32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-5.064 (2005)

Magnetic ELM Triggering and Edge Stability of Tokamak Plasma

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Ideal MHD external kink modes driven by large current density and pressure gradient values in the pedestal region of the tokamak plasma are believed to trigger the edge localized modes (ELM). Since the ELM triggering mechanism depends on the edge current and pressure profiles, a modification of these parameters can lead to a variation of the ELM cycle controlling their frequency and amplitude. In experiments on TCV the vertical oscillation of the plasma generates an edge current which, in turn, triggers or inhibits ELMs depending on the sign of the induced edge current [1]. Similar experiments have been performed on ASDEX Upgrade (AUG) to test this technique on an additionally heated H-mode plasma with type I ELMs [2].

To understand the difference in the triggered ELM behavior the detail quasi-equilibrium modeling of the edge current induction in the ELM triggering experiments was performed with the PET code integrated into the DINA-CH Simulink [3] environment taking into account the magnetic field diffusion and with realistic plasma profiles in the pedestal region. Plasma shape perturbation in the ELM controlling sequences was reproduced for realistic profiles with pedestals and self-consistent bootstrap current. Stability calculations were performed with the KINX code interfaced to the environment. Higher local squareness of the boundary, corresponding to the downward plasma motion, was found to destabilize kink-ballooning external modes. The corresponding reduction of the edge current density is typically accompanied by a current density increase at the top of the pedestal that diminishes its influence on the stability. The overall effect of the plasma shape distortion on the stability is significantly stronger than that of current density perturbations.

The results of the magnetic triggering simulation for ITER parameters are presented.

1 Quasi-equilibrium modeling with pedestal profiles

The new option to prescribe temperature and density profiles in terms of the normalized toroidal flux $\Phi/\Phi_s = \rho^2$ was implemented into the DINA-CH. The equilibrium pressure is self-consistently calculated from the input profiles and, together with a prescribed averaged current density and total current value, fully describe the initial equilibrium.

The profiles were prescribed using the following expression:

$$f = (f_0 - f_p - f_s + f_e)(1-\rho^a)^b + \frac{1}{2} f_p \left(\tanh\frac{d-\rho}{c} + 1\right) + f_s - f_e;\ f_e = \frac{1}{2} f_p \left(\tanh\frac{d-1}{c} + 1\right),$$

that allow to independently change the values at the axis f_0, at the separatrix f_s and at the top of the pedestal f_p and pedestal width and position. For the ASDEX Upgrade (AUG) case examples of the profiles are given in Fig.1a. A simple parabolic current density profile was chosen for the initial equilibrium. The self-consistent bootstrap current calculated taking into account the effect of the collisions [4] builds up in approximately 0.05s in the pedestal region.

The ELM triggering scenario described in [2] was considered. The results of the modeling confirm the analysis of the plasma shape evolution pattern performed in [5]. In Fig.1c the extreme positions of the separatrix during the period in the voltage perturbations are shown. The local increase/decrease of the boundary squareness during the perturbation correlate well with plasma downward/upward motion and the minimal/maximal value of the current density at the plasma boundary, respectively. The upper triangularity, $\delta = 0.03$, changes very little during the perturbation.

The dependence of the edge current perturbations on the plasma temperature was studied in the series with different values of the temperature at the separatrix. The magnitude of the current density perturbations scales approximately linearly with the temperature. A remarkable feature of the current density perturbation pattern is the correlation of the minimal values at the plasma edge with the maximal perturbation at the top of the pedestal (Fig.2b).

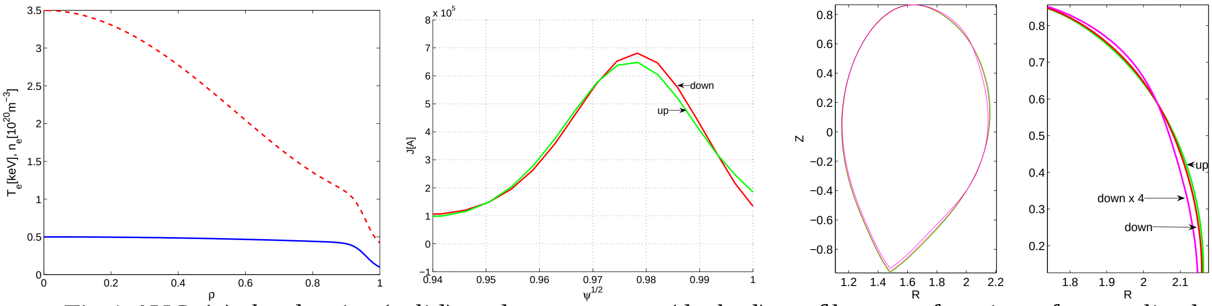

Fig.1 AUG (a) the density (solid) and temperature (dashed) profiles as a function of normalized radius; (b) averaged current density perturbation during the period; (c) the extreme boundary positions during the period and the boundary with the perturbation amplified four times.

2 Stability analysis

Ideal MHD stability of the equilibrium sequences in the ELM controlling scheme was investigated with the KINX code that includes plasma up to the separatrix.

Two equilibria with minimal and maximal current density at the edge (downward and upward phases of plasma motion respectively) during the period were chosen. The stability margins were calculated in the equilibrium series generated by rescaling the parallel current density and pressure gradient profiles in the pedestal region for each equilibrium keeping the total current and plasma boundary fixed (a similar procedure was used in [6]). A good approximation for an equilibrium with self-consistent bootstrap current is obtained when the current density and pressure gradient are multiplied by the same factor S. The comparison of the stability margins in S showed about 2% difference between the two equilibrium series: $S = 1.07$ - downward and $S = 1.05$ - upward for the most unstable mode $n = 7$. It correlates with the observed ELM triggering during the downward plasma motion despite lower current density at the edge. In order to separate influence of the current density perturbations on the stability from the shape influence, the profiles and the boundaries were swapped between the equilibria. It was found that the stability margins due to the profile change differ by less than 0.5% with the profile having a maximal edge value being slightly more unstable. Such a weak influence of the current density profile perturbation on the stability can be explained by the special pattern of the perturbation mentioned above.

For the stability diagrams shown in Fig.2 the equilibrium corresponding to the downward plasma motion was chosen as reference. The current density and pressure gradient profiles were rescaled independently in order to obtain the stability boundaries in the parametric parametric plane $(p'/p'_c, J_{||}/<J>)$: the maximal parallel current density $J_{||}$ in the pedestal is normalized by the averaged plasma current density $<J> = I_p/S_p$ and the maximal pressure gradient is normalized by the limiting value in the first region of the high-n ballooning mode stability at the separatrix. In order to visualize the influence of the boundary perturbation on the stability, another reference equilibrium with the perturbation of the boundary amplified four times (Fig.1c) was generated with the same profiles. The reference equilibria are shown by the green circle with the error bar corresponding to the current density perturbation during the period.

The difference in the stability margin along the bootstrap line due to the stronger boundary perturbation is approximately proportional to the scaling factor 4 in the boundary perturbation: $S = 0.99$ versus reference $S = 1.07$ for $n = 7$ – about 8% drop. The high-n stability boundary shifts to higher values of the normalized current density in the pedestal due to the increase of the plasma boundary squareness. This feature is accompanied by a shift of all medium-n mode stability boundaries to lower values of pressure gradient. The effect is stronger for higher n: in particular, the $n = 10$ mode instead of $n = 7$ becomes most unstable along the bootstrap current line (dashed). The obtained results are in agreement with the study of the plasma shape influence on the edge kink-ballooning instabilities [7] where the destabilizing influence of the cross-section squareness was associated with higher values of pedestal current density needed for the second stability access.

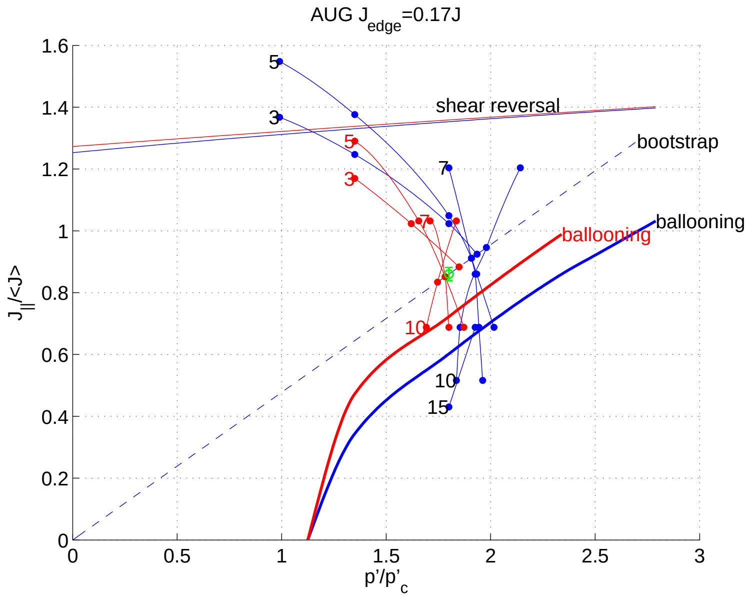

Fig.2 AUG (a) the edge stability diagrams for the reference equilibrium (blue) and the equilibrium with the amplified boundary perturbation (red)

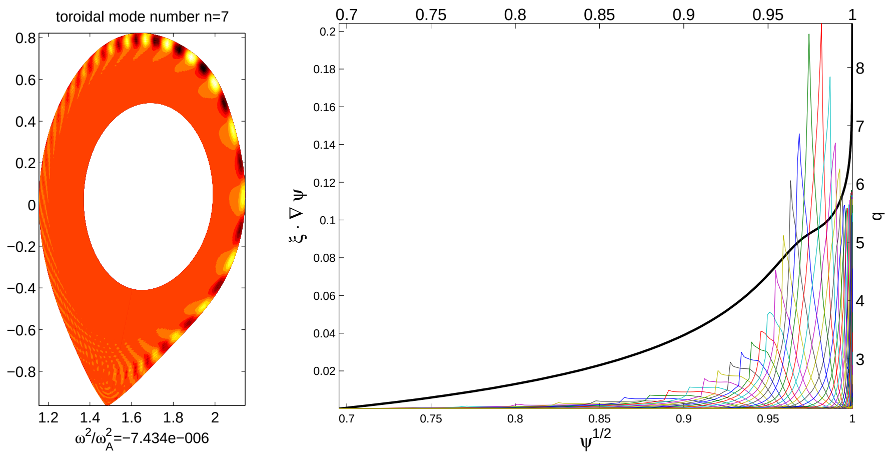

Fig.2 AUG (b) contour lines of the plasma normal displacement and (c) the corresponding harmonics in the straight field line coordinate.

3 ELM triggering in ITER

The first results on the current induction in ITER configuration were presented at the EPS2004 [8]. The new version of the DINA-CH90 code was used for the simulations with the realistic profiles with pedestals (Fig.3a). The self-consistent bootstrap current builds up in approximately 0.5s in the pedestal region. The perturbing voltages $\pm 10V$ per turn were applied to the coils PF2-3 and PF4-5. The voltage perturbation wave-forms were chosen as in TCV experiments [1]: pulses with a duration of 0.2s and a period of 2s. The resulting magnetic axis vertical position trajectory during the period is shown in Fig.3c. The current density perturbation pattern during the plasma upward motion is similar to the AUG cases. However, the magnitude of the perturbation at the edge is about 4 times higher compared to the values at the top of the pedestal (Fig.3b). That is connected with a narrower skin depth for the higher temperature ITER plasma.

For high triangularity the edge kink-ballooning mode stability boundary corresponds to higher values of the pedestal pressure gradient so a narrower pedestal width was prescribed. However for the chosen $\beta_p = 0.2$ the stability margin along the bootstrap line is still within a factor of 2 above the the reference equilibrium with the upper triangularity $\delta = 0.52$. The most unstable toroidal mode number is $n = 15$ that corresponds to a shift in the wave numbers having the second stability access in accordance with the scaling $w \times n \times q_{95} = \text{const}$ [8] for narrower pedestal width w compared to the AUG case. Reaching the stability margin in the self-consistent equilibrium would require narrower pedestals for the same values of the pedestal temperature and density. It takes finer resolution near the plasma edge both for the rectangular and adaptive flux grids used in the present versions of DINA and PET codes. Despite quite strong current density perturbations at the edge, the stability margin S calculated in the series with rescaled profiles in pedestal region are close to each other: $S = 2.06$ for downward motion and $S = 2.02$ for upward motion. In relative figures it gives the difference 1.5% comparable to the effect of relatively small boundary perturbations in the AUG case.

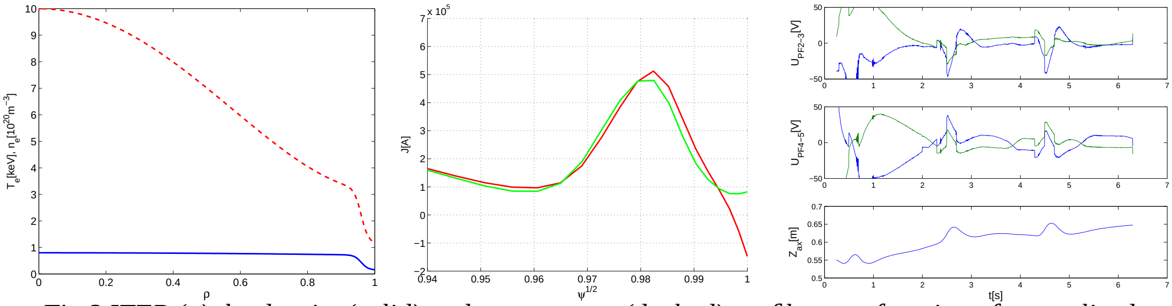

Fig.3 ITER (a) the density (solid) and temperature (dashed) profiles as a function of normalized radius; (b) averaged current density perturbation during the period; (c) voltages and the coordinate of the magnetic axis in time

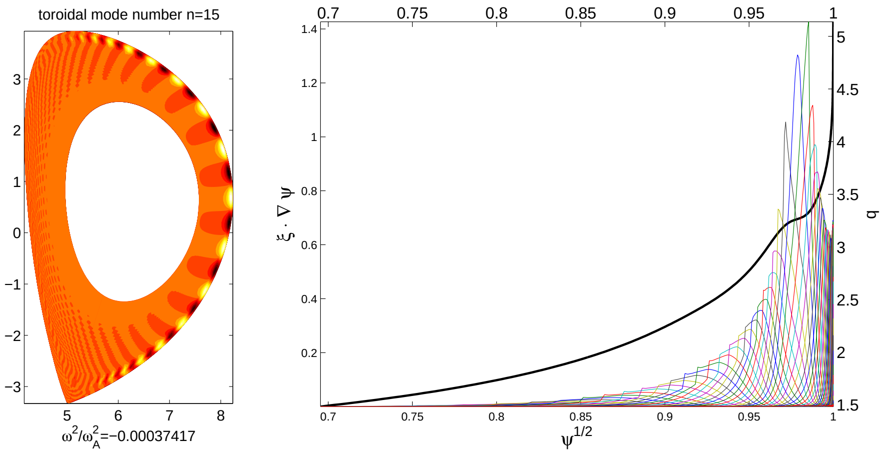

Fig.4 ITER (a) contour lines of the plasma normal displacement and (b) the corresponding harmonics in the straight field line coordinate.

3 Conclusions

The local plasma boundary squareness increase during the voltage perturbation cycle was found to be destabilizing for medium-n edge kink-ballooning modes in accordance with the ELM triggered in the AUG experiment when the plasma moves down. The relative influence of the boundary perturbation is much stronger than the variations in the current density. However, for higher temperature ITER plasma the current density variations alone can be responsible for the kink-ballooning mode destabilization. Both current density and plasma boundary variations are possible candidates for the ELM triggering in TCV [5].

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Acknowledgements The CRPP authors are supported in part by the Swiss National Science Foundation.