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Advanced shaping and stability limits in the TCV tokamak

S.Yu.Medvedev[1], A.A.Ivanov[1], A.A.Martynov[1], Yu.Yu.Poshekhonov[1],
Y.R.Martin[2], J-M.Moret[2], F.Piras[2], A.Pitzschke[2], A.Pochelon[2], H.Reimerdes[2], O.Sauter[2], L.Villard[2]
and the TCV team
[1]*Keldysh Institute, Russian Academy of Sciences, Moscow, Russia*
[2] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, Lausanne, Switzerland*

In support of the TCV experimental campaign aiming at studying H-mode plasmas at various separatrix shapes, in particular for advanced shaping including negative triangularity [1, 2] and snowflake (SF) divertor [3, 4], beta limit and edge stability studies are performed with the stability KINX code. It includes a sensitivity study of the edge stability (stability boundaries and most unstable toroidal mode number dependence on the pedestal profiles) for the up/down negative/positive triangularity equilibria. Possible consequences for the ELM behavior are discussed. External kink beta limits without/with TCV wall stabilization and resistive wall mode (RWM) growth rates are computed for the negative triangularity equilibria as candidates for RWM studies on the TCV.

1 TCV negative triangularity shots and edge stability

The TCV mission "H-mode at negative triangularity" is a continuation of the campaign 2008-2010, when initial experiments were attempted. During this period several equilibria with a LFS single null X-point were tested at different shapes and values of safety factor q_{95}. This was to test how to set up a LFS divertor with an horizontal leg on the continuous carbon tile ring just below equator, and with a vertical divertor leg reaching the bottom floor. These Ohmic plasmas were generally entailed by more or less strong mode activity and H-mode was not reached. No additional heating was however delivered to these plasmas so far. So during these short initial experiments, the existence of H-mode in such LFS X-point has neither been demonstrated nor proven impossible. On the other hand, during this same campaign, a standard plasma with HFS single-null X-point was used while changing during the discharge the positive upper-triangularity to negative ($\delta_{up} < 0$). This resulted - as expected from the ideal MHD stability [1] - in higher frequency ELMs of lower expelled normalized energy $\Delta W_{ELM}/W_p$. This was realized in two shots with a minimum negative triangularity reached of $\delta_{up} = -0.26$.

The plasma shape from the TCV shot #40530, $t = 1.25s$ was used for the free boundary equilibrium reconstruction with the SPIDER code [5]. The pressure profile for the equilibrium calculation was taken similar to the one measured in the TCV H-mode shots described in [6].

Collisionless bootstrap current in the pedestal was assumed. This negative/positive (top/bottom) triangularity plasma is compared to the same kind of reconstruction performed for the shot #40630, $t = 0.5s$ featured negative/negative triangularity (Fig.1a, Fig.1b). The vertical $n = 0$ growth rates of the two equilibria within TCV wall are close to each other: $275/350s^{-1}$ for the profiles with pedestal (internal inductance $l_i = 0.75$) and $350/460s^{-1}$ for the profiles without pedestal ($l_i = 0.85$) for the shots #40350/40630. Higher elongation, negative triangularity #40630 configuration profited from the proximity to the outer wall and the roof of the chamber and low upper triangularity as well.

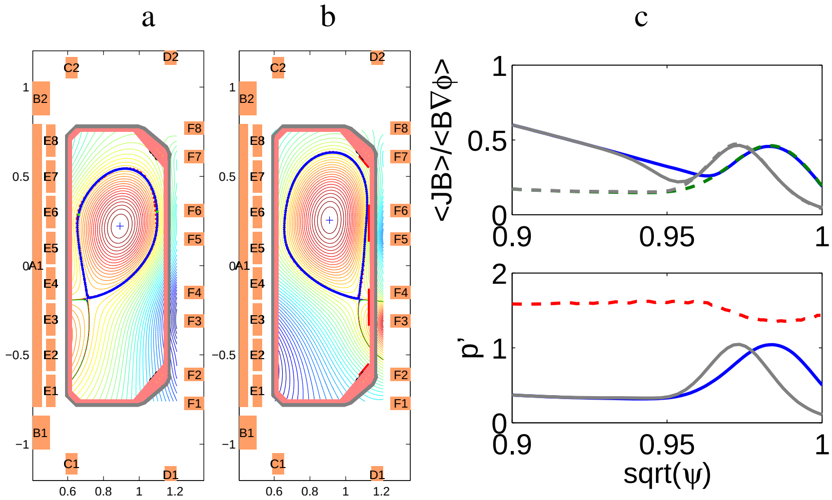

Fig.1. Level lines of poloidal flux for the TCV equilibria #40350 $t = 1.25s$ (a) and #40630 $t = 0.5s$ (b). The pedestal profiles for the two positions of the pedestal maximum are also shown (c) together with ballooning limit for pressure gradient (dotted line).

The edge stability diagrams were generated for the fixed boundary equilibria with the separatrices taken as plasma boundaries. Pedestal profiles with two different positions of the pedestal were used (Fig.1c). In accordance to [1] the negative triangularity of the X-point has a major influence on closing up access to the second stability. However, even modest negative triangularity of the #40350 plasma produces the same effect. Concerning the pedestal profile variations, the inward shift of the pedestal, that opens a wide access to the second stability region in the positive triangularity plasma, does not open access for the negative triangularity. Again, the negative triangularity X-point case is less sensitive to the pedestal variations being more unstable (Fig.2). Taking into account the diamagnetic stabilization should shift the ideal MHD stability limits in case of negative/positive triangularity. But crossing the ballooning stability boundary in the negative X-point triangularity case leads to Mercier criterion violation thus destabilizing global internal modes not sensitive to the diamagnetic effects.

To estimate beta limits against global external kink modes, the pressure gradient was lowered both in the plasma core (that is consistent with Mercier instability of the negative triangularity plasma in the absence of shear due to the lack of magnetic well) and in the pedestal (in order to decouple from the edge stability details). The value of axis safety factor q_0 was kept above 1 to avoid the $m = 1$ mode.

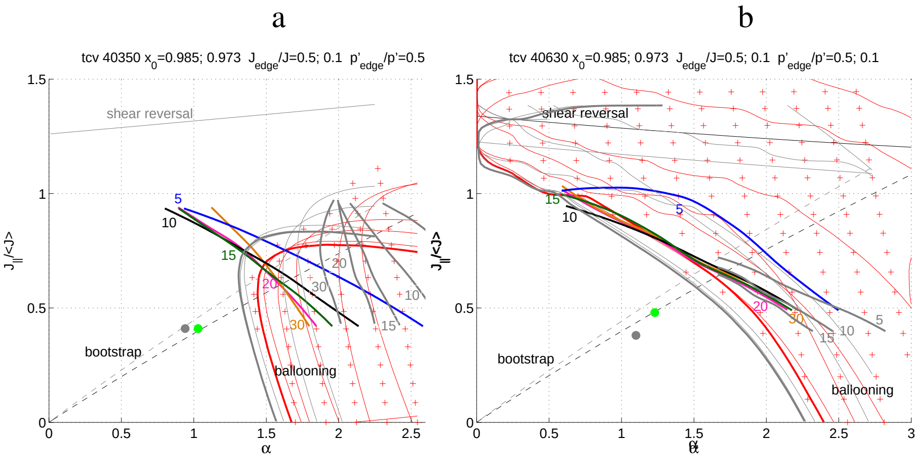

Fig.2. Edge stability diagrams for the plasma shapes of the shot #40530 (a) and #40630 (b). The colored and gray lines corresponds to the pedestal profiles shown in Fig.1c.

It turned out that the $n = 1$ beta limits with and without TCV wall are close to both geometries: $\beta_{Nnowall}/\beta_{Nwall} = 1.98/2.91$ vs $1.93/2.86$. However, the $n = 2,3$ limits are lower and close to the $n = 1$ no-wall limit in the negative X-point case: $\beta_{Nnowall}(n = 2)/\beta_{Nnwall}(n = 3) = 2.69/2.85$ vs $2.36/2.01$. This is most probably due to the Mercier criterion violation, that takes place in the region of high pressure gradient in the outer half of the plasma, and corresponding destabilization of global internal modes coupled to external kinks.

The $n = 1$ RWM growth rates with the TCV wall were computed for the series of equilibria without pedestal. For all considered cases, and despite large variations of the gap between β_{nowall} and β_{wall} limits, the growth rates are within 10% of the scaling $\gamma_{RWM} = C\tau_w C_\beta/(1 - C_\beta)$, $C = 4$, proposed in [7] with the resistive wall time for TCV $\tau_w = 8 \cdot 10^{-3} s$ and scaled beta between no-wall and ideal wall limits $C_\beta = (\beta - \beta_{nowall})/(\beta_{wall} - \beta_{nowall})$.

2 Positive/negative versus negative/positive triangularity plasmas: beta limits and RWM study perspective

The $n = 1,2,3$ beta limit computations were performed for the TCV equilibria with positive/negative and negative/positive triangularity (Table 1). The results suggest that the overall higher beta limits for positive/negative case are connected with the fact that the upper positive triangularity has more influence on the core plasma than the negative triangularity of the separatrix. At the same time the $n = 2,3$ no-wall beta limits are close to the $n = 1$ limit for the pos/neg cases: negative X-point triangularity leads to destabilization of Mercier modes near the boundary resulting in lower beta limits for coupled internal/external kink modes. Moderate values of negative triangularity may help making Mercier modes more stable, but this requires higher PF currents in the TCV PF coils. On the other hand, despite the lower beta limits for negative/positive equilibria, the $n = 1$ and $n = 2,3$ beta limits are well separated providing big room for the RWM studies. Moreover, the $n = 1$ no-wall beta limit can be controlled: the larger the negative triangularity the lower the beta limit, thus probably less power is needed to reach it.

	$\beta_N(n=1)$	$\beta_N(n=2)$	$\beta_N(n=3)$
$\delta/\delta_x = 0.30/-0.8$	2.46	2.62	2.55
$\delta/\delta_x = 0.13/-0.8$	2.13	2.56	2.53
$\delta/\delta_x = 0.18/-0.4$	2.30	3.25	3.21
$\delta/\delta_x = -0.40/0.8$	1.40	2.04	2.23
$\delta/\delta_x = -0.20/0.7$	1.98	2.69	2.85

Table 1. Normalized beta limits for plasmas with different combinations of up/down triangularities.

3 Conclusions

The following suggestions/questions can be proposed for the TCV experimental mission:

- Extension of HFS single-null X-point to H-mode with higher upper negative triangularity would further reduce $\beta_N(n=1)$ limits, leaving a sizeable separation between $n=1$ and $n=2,3$ no-wall limits. This makes such plasmas good candidates for RWM studies in TCV. In H-mode operation, no large type I ELMs are expected because of the closed access to the second stability in the pedestal.

- Would higher beta limits in the equilibria with positive triangularity help to attain H-mode at negative X-point triangularity? Once the H-mode is attained, there is a possibility to reach even higher pedestal pressure (at least at low bootstrap current density) compared to the conventional positive triangularity H-mode cases.

- The SF configurations or double null equilibria with the nulls at the LFS would lead to still higher pressure gradients in the first region of ballooning stability due to higher shear.

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