Axisymmetric mode stability in tokamak plasma with finite current density at the separatrix

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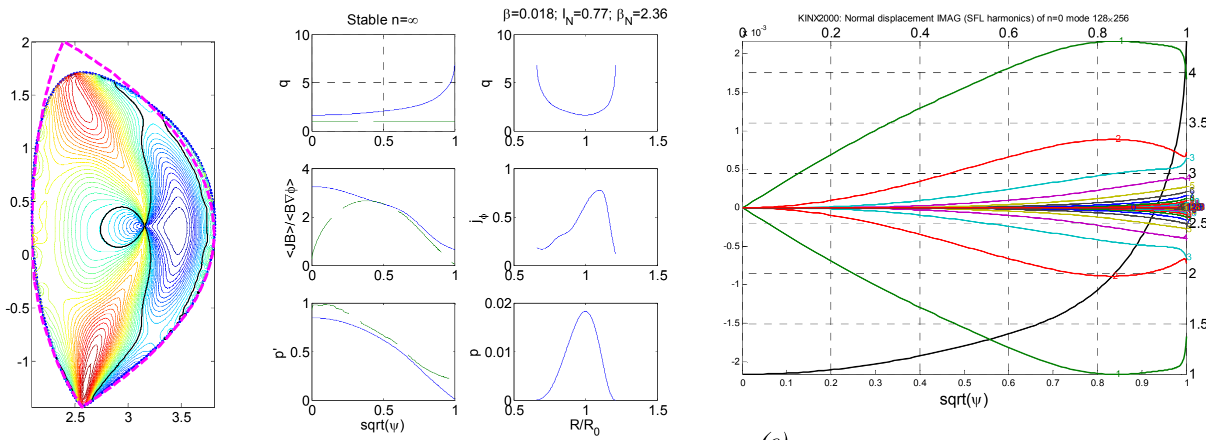
The $n = 0$ tokamak diverted double null (DN) plasma stability features the separatrix localized mode once the current density at the separatrix is finite [1]. The conducting wall very close to X-point is needed to stabilize the $n = 0$ peeling mode. Besides the value of positive (with respect to the total plasma current) current density at the plasma edge, the proximity of the plasma boundary cutoff to the separatrix is destabilizing. On the contrary, the deviation from up-down symmetric DN configuration, for which perturbed surface current is induced only in case of finite edge current density, to the single null (SN) configuration is strongly stabilizing for the $n = 0$ peeling mode. These features are consistent with the analytic results presented in [2]. Being the separatrix localized mode, the $n = 0$ peeling mode is susceptible to strong stabilizing influence of the plasma outside the separatrix in contrast to the standard global $n = 0$ mode when conducting wall is far enough from the plasma boundary. The unstructured grid MHD_NX code is used to investigate the SOL plasma stabilizing influence [3]. This $n = 0$ peeling mode may be related to the M-mode triggering in JET during L-H transitions [4]: rising current density at the separatrix could destabilize the ideal mode with the growth rate which scales with poloidal Alfvén frequency. The suite of equilibrium and stability codes for diverted plasmas with SOL is ready for the experimental data analysis [5].

1. *n* = 0 peeling mode modeling. Recent discovery of the n=0 peeling mode in 2015 is due to numerical modeling of the axisymmetric stability of the DN ST40 tokamak plasmas [6] with the KINX code. The parallel current density profile with finite value at the separatrix was chosen for the modeling and after some time it was recognized that the passive stabilizers in the vacuum chamber did not provide even assuming ideal conductors unless their positions were very close to the X-points. Assuming plasma boundary at $\psi_b / \psi_{sx} = 0.995$ poloidal flux fraction inside the separatrix or reducing the edge current to zero restores the conventional picture of the passive stabilization.

The stability calculations with the KINX and MHD_NX codes revealed the n=0 peeling mode for DN negative triangularity tokamak plasmas (NTT-DN) optimized for ballooning/Mercier mode stability [7]. The updated version of the MHD_NX stability code featuring hybrid triangular/quadrangular grid and unstructured grid generation in the vacuum region around the whole divertor configuration was used to estimate the SOL plasma influence on the *n*=0 peeling mode stability both in the DN and SN configurations.

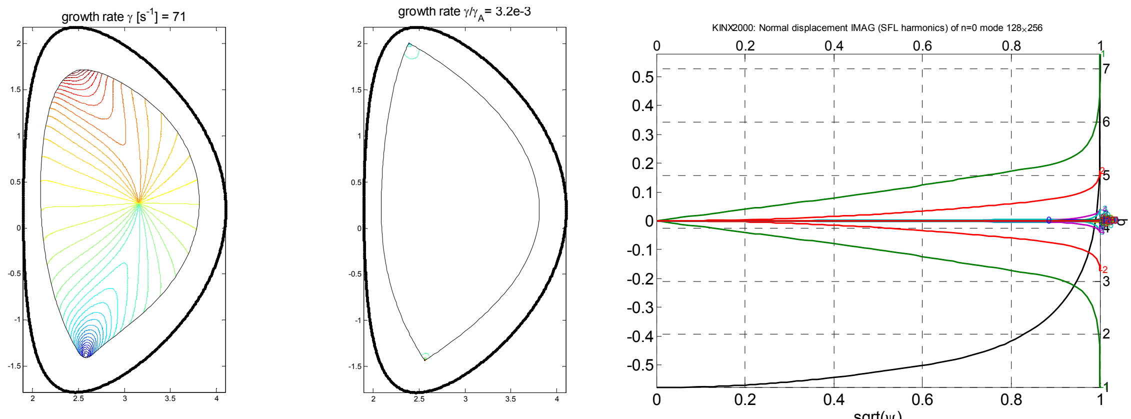
2. *n*=0 peeling mode in SN configuration. The DN configurations can easily become unstable against axisymmetric *n*=0 peeling mode once the current density at X-points is finite [1]. The core plasma properties and not only the edge current density value determine the stability conditions. For the core plasma stability a conventional "rule of thumb" is applicable both for conventional global and *n*=0 peeling mode: the lower the internal plasma inductance l_i (flatter current profile) the better the stability. Something quite opposite holds for finite current density at the separatrix: the higher the current density at the separatrix (corresponding to lower l_i) the worse the *n*=0 peeling mode stability.



(a) (b) (c)

Figure 1. a) Connected DN plasma shape (dashed) and the original plasma cross-section with level lines of scaled local shear. (b) Plasma profiles. c) Harmonics of $\xi\cdot\nabla\psi$ in straight field line coordinates for global n=0 mode with resistive wall at a_w/a=1.3. The resistive wall growth rate 71 s^{-1}.

What about the *n*=0 peeling in SN plasmas? The KINX stability code was employed for the *n*=0 stability analysis of JET-like plasmas in SN and connected DN configurations. The plasma profiles and boundary shape were taken from the JET shot #74221 [8]. The connected DN (but not up-down symmetric) configuration was approximated with the analytic separatrix shape (figure 1a) featuring 90 degree angle at the X-points [9]. For the original SN configuration ideal *n*=0 mode is stable with relatively far away wall and only the resistive wall mode is unstable due to finite wall resistivity for the wall position at $a_w / a \sim 1.3$ (figure 1b, figure 2a). In contrast to the SN the connected DN configuration remains ideally unstable (growth rate scales with inverse poloidal Alfvén time) even with the same close fitting wall. Note that despite normal plasma displacement highly localized near the X-points (figure 2b), the dominating *m*=1,2 harmonics of the plasma displacement projection $\xi\cdot\nabla\psi$, where ψ is equilibrium poloidal magnetic flux, well extend into the core plasma besides the skin at the boundary.



(a) (b) (c)

Figure 2. a) Level lines of plasma displacement normal to magnetic surfaces for global n=0 resistive wall mode in the original SN equilibrium. b) Level lines of normal plasma displacement for n=0 peeling mode in the connected DN equilibrium. c) Harmonics of $\xi\cdot\nabla\psi$ *in straight field line coordinates for n=0 peeling mode. The ideal growth rate is* γ/γ_A*=3.2e-3.*

The proximity to the secondary X-point to the SN separatrix was changed in the series of equilibria of varying shape by approximately keeping the lower part of the plasma cross-section with X-point fixed and merging it with "cut off" upper plasma boundary. The spikes with variable amplitude were added to the original profile of parallel current density at the separatrix. Only for the upper plasma shape corresponding to the $\psi_b/\psi_{sx}=0.999$ cutoff the ideal n=0 peeling mode destabilizes at reasonable value of the edge parallel current density $J/\langle J\rangle=1.2$, where $\langle J\rangle$ is plasma cross-section average, for the chosen wall position at $a_w/a=1.3$ (0.9 for $a_w/a=1.4$). The corresponding value for the $\psi_b/\psi_{sx}=0.99$ is 2.5 times higher: the marginal normalized edge value is 3 (2.4 for $a_w/a=1.4$). Compare these values to $J/\langle J\rangle=0.5$ for the original profiles (figure 1b). As a consequence, the corresponding free boundary equilibrium would feature strongly deformed magnetic surfaces near the X-point even in case of low current density outside the separatrix (also very acute X-point angle with finite current density in SOL) and probably would not be feasible.

3. Stability with SOL plasma: ITER example. High resolution equilibria with SOL for the SN configuration close to the ITER 15MA plasma was produced by the CAXE6-SOL equilibrium code [5] based on the modified EQDSK file processed with the CARRE code. The original poloidal flux function was modified to shift the external separatrix close to the plasma boundary thus provoking ideal n=0 peeling mode destabilization when edge current density is high, $J/\langle J\rangle=2$ in the presented case. The mode is stabilized by relatively thick conducting plasma layer in SOL (about half the region between the separatrices) or by an ideal wall of dome-like shape placed closely to the X-point (in addition to the ideal wall at the outer domain boundary). Figures 3b,c present marginally unstable plasma displacements for both cases.

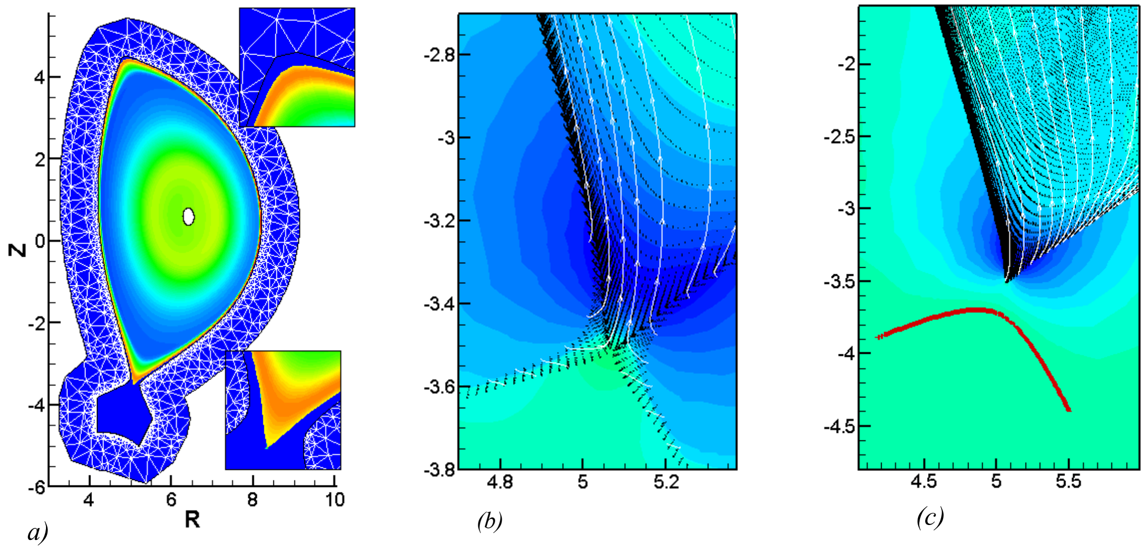


Figure 3. a) ITER-like configuration surrounded by vacuum region (triangular mesh). Inserts show the region between the separatrices - blue layer with zero current density in the toroidal current density contour plot, delimited by the outer SOL boundary (black line) from the vacuum region with triangular mesh. b) Marginally unstable plasma displacement with streamlines in plasma and SOL around X-point for the case with conducting plasma in SOL and c) for the case with dome-shaped ideal wall (red curve).

Conclusions. Finite current density at the separatrix drives axisymmetric *n*=0 mode unstable in divertor tokamak configurations. The critical value of current density near the separatrix depends on the proximity of the separatrix to connected DN configuration. In principle, every fixed boundary SN equilibrium will be *n*=0 unstable with large enough spike of the current density at the separatrix. However, this is not compatible with conventional divertor configurations assuming free plasma boundary. For ITER-like configurations a reasonable value of normalized parallel current density at the separatrix $J/\langle J\rangle = 1$ leads to *n*=0 peeling mode destabilization for $\psi_b/\psi_{sx} = 0.999$ cutoff from the secondary X-point with the wall position at $a_w/a = 1.3-1.4$. The conditions of *n*=0 peeling mode stabilization with the conducting plasma outside the separatrix and its destabilization with finite current density in SOL are to be further investigated.

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Acknowledgement *The work was supported by the grant from the Russian Science Foundation №16-11-10278.*