26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 141 - 144

High-β second stability in the Spherical Tokamak

S Medvedev[1], T C Hender[2], S J Allfrey[2], H R Wilson[2], O Sauter[3] and L Villard[3]

[1]*Keldysh Institute, Russian Academy of Sciences, Moscow, Russia*
[2]*Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK*
[3]*CRPP Euratom-Confédération Suisse, Ecole Polytechnique Fédéral de Lausanne, Switzerland*

Introduction

The START experiment has demonstrated the very high-β potential of the Spherical Tokamak (ST) – achieving a toroidal volume average β_v~40% and a normalised $\beta_n \lesssim 5$ (where in β definitions the vacuum toroidal magnetic field at the geometric axis is used). While these parameters begin to bring the ST into the regime needed for the economic realisation of fusion power, further increases are desirable. ST power plant studies typically show β_n~8 is desirable [1] so that a high pressure-driven current fraction can be maintained; this is important both to minimise expensive current drive power and also to minimise penetrations through the blanket (eg. by neutral beam lines) which reduce tritium breeding capability. β_n~8 implicitly requires operation in the second stable regime for ballooning modes. A discussion of the stability properties of such equilibria is the subject of this paper.

Stability of limiter equilibria

For the equilibria studied $I_p \approx I_{rod}$ is chosen (where I_{rod} is the total Toroidal Field current). Ideally the ratio I_p/I_{rod} should be as large as possible but is limited by the need to attain acceptable MHD stability at a high pressure driven current fraction. The limiter equilibria presented here and their pressure driven current fractions are calculated using the SCENE code [2] which has a full (non aspect ratio ordered) evaluation of the bootstrap current.

The pressure profile is specified in the same form as Ref [3]:

$$p'(\psi) = p_0\left[1+39\left(\frac{\psi}{\psi_a}\right)^3 - 40\left(\frac{\psi}{\psi_a}\right)^4\right]$$

where ψ = poloidal flux and the subscript *a* indicates the edge value. The driven current profile, which is combined with the pressure-driven currents to give the total current, is of the form:

$$\frac{\langle \boldsymbol{J}_{driven} \bullet \boldsymbol{B}\rangle}{\langle B^2\rangle} = J_0\left[\left(1-\frac{\psi}{\psi_a}\right)^{90} + 9\left(1-\frac{\psi}{\psi_a}\right)^{1.1}\left(\frac{\psi}{\psi_a}\right)^{10} + 7.75\left(1-\frac{\psi}{\psi_a}\right)^{9}\left(\frac{\psi}{\psi_a}\right)\right]$$

Aspect Ratio	1.4
Elongation	3.0
Total ∇P driven current	88%
Diamagnetic current	20%
β_v (wrt vacuum TF at geometric axis)	58%
β_t (wrt volume average equilibrium $\lvert B \rvert$)	41%
β_n	8.2

Figure 1 shows the current and q-profiles for the equilibrium whose parameters are given in Table 1. The current drive requirements using neutral beam injection (NBI) to drive the residual current, have been worked out in detail [4]; for I_p=31MA 76MW of NBI is needed.

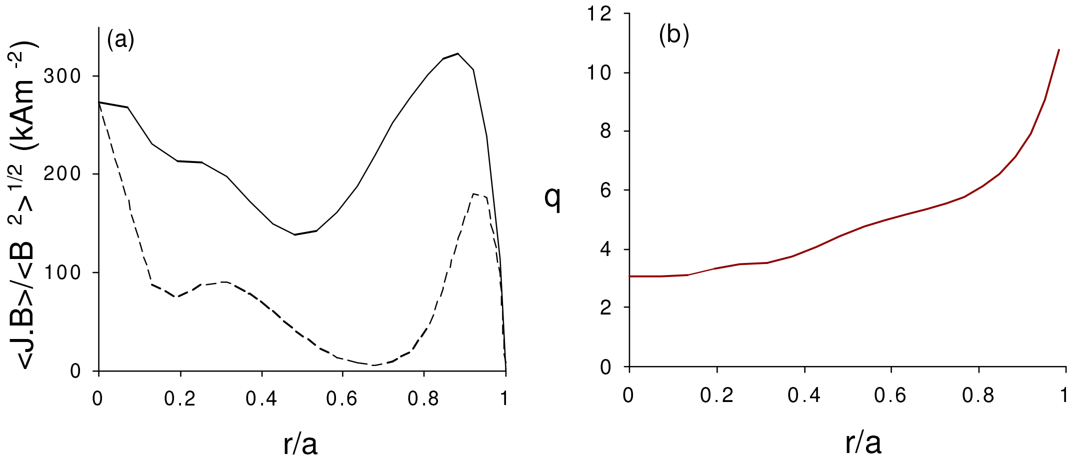

Fig 1 (a) Flux surface averaged total current (solid line) and driven current requirement (broken line). (b) The associated q-profile as a function of minor radius (defined as the geometric radius on the horizontal mid-plane).

Raising q above unity in this manner gives a sufficiently large magnetic well to give direct access to second ballooning stability at all radii; a typical S-α plot demonstrating this is shown in Fig 2.

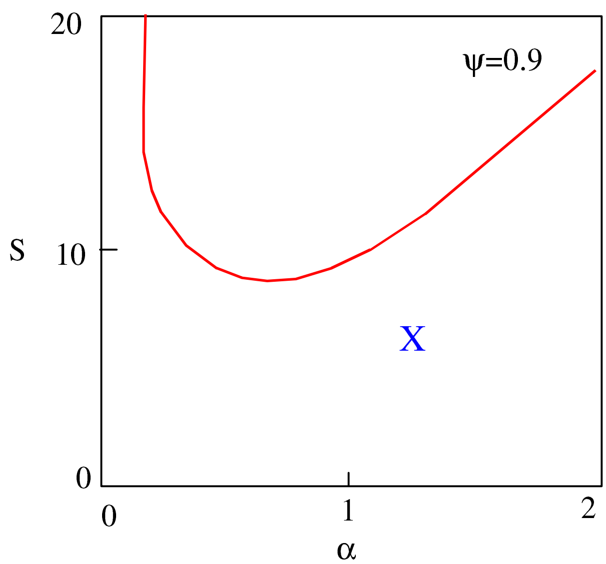

Fig 2 S-a curve for surface near the plasma edge, the top right region bounded by the curve is unstable. The 'X' shows the equilibrium S and a value. Due to the large H-mode like edge pressure gradients the closest approach to ballooning instability is near the edge (NB J_{edge}=0).

The penalty for gaining stability to ballooning modes is the need to have a nearby conducting wall to stabilise the low-n kink modes. The low-n stability has been calculated independently with the MISHKA [5] and KINX [6] codes, the results being in good agreement. High resolution is needed to resolve these instabilities – 75 (m,n) harmonics in MISHKA and 256x256 grid in KINX. The large edge current tends to destabilise low-n modes which are relatively edge localised as shown in Fig 3.

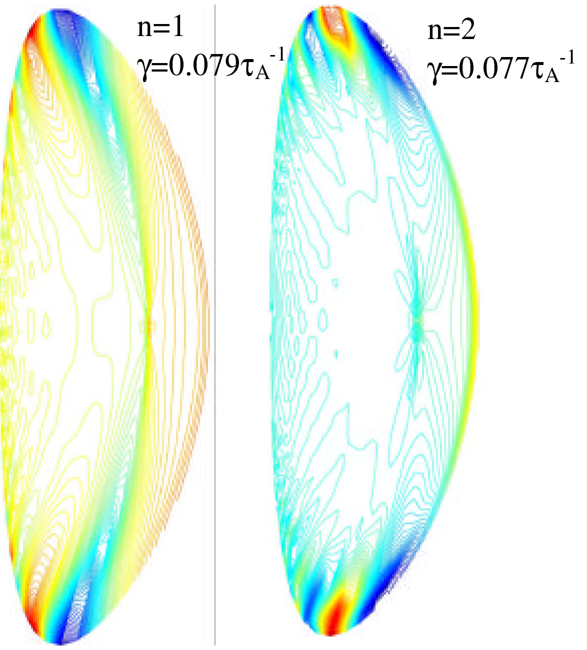

Fig 3. Contours of normal displacement magnitude for n=1 and 2 with a conformal wall at 1.3 minor radii. The clustering of contours near the plasma edge indicates the localisation of the mode in that region.

The conformal wall position needed for n=1,2 and 3 stability are 1.13, 1.19 and 1.17 minor radii, respectively. As discussed below these marginal wall radii increase markedly with the triangularity of the plasma.

Stability of free boundary equilibria

Free boundary equilibria have been calculated with the CAXE code and their low-n stability checked with the KINX code [6]. Figures 4 and 5 show radial profiles of equilibrium quantities and the flux surfaces for a free boundary equilibrium with β_n=8.16.

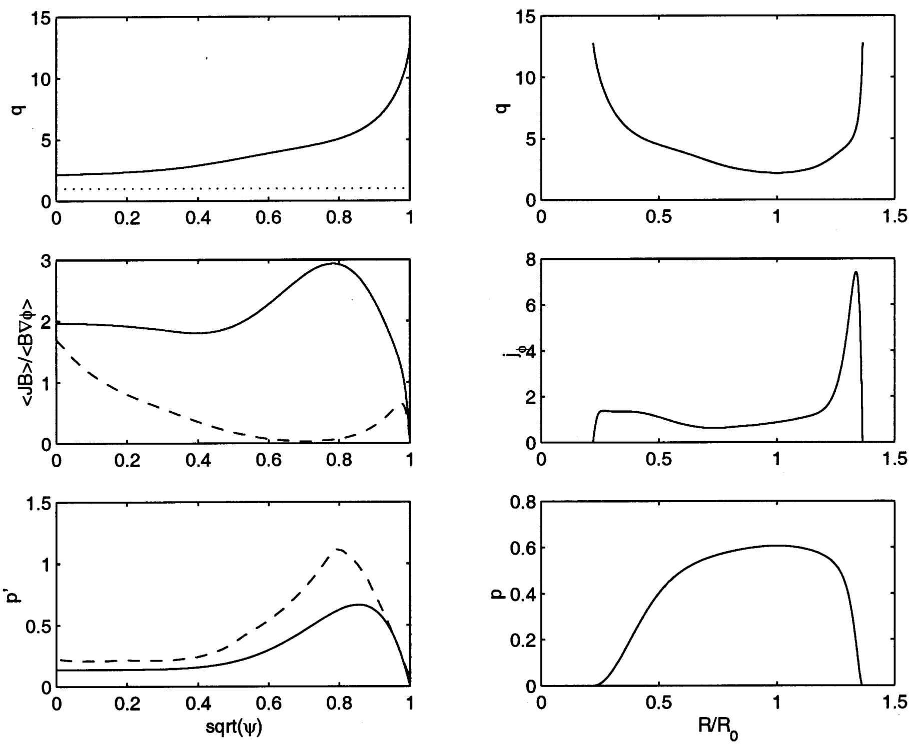

Fig 4 Radial profiles of equilibrium quantities for an equilibrium with R/a =1.39, b_n=8.16, b_v=60.6%, elongation=2.97 and triangularity=0.56. The broken lines indicate the driven current requirement in the flux surface averaged current plot and the marginal ballooning stable pressure gradient in the pressure gradient plot.

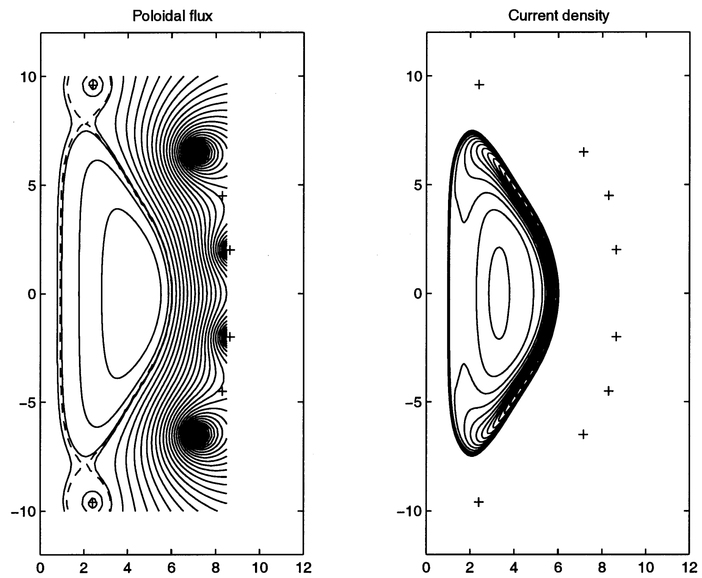

Fig 5 Left-hand figure shows flux surfaces and right-hand figure current density contours for the equilibrium shown in Fig 4.

For the equilibrium in Figs 4 and 5 the SCENE code gives a total pressure driven current fraction of 88%, with the diamagnetic term contributing 19% to the total. Low-n stability benefits from the higher triangularity - for this equilibrium, if $\psi_{edge}=0.9775\psi_{x\text{-}point}$, the marginal n=1 and 2 wall locations are ~1.34 and ~1.45 minor radii, respectively. Calculations with the equilibrium boundary closer to the separatrix, $\psi_{edge}=0.993\psi_{x\text{-}point}$, show that proximity to the separatrix is also beneficial, increasing the marginal n=1 and 2 wall radii by 34% and 11%, respectively.

Discussion

Equilibria with high pressure-driven current fractions have been demonstrated for the ST. These require second stable access for ballooning modes and a wall for stability to low-n modes, whose radius depends on plasma triangularity and proximity of the separatrix (both of which are stabilising).

Further investigations are in progress to systematically understand the effects of triangularity on low-n stability. Also the effect of the separatrix on stability at ~100% pressure driven current fraction is being studied.

References

[1] G M Voss et al, Proc 6th IAEA TCM on Fusion Power Plant Design, Culham, (1998)
[2]H R Wilson, ‘SCENE – Simulation of Self-Consistent Equilibria with Neo-classical effect’, UKAEA report, UKAEA FUS 271 (1994)
[3] R.L.Miller *et al*, Phys Fluids **4,** 1062 (1997).
[4] R J Akers et al, ‘ Fus Tech application of the ST’, 1998 IAEA Conf, paper FTP/05.
[5] A.B.Mikhailovskii *et.al.*, Plasma Phys. Rep. **23,** 844 (1997
[6] L.Degtyarev *et al*, Comput Phys Comm **103,** 10 (1997)

Acknowledgements

The authors thank Drs Huysmans, Sharapov, Mikhailovskii and Kerner for providing the MISHKA stability code. The UKAEA authors were jointly funded by the UK Department of Trade and Industry and Euratom. The CRPP authors were supported in part by the Swiss National Science Foundation.