External kink mode stability in a tokamak with a finite current density in the SOL

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1. Introduction The issue of the pedestal stability of ITER plasmas, taking into account high pressure gradient in SOL, was addressed in [1]. The scaling [2] predicts very narrow SOL width ~1 mm, leading to the corresponding values of pressure gradients exceeding several times the values in the pedestal. The new version KINX-SOL of the ideal MHD stability code KINX [3] allowed estimating systematically the quantitative changes in the pedestal height limit due to the presence of the narrow SOL with finite current density. The maximal stable pedestal height is rather insensitive to the pressure gradient profile in the pedestal and in the SOL at fixed pedestal width for medium-*n* modes $n < 20$ [4]. The effect of finite parallel current density in SOL on the equilibrium near the X-point was also demonstrated. The family of current density profiles in SOL with maximum value shifted outside the separatrix allows for larger total current values in SOL before reaching the X-point angle collapse [5]. Low-*n* mode can become unstable once the parallel current density in SOL is large enough.

The ELM triggering conditions in JET with ITER Like Wall were recently under consideration in [6], where high gas puff discharges were typically found not reaching the standard peeling-ballooning (P-B) stability boundary at the ELM onset (in contrast to the low gas puff discharges with second stability access for high-*n* ballooning modes). For reconstructed JET H-mode equilibria the possibility of ELMs being triggered due to an existence of currents in the SOL has been studied for the low triangularity discharges #84797 and #87342 corresponding to the low and high gas puff cases respectively.

2. Equilibrium and stability with finite SOL currents in ITER plasmas The study of the pedestal limits in divertor tokamak plasmas with SOL extends investigations of the pedestal profile influence on the pedestal height [7]. Free boundary equilibrium for ITER 15 MA scenario was used as a starting point for the computations of a series of high resolution equilibria under variations of pedestal and SOL profiles. In addition to that the plasma profiles in the original ITER equilibrium are cut-off at the 0.995 fraction of the poloidal flux inside the separatrix and expanded to a new separatrix to get a basic equilibrium with finite parallel current density at the separatrix [4]. Then both pressure gradient and averaged

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parallel current density in the pedestal were rescaled by a factor of 1.25 (with zero current density in SOL) to get the equilibrium unstable to the modes with toroidal mode numbers $n > 4$. As the width of conducting plasma outside the separatrix increases, the kink modes get eventually stabilized at some critical value. In figure 1a the critical width of the conducting plasma measured at the outboard equatorial plane is plotted versus toroidal mode number. The assumption of current-less plasma in SOL leads to stabilization of all P-B modes with 5mm layer of conducting plasma outside the separatrix (figure 1a, SOL0). When large pressure gradient p' (3 times higher than at the separatrix) is added in SOL (still assuming zero magnetic surface averaged parallel current density $j_{||}$) to further increase the pedestal height then 1 cm conducting mantle is enough for stability (figure 1a, SOLPx3).

One of possible sources of the finite parallel current density in SOL is related to the thermoelectric current flowing from the hotter outer divertor plate to the cooler inner one. This current is co-directed with the plasma current when the ∇B drift is directed to the active X-point – exactly the case for the ITER baseline scenarios (the diamagnetic poloidal current due to finite p' in SOL flows in the opposite direction). The magnitude of this current can be roughly estimated from the results of SOLPS4.3 [8] modelling by assuming an equal potential drop between the mid-plane and each of the targets. If the maximal value of the current density in SOL were at the separatrix, then the equilibrium calculations would be problematic because of the separatrix angle collapse (at least, in the conventional single null magnetic topology). However, the estimates show the current density maximum shifted outside the separatrix (figure 1b). Even in this case, the equilibrium limit due to the X-point splitting is about 150KA for the poloidal current in the SOL, despite the wider current carrying layer [5]. As a rough estimate of the current due to different electrostatic potential of the divertor targets is 500 kA in ITER, the parallel current density assessment would require self-consistent SOL simulations also taking into account the diamagnetic current due to finite p'. However, low-n kink modes become unstable well before reaching the equilibrium limit (SOLPx3Jx4 in figure 1a) for the current density in SOL 4 times larger than at the separatrix: for the maximal $j_{||}$ in SOL J_{SOL} it corresponds to J_{SOL}/J_{ped} =2.5 in terms of the maximal $j_{||}$ in the pedestal J_{ped} = 0.7 MA/m^2 for the original ITER equilibrium. Such a destabilization suggests an existence of a new edge peeling mode driven by the SOL current density. Indeed, if we plot marginally stable values of J_{SOL}/J_{ped} under variation of $j_{||}$ in SOL versus the conducting plasma width, then the curve corresponding to the toroidal mode number n=3 would feature non-monotonic behavior with the minimum J_{SOL}/J_{ped} ~2 reached beyond the location of the maximal parallel current density in SOL (figure 1c). For higher toroidal harmonic numbers the coupling between the edge peeling mode (resonantly sensitive to the current density value at the conducting plasma edge) and the P-B modes determines the SOL current density limit. Such a situation seems quite natural for ITER plasmas with very thin SOL but presumably thicker layer of plasma hot enough to carry the eddy currents necessary for external kink mode stabilization.

3. SOL peeling modes as possible ELM triggers in JET As discussed in [6] the JET shots #84797 and #87342 feature quite different ELM triggering conditions. The former one corresponds to conventional type-I ELMs triggered by P-B modes, while for the latter the pedestal p' is below P-B stability threshold, so an alternative ELM triggering mechanism is under discussion. Taking into account the SOL width estimates for JET λ_q~2 mm, λ_p~7 mm [2], the sensitivity of the external kink mode stability on the SOL current density was studied. The same family of $j_{||}$ profiles shifted from the separatrix into SOL (figure 1b) but rescaled to fall-off length 7 mm was used. Figure 2a illustrates the edge peeling mode thresholds in terms of parallel current density ratio J_{SOL}/J_{ped} ($J_{ped} = 0.16$ MA/m^2 is the maximal $j_{||}$ value in pedestal) featuring the resonance with the maximal current density at the conducting plasma edge for the shot #87342. Figure 2b shows the mode structure with maximal plasma displacement at the inboard SOL. Some coupling between the edge peeling mode and the P-B mode inside the separatrix also takes place (figure 2c shows typical P-B mode structure inside the separatrix) but not sufficient to drive the mode unstable with wide conducting mantle in SOL in contrast to the ITER example with the pedestal deeper into the P-B unstable range of parameters. For the same reason there is no perceptible difference in the SOL current density thresholds between the two considered JET shots.

4. Discussion Low to medium-*n* edge peeling modes are destabilized with finite parallel current in SOL and can be considered as an alternative ELM trigger in tokamaks with divertor. A possible source of the SOL current is the thermoelectric current between the divertor plates. On the other hand, conducting plasma in SOL provides an additional stabilization for external kink modes. That is why the edge peeling mode, when it is weakly coupled to P-B modes in the pedestal, manifests itself in a resonant manner being the most unstable with maximal parallel current density close to the edge of conducting plasma in SOL. No difference with respect to the edge peeling stability margin exists between #84797 (low gas puff, pedestal at P-B limit) and #87342 (high gas puff, stable P-B modes) JET shots. The stability margin in the SOL current density is a factor of 2 above the current density in the pedestal. Realistic/measured SOL current density profiles would probably tell more about a possibility to attribute the ELM trigger to the edge peeling instability. In ITER plasmas with thin SOL width and pedestal deeper into the P-B unstable range of parameters, a strong coupling of the edge peeling modes to the P-B modes takes place reducing the threshold for low-*n* mode instability.

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(a) *(b)* *(c)*

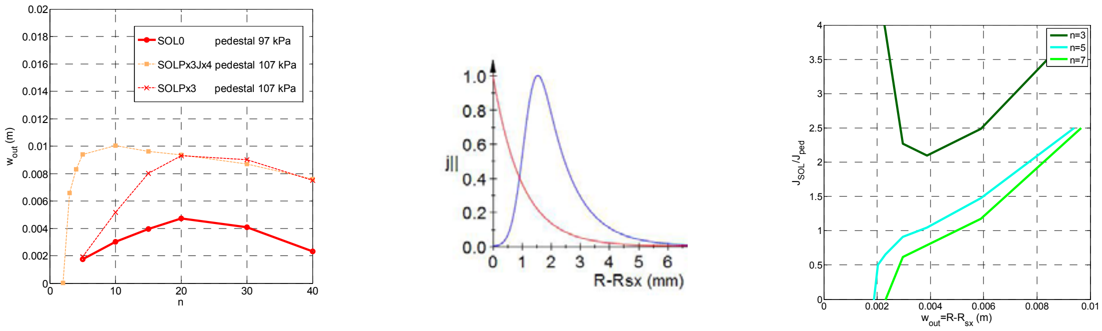

Figure 1. ITER: a – critical width of the conducting plasma outside the separatrix vs toroidal wave number; different plasma profiles in SOL, the legend shows the pressure values at the top of the pedestal in kPa; b – normalized profiles in SOL: exponential with a fall-off length 1 mm (red line) and shifted from the separatrix (blue line); c – marginal values of SOL current density vs conducting plasma width for different toroidal wave numbers.

(a) *(b)* *(c)*

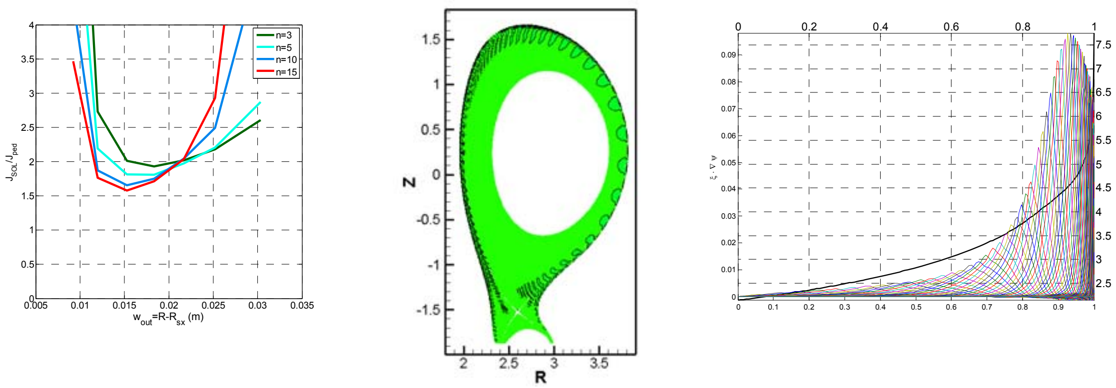

Figure 2. JET #87342: a – marginal values of SOL current density vs conducting plasma width for different toroidal wave numbers; b – level lines of normal plasma displacement, n=15, ω^2/ω^2_A=-8e-3; c – harmonics of $\xi\cdot\nabla\psi$ inside plasma vs square root of normalized poloidal flux.