1D cylindrical approximation only $|m/n| = 1/1$ modes contribute to the sideways force [3], so the $n = 1$ RWM kink mode for the edge safety factor value $q < 1$ is the only candidate for the instability to drive the force. As an example the flat current density distribution over the plasma with large aspect ratio is assumed which gives the stability gap $0 < q < 0.6$ for the circular plasma and the wall at the radius $a_w / a = 1.3$ from the plasma with minor radius a. The qualitative behavior of the net sideways force on the wall with increasing growth rate is in accordance with the action-reaction law for the inertia-less plasma/wall system nearly magnetically isolated for $\gamma\tau_w \to \infty$: the net force on the wall is going to zero. The behavior of the ratio of the force to the perturbed magnetic field at plasma normalized by the squared plasma equilibrium current value $F[MN]/(b_p/B_p)/I_p^2[MA]/(2\pi R/L)$ vs. $\gamma\tau_w$ is shown in Fig.1a,b. Here b_p/B_p is maximal perturbed magnetic field at the plasma boundary over equilibrium poloidal field, I_p, *R, L* are plasma current, major radius and contour length respectively. Of course, for $q<1$ only one resonant harmonic *m/n* = 1/1 is present in the unstable mode for 1D plasma but the net sideways force from the toroidal and poloidal equilibrium fields is balanced to zero in the ideal wall limit in accordance with the inertia-less plasma assumption. The maximal force estimate in [3] is close to the computed one despite a special mode coupling conjectured there.

2. Sideways force in ITER due to n = 1 RWM: *q* > 1 stability gap. The ITER disruption scenario is considered for plasma after the thermal quench with account of the runaway electron (RE) current generation as calculated with the DINA code [1]. The plasma displaced close to the top of ITER vacuum vessel was further cut off from the separatrix and moved even closer to the inner shell of the vacuum vessel in order to get stronger stabilization from the conducting wall. Free boundary equilibrium in Fig.2a is computed with ITER PF coil currents fitted to sustain the shape characteristic to the plasma after the thermal quench. In this case the external $n=1$ kink mode can be stabilized by such "one-sided" ideally conducting wall with low safety factor $q\approx 1$. Values of the plasma current $I_p \sim 5$MA correspond to the stability gap 1< q <1.3 for the flat current density. An important difference from the $q<1$ case is that the sideways force arises due to a sideband $m=1$ mode coupled due to toroidicity to the dominating $m=2$ mode (Fig. 2c).The normalized sideways force vs. RWM growth rate presented in Fig.1c is about 10 times lower than for the $q<1$ case with dominating $m=1$ mode. In turn in a conventional case with conformal wall position at $a_w/a=1.3$, the net sideways force values are more than 5 times lower as compared to the one-sided RWM for $q>1$ which gives a factor of 50 difference from the $q<1$ case for the aspect ratio 5 with the conformal wall. Let us note that an exact self-consistent equilibrium poloidal field for a specific equilibrium is needed to get the right force balance with the equilibrium toroidal field: the field generated by plasma only is not sufficient for that (cyan lines in Figs. 2b, 3b) unlike the 1D case.

3. Forces on the conductors and the wall: peaking factor. In all considered cases the toroidal field generated forces reach their maximal values for $\gamma\tau_w \to \infty$, as revealed in [1], and only the balance from the self-consistent poloidal equilibrium field restores the right asymptotic behavior for the net sideways force in the ideal wall limit. A simple interpretation of this force behavior is based on the fact that due to toroidal mode decoupling the same *n* = 1 RWM calculation is applicable to a variety of external confining *n* = 0 fields including cases with conductors inside the vacuum vessel. So once the equilibrium poloidal field at the wall is shielded by some current-carrying conductors, the necessary balance is restored taking into account the force on the conductors from the perturbed $n = 1$ magnetic field. This simple example illustrates the general fact that the sideways force depends on the equilibrium field configuration outside plasma: even without any conductors with currents inside vacuum vessel the force may vary due to ill-posed problem of vacuum field reconstruction outside the plasma given the magnetic field at the plasma boundary (compare Fig.2ab and Fig.3ab). Not only the maximal force value but also the force peaking factor (ratio of maximal force density to the average) depends on the external field structure. It can be shown by calculating the force on a conducting shell with $n = 0$ equilibrium surface currents, which completely shield the equilibrium plasma field provided by so-called virtual casing (VC) principle [5]. In Fig. 3c the force on the VC surface currents is compared to the force on the wall at the same position $a_w / a \approx 1.3$ for the same free boundary equilibrium but in the absence of any conductors interior to the wall. Note that the peaking factor for the VC force can be several times higher than for the force on the wall due to perturbed eddy currents, but the peaking factor times the force values for this two cases saturate at the same level for $\gamma\tau_w \to \infty$. In general, larger force peaking factors are also characteristic to the case of the RE current profile in ITER equilibria [1], however quite high RWM growth rates just above $q = 1$ result in the net sideways force not exceeding the forces for the flat current density case.

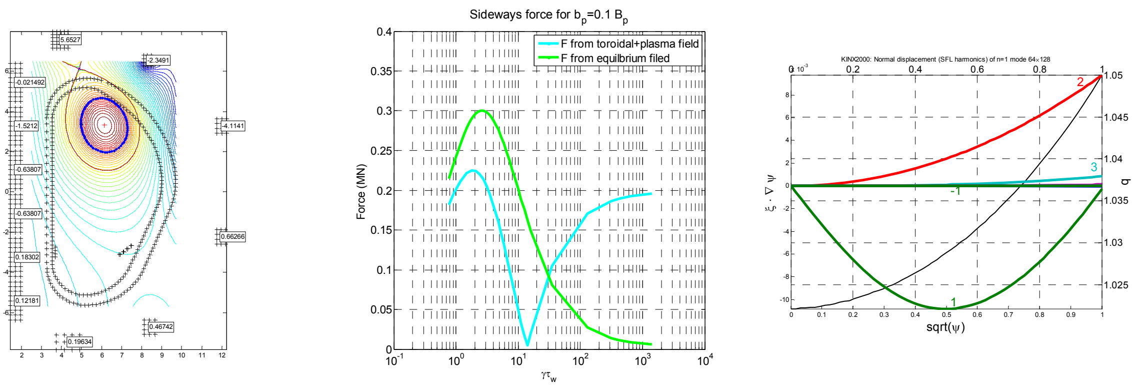
4. Discussion. The presented external $n = 1$ kink mode stability calculations confirm that the net sideways force reaches maximum at low values of $\gamma\tau_w$ and goes to zero in the ideal wall limit $\gamma\tau_w \to \infty$ also for one-sided $n = 1$ RWM and $q > 1$ in ITER early disruption phase plasmas. For $q > 1$ the $m = 1$ poloidal harmonic couples to the dominating $m = 2$ surface wave harmonic and generates sideways forces lower than for $m = 1$ dominated RWMs for $q < 1$. We note that an exact balance between self-consistent toroidal and poloidal equilibrium field generated forces is necessary to ensure the right asymptotic for the net sideways force in case of inertia-less plasma. The force peaking factor naturally increases with $\gamma\tau_w$ and depends on the equilibrium current density profile and mode structure for $q > 1$ and can also increase for equilibria partially sustained by axisymmetric eddy currents when a part of the sideways force is due to the perturbed magnetic field and axisymmetric eddy currents. Summarizing, for $q > 1$ the sideways force is an order of magnitude lower as compared to $q < 1$ case which is in turn significantly lower compared to other sideways force scalings, and 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.

[1] S.Yu. Medvedev et al. 45th EPS Conference on Plasma Physics, 2018, ECA Vol. 42A, P4.1060.
[2] L. Degtyarev et al., Computer Phys. Commun. **103** (1997) 10-27.
[3] D.V. Mironov and V.D. Pustovitov, Phys. Plasmas **24** (2017) 092508.
[4] A.A. Ivanov et al. 32nd EPS Conference on Plasma Physics, 2005, ECA Vol. 29C, P5.063.
[5] V.D. Shafranov, L.E. Zakharov, Nuclear Fusion **12** (1972) 599-601.



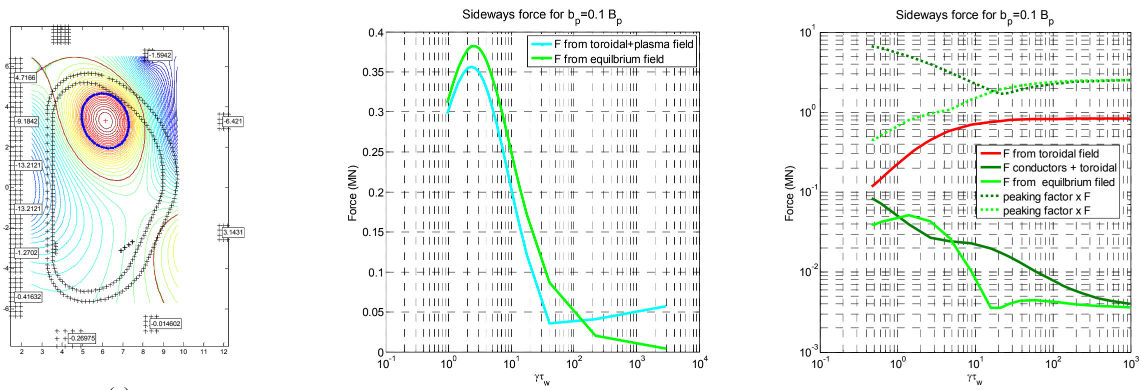
(a) (b) (c)

Figure 1. a) Normalized force vs RWM growth rate $\gamma\tau_w$ for n = 1 RWM for large aspect ratio q < 1 tokamak plasma with uniform current density, conformal wall a_w / a =1.3; b) The same plot with logarithmic $\gamma\tau_w$ scale; c) Normalized force vs $\gamma\tau_w$ for ITER equilibrium from Fig. 2a, one-sided RWM, q > 1 .



(a) (b) (c)

Figure 2. a) Poloidal flux level lines for free boundary equilibrium in ITER with fitted plasma boundary (blue dots), flat current density, I_p=8.6MA, PF coil currents displayed in MA; b) Sideways force for perturbed magnetic field at plasma boundary equal to 10% of plasma poloidal field vs. $\gamma\tau_w$; c) Poloidal harmonics of n = 1 RWM plasma displacement for q=1.05, $\gamma\tau_w = 3$.



(a) (b) (c)

Figure 3. a) Poloidal flux level lines for free boundary equilibrium in ITER with fitted plasma boundary, zero upper PF coil current; b) Sideways force for perturbed magnetic field at plasma boundary equal to 10% of plasma poloidal field vs. $\gamma\tau_w$; c) Sideways forces and peaking factors generated by perturbed eddy current in the wall and by VC surface currents for free boundary equilibrium with closed magnetic surface at a_w / a =1.3.