MHD stability of plasma with large bootstrap current fraction in spherical tokamaks

S.Yu.Medvedev[1,3], A.A.Ivanov[1,3], B.V.Kuteev[2], V.E.Lukash[2], R.R.Khayrutdinov[2]
[1]*Keldysh Institute of Applied Mathematics, 125047 Moscow, Russia*
[2]*NRC «Kurchatov Institute», 123182 Moscow, Russia* [3]*Fusion centre*

Optimization of plasma parameters for spherical tokamaks (ST) with low aspect ratio and high bootstrap current fraction is an actual problem both in application to a compact tokamak-reactor and to new concepts of the fusion neutron sources (FNS) based on tokamak. Maximization of the bootstrap current fraction in non-inductive stationary discharges implies the geometry of the plasma cross-section with high elongation and triangularity.

1 Equilibrium and stability of FNS-ST Theoretical MHD limits in the tokamaks with separatrix at the plasma boundary show a strong enhancement of the current and beta limits with decreasing aspect ratio [1, 2]. At the same time, better vertical stability of ST plasmas allows for high elongation. As applied to advanced stationary regimes with low values of internal inductance l_i =0.3–0.4 in the proposed compact tokamak FNS-ST [3] (aspect ratio R/a = 1.75, elongation κ=2.75 and triangularity δ=0.4), the vertical instability growth rates below 100 s^{-1} are attainable with divertor plates playing a role of passive stabilizers (Fig.1). The stability limit on the plasma current set by

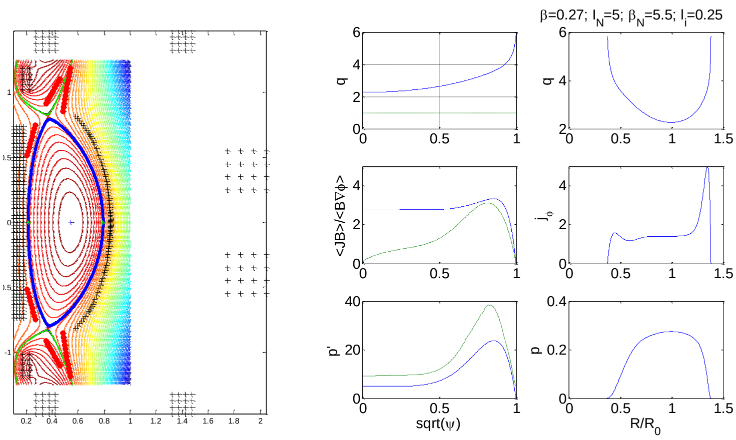

Figure 1. Level lines of the poloidal flux and PF coils for free-boundary equilibrium computed with the SPIDER code [4], divertor plates shown in red (left); plasma profiles in FNS-ST (right)

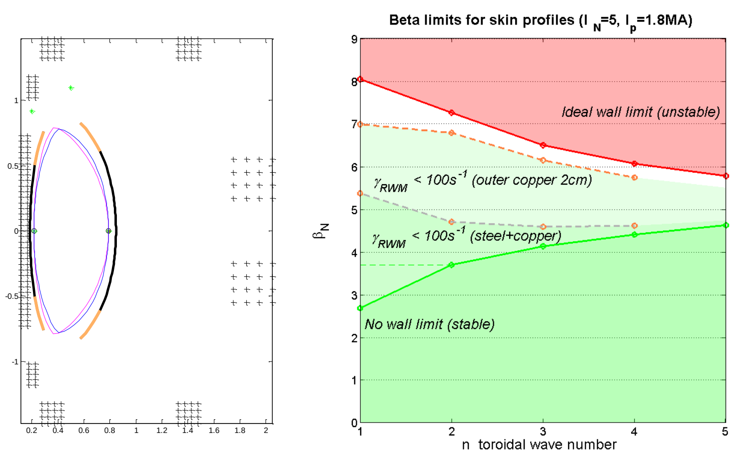

Figure 2. Plasma boundary variations and the conducting wall position (left); limiting normalized beta values vs toroidal wave number n (right)

external kink modes corresponds to the value of normalized current I_N <8 (plasma current I_p=2.9MA for a=0.27m and B=1.35T). For the stationary regimes with high beta and for the safety factor at the magnetic axis q_0>1, the optimal current value is I_N <5 (I_p <1.8MA). Global kink modes set the upper limit for the normalized beta β_N < 6, provided that the corresponding resistive wall modes (RWM) are stabilized and q_0>2. Peeling-ballooning modes with medium toroidal mode numbers n >5 are weakly stabilized by the conducting wall but give the same limit β_N < 6 (Fig.2).

2 Edge stability limits and pedestal in ST The ELM triggering conditions and ELM regimes in the ST are discussed based on the edge stability calculations with the KINX stability code taking into account the separatrix at the plasma boundary that leads to stabilization of localized peeling modes [5]. The edge stability diagrams calculated for NSTX shots [6], including shots with lithium, show that the values of normalized pressure gradient α are about 2 times lower as compared to the peeling-ballooning limit (Fig.3). The ELM triggering picture in NSTX related to destabilization of the current driven peeling modes (and stabilization with lithium) [7] needs thorough clarification and refinement. The calculations with the KINX code show current driven mode stability with the separatrix at the plasma boundary, even with artificially increased current density in the pedestal by 40%. The cutoff to define the plasma boundary away from the separatrix can influence the results, but the related uncertainty makes questionable the ELM triggering predictions in NSTX.

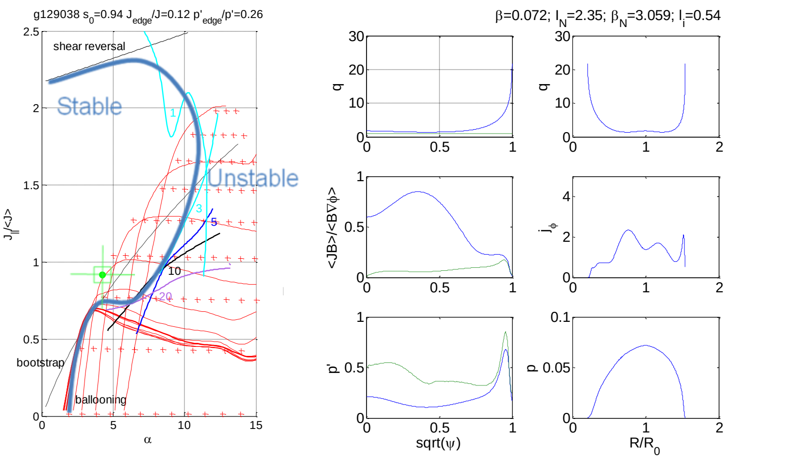

Figure 3. Edge stability diagram for the NSTX shot #129038 (left); plasma profiles in NSTX with lithium (right)

Important issues of pedestal width and ELM power exhaust also remain uncertain. However the following scaling for the pedestal height

$$\beta_{p,ped} = 2\mu_0 p_{ped} / B_{p,sx}^2 = C_1 D^{3/4} / I_N^{1/3}, \qquad (1)$$

where D is the pedestal width in units of normalized poloidal flux in plasma, and $I_N = I_p[MA]/(a[m]B[T])$ is normalized plasma current, predicts the peeling-ballooning limit also in ST with the coefficient C_1 depending on the plasma geometry and pedestal profile shape but typically C_1~3 [8]. The scaling (1) can be combined with scalings for the pedestal width: $D = C_2 \beta_{p,ped}^{\gamma_2}$, where $C_2 = 0.076, \gamma_2 = 0.5$ for DIII-D [9] and $C_2 = 0.36, \gamma_2 = 0.94$ for NSTX (one of possible fits for the data from [10]).

3 Stability of full bootstrap driven equilibria The application of the pedestal height (1) and width (NSTX) scalings to full bootstrap driven equilibria (FBS) give the following predictions for the parameters of FNS-ST: $\beta_p = 0.84$ at $\beta_N = 1.8$ for $I_N = 1.5$, $D = 0.68$ assuming $C_1 = 3$ and pressure peaking factor $p_0 / \langle p \rangle = 1.5$. However, the limit strongly depends on the value of C_1: for $C_1 = 4$ we have $\beta_N = 4.4$ for $I_N = 3.6$, $D = 0.68$.

The FBS equilibria (using low collisions approximation [11, 12]) were generated by prescribing the pressure gradient and parallel current density profiles and adjusting their amplitudes to get the bootstrap alignment (Fig.4) in the FNS-ST plasma boundary. The limiting values of normalized current and beta in the bootstrap driven equilibria can be determined by changing the normalized current while keeping the plasma profiles fixed (toroidal field scaling). Results of the stability computations with the KINX code taking into account separatrix at the plasma boundary are presented in Fig.4. First of all, the internal (fixed boundary) stability limits for all toroidal mode numbers,including the global mode $n = 1$, is nearly uniform in n and consistent with the $n = \infty$ ballooning mode stability violation in the outer part of plasma for sufficiently high beta (as for the case shown in Fig.4). The external kink mode limit behaves similar to the original FNS-ST configuration: without conducting wall stabilization external $n = 1$ mode sets the Troyon limit $\beta_N = 2.5 - 3.5$ even for very low internal inductance values $l_i < 0.3$. The wall stabilization is more effective for lower n, also the change from a single

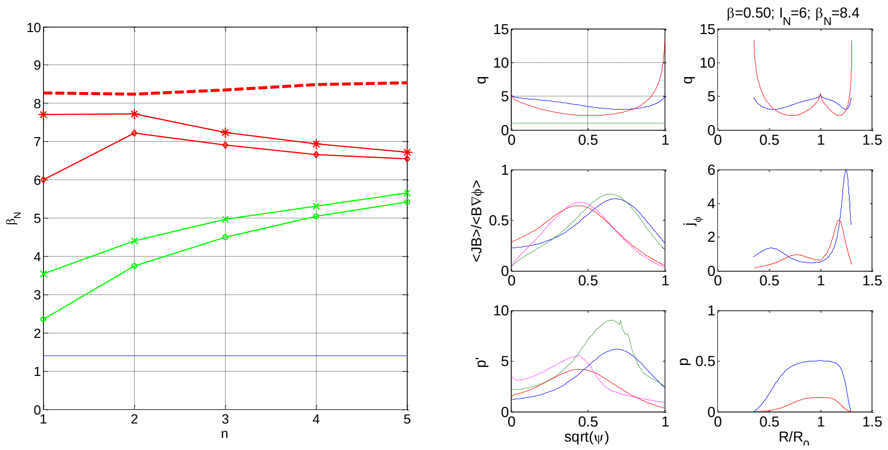

Figure 4. Normalized beta limits for 100% bootstrap driven equilibria: no-wall (green), wall stabilized (red), internal (dashed), the β_N / I_N ratio is shown by blue line (left); plasma profiles at the ballooning limit (right), the profiles for the more peaked case are shown by red lines; dashed lines show bootstrap current and limiting pressure gradient.

null to double null divertor brings additional stabilization in the case of finite current density at the edge (compare circles and diamonds to crosses and stars in Fig.4). The variation of the position of the current density maximum shows that lower internal inductance value (outer maximum location) is beneficial for stability of these hollow current high-q equilibria. Global shear $q_{95}/q_{\min}$ enhances for higher l_i, but lower values of $q_{\min}$ in this case lead to violation of the ballooning stability in the positive shear region right outer of the $q_{\min}$ location where the plasma is still in the first stability region. The pressure peaking factor is also higher leading to lower β_N for approximately the same $\beta_p = 8\pi < p >_S S/(\mu_0 I_p^2)$ =0.88 needed for 100% bootstrap despite significantly higher $\beta_{p,ped}$ (the coefficient C_1 significantly varies depending on the current density profile). In the Table below the parameters of two FBS cases at the $n=5$ no-wall limit (representing the medium-n mode stability) are compared to the FNS-ST with 60% bootstrap fraction:

	I_N	β_N	β_p	$p_0/<p>$	l_i	$\beta_{p,ped}$	D	$\alpha \mid j_\parallel/<j>$	C_1
FBS l_i=0.2	3.88	5.42	0.83	1.54	0.20	1.96	0.89	14.5|1.4	3.3
FBS l_i=0.47	2.18	3.43	0.88	2.71	0.47	4.06	0.97	6.2|1.85	5.3
FNS-ST	5.0	4.60	0.56	1.63	0.25	1.28	0.67	7.0|1.25	2.9

4 Discussion The KINX stability calculations confirm the Troyon beta limit β_N ~2.5 against $n=1$ external kink mode for ST even at very low internal inductance values $l_i < 0.3$ including hollow current 100% bootstrap driven equilibria. Provided that global resistive wall modes (RWM) are stabilized (e.g. with rotation or kinetic effects), medium-n peeling-ballooning modes $n \geq 5$ set the limit β_N < 6 in high bootstrap fraction ST which is well described by the scaling (1) for poloidal beta. In case of FBS with hollow current, stability of double tearing modes can affect the performance.

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