MHD LIMITS IN LOW ASPECT RATIO TOKAMAKS WITH SEPARATRIX

S. Medvedev[1], **L. Degtyarev**[1], A. Martynov[1], L. Villard[2], and T.C. Hender[3]

[1]*Keldysh Institute of Applied Mathematics, Russian Academy of Sciences,*
Moscow, Russia
[2]*Centre de Recherches en Physique des Plasmas, Association Euratom - Confédération Suisse,*
Ecole Polytechnique Fédérale de Lausanne, Switzerland
[3]*UKAEA/EURATOM Fusion Association, Culham, Abingdon, Oxon, OX14 3DB, UK*

1. Introduction

The low aspect ratio tokamak (spherical tokamak) is an attractive concept for future volumetric neutron sources and fusion reactors. The key advantage of this concept is the high value of stable β that follows from the theoretical Troyon-Sykes scaling [1, 2] $\beta[\%] = \beta_N I_N$, $\beta_N \simeq 4$ due to higher values of normalized current $I_N = I[MA])/(a[m]B[T])$ achievable at low aspect ratio $A = R/a$, where I is plasma current, a is plasma minor radius and B is vacuum toroidal field in the plasma center $R = R_c$.

Limiting values of $\beta = 2 \int p dV/(V B^2)$ and current for the aspect ratio range from 2 to 1.2 and conventional plasma shape with elongation $\kappa = 1.6$ and triangularity $\delta = 0.3$ were studied in [3]. It was found that for plasma with an axial safety factor, $q_0 > 1$, the overall β limit is set by ballooning modes in the first stability region with $\beta_N \simeq 4$. External kink modes set the limit for normalized current. The current limit corresponded to a safety factor at the plasma boundary higher than 2 for aspect ratios lower than 1.5. Nevertheless the normalized current limit was found to increase with decreasing aspect ratio.

Recent results from START spherical tokamak [5] demonstrate values of $\beta \geq 30\%$ and $I_N \simeq 8$. The value of normalized current is close or even higher than the theoretical limit set by external kink modes. However previous computations of external mode stability were performed using the ψ_{95} magnetic surface inside the separatrix as plasma boundary.

Equilibrium and stability codes CAXE and KINX [4] were used to compute the current and β limits taking into account the separatrix at the plasma boundary. It was found that the current limit for plasma configurations close to that of START can be as high as $I_N = 16$ provided that $q_0 < 1$. The aspect ratio and current profile scans lead to more general conclusion that the maximal current value achievable at low β is reached at $q_0 < 1$ and is set by "toroidal kink" mode [6]. The maximum current value is sensitive to the plasma boundary proximity to the separatrix.

The limiting values of β against both ballooning and external kink modes were found to be consistent with the results in Ref.[3] for the case of $q_0 > 1$. A typical condition for kink mode stability at $q_0 < 1$ is that the pressure gradient is low inside the $q = 1$ surface when it lies in low shear region. However in the "advanced low q" case with very low $q_{95} < 1.2$ the $q = 1$ surface is close to the plasma boundary where the shear is higher. It leads to internal kink mode stability with finite p' on it and a possibility to get very high β values against external kink modes taking into account conducting wall stabilization. For $A = 1.2$ it gives $\beta > 100\%$ in the first ballooning stability region and stable external $n = 1$ kink mode with the wall at $a_w/a = 1.5$ position.

2. The current limit at $q_0 < 1$

A starting point of the calculations of the plasma stability was a free boundary equilibrium computed with the PF coil and plasma currents corresponding to a high-β START pulse. The

plasma profiles were chosen to obtain $\beta = 31.4\%$, $\beta_p = 0.25$, $I_N = 6.9$ and $q_0 = 0.8$. This is close to the corresponding equilibrium reconstruction from TOPEOL [5], which gives separatrix parameters $A = 1.35$, $\kappa = 1.8$, $\delta = 0.55$ (Fig.1).

To deal with current driven modes series of equilibria with $\beta = 0$, and prescribed averaged toroidal current density profile $I^* = dJ/dS$ (J is toroidal current within magnetic surface and S is the toroidal cross section area) were considered. For fixed boundary equilibria with the current profiles defined by $I^* = (1 - \psi)^\alpha$ and $I^* = 1 - \psi^\alpha$ (ψ is normalized poloidal flux) the normalized current limit was computed for a range of α's. Fig.2 shows the limiting values against $n = 1$ modes for the START aspect ratio. For the two series of current profiles the maximal value of normalized current is reached for approximately the same value of internal inductance $l_i \simeq 0.5$ ($l_i = 2\int B_p^2 \, dV/(R_c I^2)$). The maximal current value is reached for $q_0 < 1$ and is set by "toroidal" kink mode with a strong coupling of surface wave components to dominating $m = 1$ poloidal harmonic. For $l_i < 0.5$ the current limit is much lower. It is reached at $q_0 > 1$ and is set by "external" kink mode with a dominating surface wave component. Similar results were obtained for aspect ratios $A = 1.2$ and $A = 2.0$ keeping the same plasma cross section shape (Figs.3-4). In the $A = 1.35$ and $A = 1.2$ cases safety factor profiles are non monotonic ($q_{min} < q_0$) for the series with flat current profile $I^* = 1 - \psi^\alpha$ at $q_{min} < 1$. Internal $m = 1$ modes can be unstable in a narrow band around $q_0 = 1$.

There is a difference between "toroidal" and "external" kink mode sensitivity to the separatrix proximity to the plasma boundary. The stability computations were redone taking the ψ_{99} surface as the plasma boundary. The obtained current limits were close to that with separatrix at the boundary for $q_0 > 1$ but much lower for $q_0 < 1$: the maximal normalized currents for ψ_{sx} and ψ_{99} at the boundary are $I_N = 23$ and $I_N = 16$ respectively for $A = 1.2$ and $I_N = 16$ and $I_N = 9$ respectively for $A = 1.35$ ($I^* = (1 - \psi)^{0.4}$). This result was verified by convergence studies.

3. The β limit at $q_0 < 1$ and high I_N

As shown in the previous section the current limit for low aspect ratio tokamaks is maximum for $q_0 < 1$. The ballooning β limit for such configurations has been obtained by optimisation of the pressure profile, at all radii, to ballooning modes keeping the safety factor profile. Fig.5 shows this limit for a sequence of equilibria with current and pressure profile shapes of Fig.1 and demonstrates that the conventional scaling, $\beta_N = 4$, is valid at very low $q_{95}(\simeq 1.1)$ and with p' localised near the boundary (Fig.6).

Stability against internal and external kink modes can be achieved by making the pressure gradient vanish inside the $q = 1$ surface. However this leads to quite low β values for the high maximal current case where the $q = 1$ surface is close to the plasma boundary. A possible alternative to that is to have relatively high shear at the $q = 1$ surface to stabilize the $m = 1$ mode. Let us give two examples of the "advanced low q" equilibria of this kind. The first one corresponds to the point with the highest $\beta = 65\%$ (lowest q_0) from the Fig.5 for aspect ratio $A = 1.35$. The equilibrium is stable against $n = 1$ mode with wall position $a_w/a = 1.3$. Another one is the equilibrium with safety factor profile corresponding to $I^* = (1 - \psi)^{0.4}$ at $\beta = 0$ and $q_0 = 0.86$ and ballooning marginally stable $\beta = 103\%$, $I_N = 27$, $q_{95} = 1.17$. This equilibrium is stable against $n = 1$ modes with the wall at $a_w/a = 1.5$.

4. Conclusions

The obtained results lead to a conclusion that the current limit is set by "toroidal" kink modes. The maximal normalized current value is reached for $q_0 < 1$ and is especially high for low aspect ratio provided that the separatrix is at the plasma boundary.

The ballooning β limit follows the conventional scaling with $\beta_N \simeq 4$, even for $q_0 < 1$ equilibria with very low q_{95}. Maximal stable β is reached for the "advanced low q" configurations with $q_{95} < 1.2$ when the shear is high at the $q = 1$ surface and taking into account wall stabilization.

This paper has demonstrated that very high β is possible at tight A, in the first stability regime. Preliminary studies show in the second stability regime, for $A = 1.4$, that high bootstrap current fraction cases ($\geq 90\%$) are possible with $\beta \simeq 50\%$, which are stable to low-n modes with a wall at $1.2a$. The influence of the separatrix on these second stability results is currently under investigation.

Acknowledgement

References

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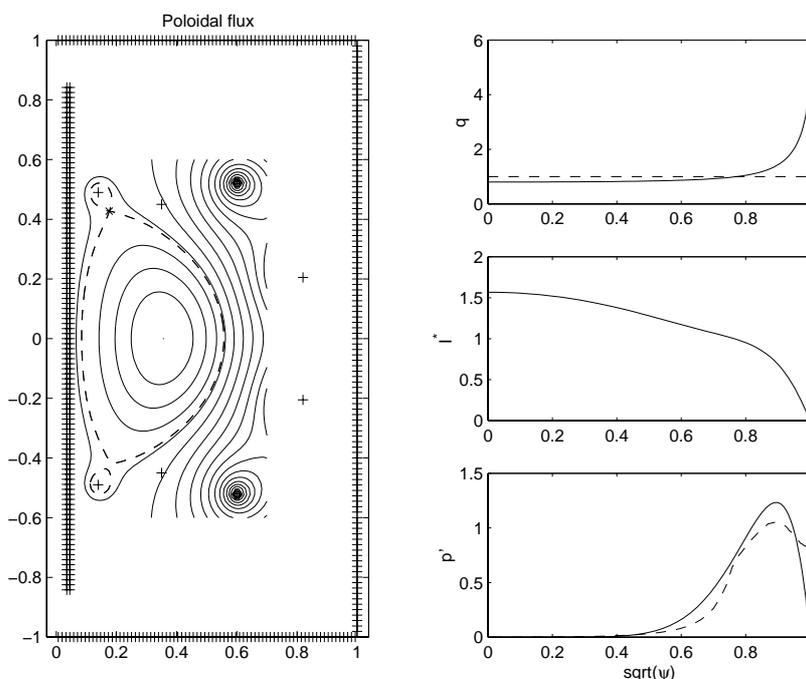
Figure 1. Free boundary equilibrium poloidal flux contours and plasma profiles. $\beta = 31.4\%$, $\beta_p = 0.25$, $I_N = 6.9$, $l_i = 0.6$, $q_0 = 0.8$, $q_{95} = 2.7$. Ballooning marginally stable pressure gradient is shown by dashed line
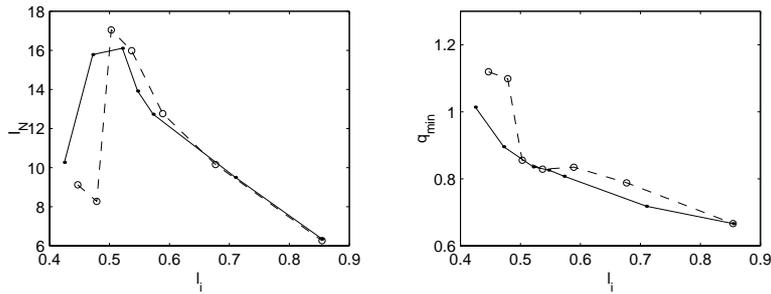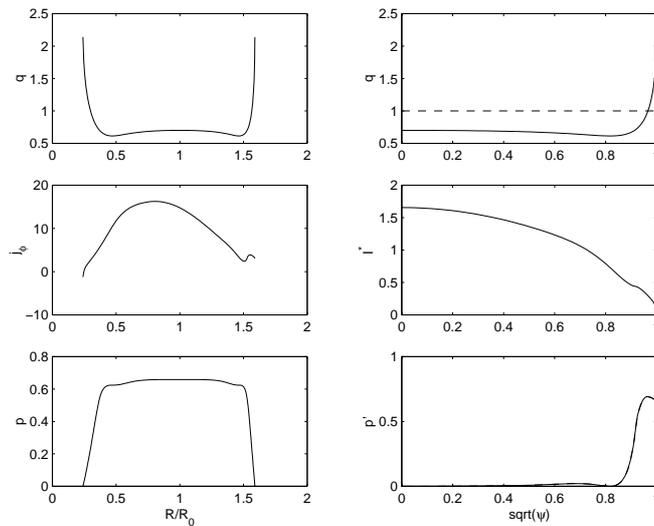
Figure 2. Limiting values of normalized current and minimal values of safety factor vs internal inductance in the equilibrium series with $I^* = (1 - \psi)^\alpha$ (solid line) and $I^* = 1 - \psi^\alpha$ (dashed line). $A = 1.35$
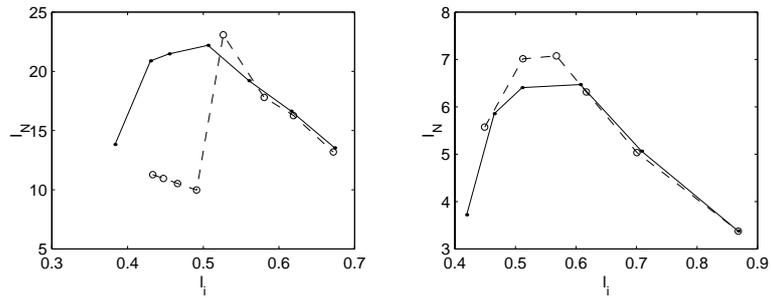
Figure 3 - 4. Limiting values of normalized current for $A = 1.2$ (left) and $A = 2.0$ (right)
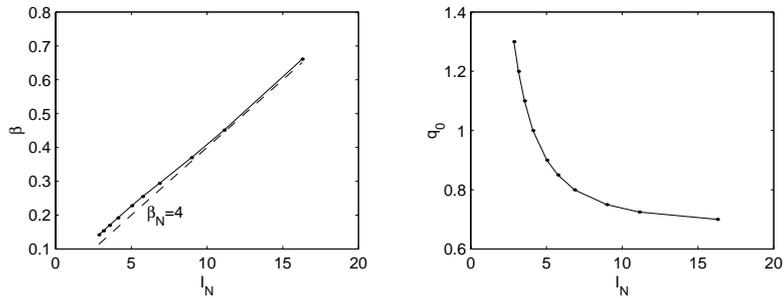
Figure 5. Limiting values of ballooning stable β in equilibria with different q_0. $A = 1.35$

Figure 6. Plasma profiles for "advanced low q" equilibrium. $\beta = 65.5\%$, $\beta_p = 0.10$, $I_N = 16.1$, $l_i = 0.67$, $q_0 = 0.7$, $q_{95} = 1.12$.