Stability limits for tokamak plasma with negative triangularity

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Negative triangularity tokamak plasmas are subject of an increased interest both in existing experiments [1] and in studies of core physics as well as power handling relevant to the fusion demonstration power reactor [2]. The ideal MHD stability calculations for the negative triangularity plasma extend the investigation of the TCV tokamak beta limits and edge stability [3, 4] to double null shapes, lower aspect ratio and negative shear. In case of the negative triangularity, the 2nd stability access is closed for ballooning modes and a well defined limiting pressure gradient profile exists in the positive shear region. The external kink mode stability limit can be obtained by rescaling the limiting profiles.

H-mode discharges with upper negative triangularity in TCV demonstrate significant mitigation of type I ELM peak power losses [1]. This is consistent with lower edge stability limits for the pedestal [3]. For double null negative triangularity configurations higher pedestals can be stable due to higher shear at low pedestal current density. At the same time a destabilization of a whole range of fixed boundary modes takes place, once the Mercier criterion for localized modes is violated, implying possible changes in the ELM characteristics. In particular, the diamagnetic stabilization on the edge stability is much less effective than in a standard case when peeling-ballooning modes set pedestal height limit.

1 Double null negative triangularity in TCV In the negative triangularity experiments on TCV in 2008-2011 LFS single null X-point configurations were tested, but the existence of H-mode with LFS X-point has neither been demonstrated nor proven impossible. In the HFS single-null X-point configurations with changing positive to negative upper-triangularity H-mode with $\delta_{up} = -0.26$ showed higher frequency ELMs together with lower expelled power $\Delta W_{ELM}/W_p$ [1].

Free-boundary equilibrium calculations with the SPIDER code [5] demonstrated that double null negative triangularity is possible in TCV (Fig.1). Under moderate PF coil currents a configuration with elongation $\kappa = 1.36$ features $n = 0$ mode growth rates $\gamma = 400 - 500s^{-1}$. The proximity of plasma to the LFS wall plays a major role in the vertical stabilization.

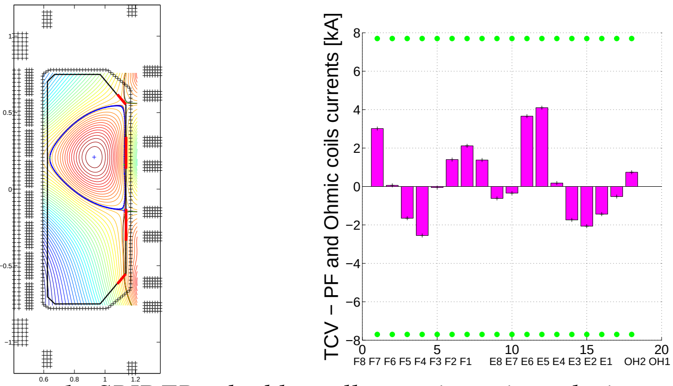

Figure 1. SPIDER: double null negative triangularity equilibrium in TCV (a); PF coil currents in kA/turn, the 7.8kA hard limit is shown by green dots (b).

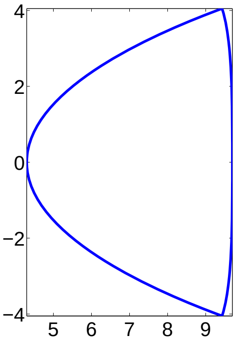

Figure 2. Analytic double null negative triangularity shape.

2 Beta limits for the reactor scale configuration with $R = 7m, a = 2.7m(A = 2.6), k = 1.5, \delta = -0.9$ [2] were investigated. The analytic plasma boundary shape with double X-points [7] was used (Fig.2). An iterative procedure was employed to obtained negative triangularity equilibria with ballooning/Mercier optimized pressure profile [6]. There is no access to the 2nd ballooning stability (at least in the regions with positive shear), and a well defined limiting pressure gradient $p' = dp/d\psi$ exists for fixed profile of parallel current density $< \vec{j} \cdot \vec{B} > / < \vec{B} \cdot \nabla\phi >$. Several iteration are sufficient to get self-consistent equilibrium with limiting p'. For a particular case with monotonic q-profile and internal inductance value $l_i = 0.9$ it gives $\beta_N = 3.4$ for normalized current $I_N \equiv Ip[MA]/(a[m]B[T]) = 0.9$ (Fig.3a, dashed lines shows collisionless bootstrap current density and limiting p' in the corresponding frames). To determine the stability limit versus external kink mode stability the p' profile is proportionally reduced in a series of equilibria. The stability calculations with the KINX code [8] give a $n = 1$ beta limit of $\beta_N = 3.2$ without wall stabilization (lowest value for checked toroidal mode numbers $n = 1 - 5$). The mode structure (level lines of plasma displacement normal to magnetic surfaces) is presented in Fig.3b. The wall stabilization gives very little increase in the beta limit because of strong coupling of fixed boundary global Mercier modes to external kink modes: with the wall proportional to the plasma boundary $a_w/a = 1.3$ $\beta_N = 3.3$ for $n = 1$ mode while $n > 2$ limits are set by internal modes at $\beta_N < 3.6$. Decreasing shear (lower l_i) leads to lower beta limit in accordance with the Mercier criterion behavior in the absence of magnetic well. However the external kink limit is not enhanced also for higher $l_i = 1.3$ at lower plasma current $I_N = 0.45$ $(q_0 > 1)$ with the limiting values close to $\beta_N \simeq 3$. For reversed shear q-profiles ballooning/Mercier stable pressure gradients are larger in the negative shear region. However large values of p' in the vicinity of low shear region lead to the destabilization of infernal modes. Approximate bootstrap current alignment with total parallel current density in the core was chosen to limit p' in the core with negative shear, but the p' profile was optimized in the positive shear region resulting in

$\beta_N = 3.55$ (Fig.4a). Rescaling the pressure gradient gives the global $n = 1$ mode stability with $\beta_N = 2.1$. Note that $q_{min} > 2$ was maintained for better infernal mode stability due to the lower normalized current $I_N = 0.7$. The mode structure is shown in Fig.4b.

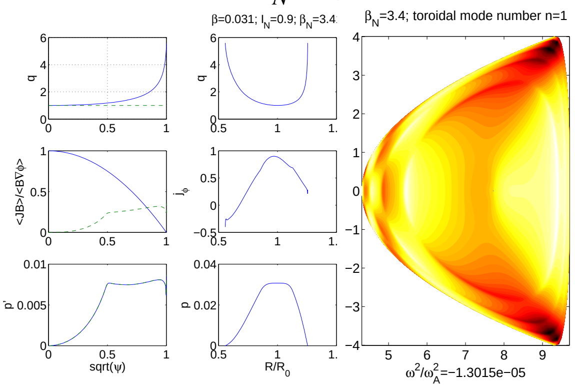

Figure 3. Plasma profiles in the equilibrium with Mercier/balloooning limiting pressure gradient (a); $n = 1$ mode structure (b).

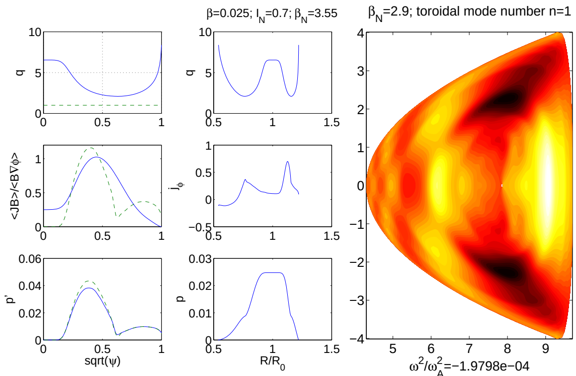

Figure 4. Plasma profiles in the equilibrium with Mercier/balloooning limiting pressure gradient, reversed shear case (a); $n = 1$ mode structure (b).

Another interesting feature of low aspect ratio negative triangularity plasmas is the significantly lower q_{95} values for the same normalized current I_N because of lower toroidal magnetic field flux $\Phi = \int F/RdS$. In particular, close to the current limit, force-free plasmas with q_{95} below 1 can be stable against external $n = 1$ kink mode. However it does not mean that the maximal current I_N increases for negative triangularity.

3 Pedestal height The edge kink-ballooning mode stability limits usually follow the changes in the high-n limit behaviour. Worse localized mode stability leads to lower pressure pedestal height attainable in the negative triangularity configurations and can potentially result in different ELM behaviour for positive and negative triangularity configurations. Indeed, changing upper triangularity in TCV plasmas from positive to negative brings an increase in Type I ELM frequency and lower expelled power per ELM. This ELM mitigation is obtained at the expense of a reduction of the pedestal height. Whether core confinement improvement at negative triangularity can compensate the confinement loss at the pedestal is still debatable and the answer may depend on the turbulent regime [1].

In the negative triangularity double null configuration, higher pedestals can be stable in the 1st ballooning stability region due to high edge shear. Plasma profiles similar to TCV pedestal profiles [9] were used. In Fig.5 the edge stability diagrams calculated with the KINX edge stability package including diamagnetic stabilization are presented. A simple model of the diamagnetic stabilization was used $\gamma_{MHD} < \omega_*/2$, where ω_* is the ion diamagnetic drift frequency, and the ratio of the ion cyclotron and Alfvén frequencies ω_{Bi}/ω_A, which enters in the expression $\omega_* = \dfrac{n\omega_A}{\omega_{Bi}}\omega_A \dfrac{R^2}{B}\dfrac{d\mu_0 p_i}{d\psi}$, was chosen as for ITER deuterium plasma typical parameters: $\omega_{Bi}/\omega_A = 5.2 \cdot 10^{-3}$. Note that diamagnetic stabilization is very inefficient for the fixed boundary Mercier modes $n \geq 5$ (compare Fig.5a and Fig.5b) which in fact set the edge stability limits. Only low-n mode limits significantly change with the free boundary.

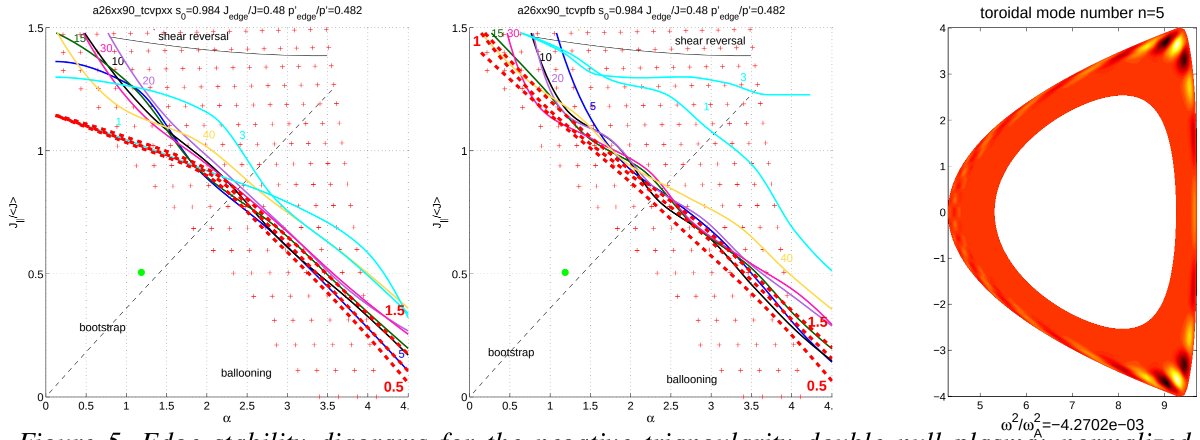

Figure 5. Edge stability diagrams for the negative triangularity double null plasma; normalized pressure gradient α *and parallel current density* $j_{||}/<j>$ *are estimated at the maximum across the pedestal region. Free boundary (a) and fixed boundary cases (b). Thick dashed lines show* $\gamma/(\omega_*/2) = 0.5, 1, 1.5$ *level lines for the most unstable mode, color solid lines show* $\gamma/(\omega_*/2) = 1$ *limits for modes with individual toroidal mode numbers, red crosses mark ballooning/Mercier instability;* $n = 5$ *mode structure (c).*

4 Discussion Negative triangularity tokamak configurations with optimized pressure gradient profiles can be stable for normalized beta values $\beta_N \simeq 3$. Wall stabilization is very inefficient due to strong coupling between fixed boundary global Mercier modes and external kink modes. Reversed shear configurations allow for larger p' in the core and larger bootstrap current fraction but coupling to infernal modes leads to lower $\beta_N \simeq 2$ and further profile optimization is needed.

Internal modes (unstable already with fixed boundary condition but localized in the pedestal region) set the pedestal height limit, which is much less sensitive to diamagnetic stabilization and pedestal profile variations than the conventional peeling-ballooning mode limits. Double null negative triangularity configurations feature quite high stable pedestals in the 1st region of ballooning stability provided that pedestal current density is low (high collisionality regimes).

Plasma vertical control should be investigated for negative triangularity double null configurations. Even for moderate elongation $\kappa = 1.5$, conducting wall at $a_w/a < 1.25$ is needed to provide ideal $n = 0$ stability for equilibrium with $l_i = 0.9$. With 6cm thick steel wall at $a_w/a = 1.2$, the corresponding $n = 0$ growth rate is $95s^{-1}$ and active feedback control should be assessed.

[1] A. Pochelon *et al.* Plasma and Fusion Research **7** , 2502148(2012)
[2] M.Kikuchi, T.Takizuka, M.Furukawa, JPS Conf. Proc., 015014 (2014)
[3] S.Yu.Medvedev *et al.* 35th EPS Conf. on Plasma Physics, ECA Vol.32D, P-1.072 (2008)
[4] S.Yu.Medvedev *et al.* 36th EPS Conf. on Plasma Physics, ECA Vol.33E, P2.143 (2009)
[5] A.A.Ivanov *et al.* 32nd EPS Conf. on Plasma Physics 29C (ECA), P-5.063 (2005)
[6] L.M.Degtyarev *et al.* On the tokamak β-values limited by ideal MHD-stability. Int. Conf. on Plasma Physics, Lausanne (Switzerland), 27 Jun - 3 Jul 1984, EUR-9708(V.1), p. 157-175 (1985)
[7] V.V.Drozdov, Private communication, March 2014.
[8] L. Degtyarev *et al.* Comput. Phys. Commun. **103**(1997)10
[9] R.Behn *et al.* Plasma Phys. Control. Fusion **49** (2007) 1289

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