

ACCESS TO “ADVANCED” REGIMES IN TIGHT ASPECT RATIO PLASMAS

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1. Introduction

There is currently great interest in “optimised magnetic shear” regimes in tokamaks as they may allow sufficiently high pressure, and therefore bootstrap current, to make steady-state operation possible with only a modest amount of non-inductive current drive, i.e. “advanced tokamak” scenarios. In these regimes dq/dr is close to zero, or even negative, at or near the plasma centre. It is important to determine whether these regimes show similar promise in tight aspect ratio “spherical tokamaks” (STs), which are receiving increasing interest following the very promising results from START [1], as they may offer a compact, high β option for a fusion device such as a materials test facility or a power plant. Experimental demonstration of regimes with steady-state potential is an important objective of the STs presently being constructed (e.g. MAST, NSTX).

In this paper we model how increasing the plasma pressure can lead to a q profile which is very flat, or even non-monotonic, in the core of the plasma. This arises because, if $p(r)$ is flat near $r = 0$ (r is the flux surface half-width in the poloidal plane), $dp/d\psi$ gives a large off-axis contribution to the toroidal current density (cf. Grad-Shafranov Eq. (1) below). Results from START are presented which are in qualitative agreement with the calculations. The equilibrium evolution model is based on the coupled solution of the Grad-Shafranov equation and the parallel component of Ohm’s law [2-4]. Use of this evolution model, instead of a fixed time equilibrium, is important since it permits study of the access to and duration of the advanced regime.

2. Formulation of the problem

The evolution of free boundary toroidal plasma equilibria can be reduced to the solution of the system of two coupled strongly non-linear equations [2-4] (for the purpose of this paper, transport equations [2] have been neglected from the system and replaced with prescribed time-dependent density and temperature profiles)

$$R \frac{\partial}{\partial R} \left(\frac{1}{R} \frac{\partial \psi}{\partial R} \right) + \frac{\partial^2 \psi}{\partial Z^2} = -\mu_0 R j_\varphi, \quad j_\varphi = \begin{cases} R \frac{\partial p(t, \psi)}{\partial \psi} + \frac{1}{2\mu_0 R} \frac{\partial F(t, \psi)^2}{\partial \psi} & \text{in } \Gamma_p \\ \sum_{i=1}^L J_i(t) \delta(R - R_i) \delta(Z - Z_i) & \text{outside } \Gamma_p \end{cases} \quad (1)$$

$$\frac{\partial \chi}{\partial t} \frac{\partial \psi}{\partial Z} - \frac{\partial \psi}{\partial t} \frac{\partial \chi}{\partial Z} = \frac{1}{\mu_0 \sigma_{\parallel}} \left(\frac{\partial^2 \chi}{\partial R \partial Z} \frac{\partial \psi}{\partial R} + \frac{\partial^2 \chi}{\partial Z^2} \frac{\partial \psi}{\partial Z} \right) + \frac{j_\varphi R}{\sigma_{\parallel}} \frac{\partial \chi}{\partial Z} - \frac{R^2}{\sigma_{\parallel}} \vec{j}_{\text{add}} \vec{B}, \quad \text{in } \Gamma_p \quad (2)$$

$$F(t, \psi) = \int_{\psi=\text{const}} \tilde{F}(t, R, Z) B_{\text{pol}}^{-1} dl / \int_{\psi=\text{const}} B_{\text{pol}}^{-1} dl, \quad \tilde{F} = \frac{\partial \chi}{\partial Z}. \quad (3)$$

Here R and Z are major radius and vertical co-ordinates, $B_{\text{tor}} = F/R$ and B_{pol} are the toroidal and poloidal magnetic fields (TF, PF), $p(t, \psi)$ is plasma pressure, $J_i(t)$ are currents in the vessel

wall, solenoid and poloidal field coils, \vec{j}_{add} are non-Ohmic plasma currents (driven by plasma pressure or non-inductive heating). Expressions for bootstrap, Pfirsch-Schluter and diamagnetic currents and neo-classical conductivity σ_{\parallel} are taken from Refs. [5-7]. The unknown functions are ψ , the poloidal flux, and χ , defined in Eq. (3), which is related to the toroidal flux. The system (1), (2) is completed by the following initial and boundary conditions

$$\psi(0, R, Z) = \psi_0(R, Z), F(0, \psi) = F_0(\psi), \lim_{R \rightarrow 0} \psi = \lim_{\substack{R \rightarrow \infty \\ Z \rightarrow \infty}} \psi = 0, \left. \frac{\partial \chi}{\partial Z} \right|_{\Gamma_p} = \frac{\mu_0}{2\pi} I_{\text{rod}}(t) \quad (4)$$

where Γ_p is the free plasma boundary, defined as the closed flux surface of maximum width, and $I_{\text{rod}}(t)$ is the current down the central rod which gives the TF.

Considering external parameters in Eqs. (1)-(4) as controls, one can formulate different control problems. In particular, one can adjust the coil currents to keep the total plasma current a given function of time and/or maintain a specified plasma shape.

Equilibrium evolution has been considered in many papers, e.g. Refs. [2-4,8,9]. One of the new features of the approach presented here is the use of the parallel Ohm's law (Eq. (2)) in cylindrical (R, Z) coordinates. Unlike other approaches, which use an analytically-averaged 1D Ohm's law equation, we first solve the 2D equation for Ohm's law in (R, Z) numerically, and then average the solution over flux surfaces. Use of (R, Z) coordinates for both Eqs. (1) and (2) results in a less complicated algorithm for the solution of the free boundary problem than the inverse variables technique or mixed inverse variables/ (R, Z) technique, but at some expense in CPU time.

The code SCoPE has been developed to solve Eqs. (1)-(4) and used to study equilibrium evolution. Results for tight aspect ratio plasmas are presented here.

3. Results of calculations

A START-like plasma has been considered, Fig. 1. The time dependence of currents in the PF coils was adjusted to maintain the plasma position in the equatorial plane to within 5 % accuracy during the simulation. The following initial parameters were used: major and minor radii $R_{\text{mag axis}} = 0.34$ m and $a = 0.23$ m, elongation $\kappa = 1.6$, $I_{\text{rod}} = 500$ kA ($B(R_{\text{mag axis}}) = 0.3$ T), density $n_e = n_i = 0.4(0.5(1 - (r/a)^n) + 0.5)10^{20}$ m⁻³, and temperature $T_e = T_i = 0.3(0.7(1 - (r/a)^n) + 0.3)$ keV, with $n = 3$, current density profile $j_0(1 - (r/a)^2)$ with j_0 adjusted to give 200 kA total current (r is the flux surface half-width in the poloidal plane).

In the first group of runs (a) the temperature was kept constant and the density increased by a factor ~ 6 during 10 ms, for various pressure profiles and initial current profiles. It was found that the flatter the pressure profile at the magnetic axis, the deeper is the shear reversal in the final q -profile. Here data for cubic ($n = 3$) density and temperature profiles is presented. Several runs showed

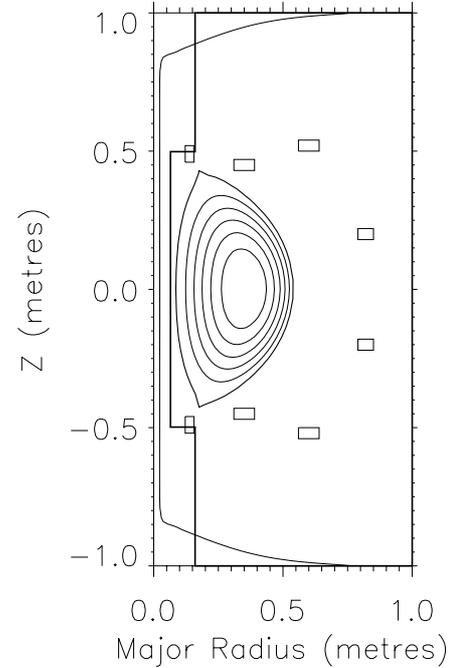


Fig. 1. EFIT reconstruction of magnetic flux surfaces in START for shot 36544.

that $n = 3$ is approximately the lowest order for access to advanced regime during the 10 ms for the parameters used. A run with current density $j_0(1 - (r/a)^3)$ gave behaviour similar to a parabolic profile. Other calculations were done for the same conditions, but with the pressure increased by (b) raising the temperature by a factor of 6 in a 10 ms period, and (c) a $\sqrt{6}$ rise in both temperature and density over 10 ms, which is close to the experimental conditions on START [10].

Fig. 2 presents time dependence of total plasma current I_p , total bootstrap current I_{bs} and, for illustration, the current in one of the PF coils, I_c , obtained with SCoPE. The oscillations in currents are caused by controlling plasma position with only 5% accuracy. Since the total current was not controlled it eventually grew, until the pressure rise stopped at 10 ms.

Fig. 3(a) presents $q(R)$ in the equatorial plane at different times. One can see the evolution of the plasma to an “advanced” regime with a very flat q profile. Shear reversal in case (b) is somewhat more pronounced (Fig. 3, (b)). This is due to a significant rise in the bootstrap current (Fig. 2, (b)) - in cases (a) and (c) the bootstrap current is small. The simulations continued after the pressure rise phase, and shear reversal was sustained until approximate steady-state was reached.

4. START experiments

The first experiments to access the “advanced” tokamak regime at low aspect ratio have been performed on the START tokamak [10]. Although there are no direct measurements of $q(r)$ on START, there are some indications of a possible negative central shear (NCS) regime formation achieved by use of early neutral beam heating and delayed fast current ramp-up. The EFIT reconstruction, Fig. 4, shows an increase in $q(0)$ value, and inverse sawteeth at the magnetic axis were also observed during this phase. ASTRA [11] transport simulations using experimental $T_e(t, r)$ and $T_i(t, r)$ profiles also show hollow $q(r)$. Values of $\beta_T \sim 40\%$, which is a new record for tokamaks, with $\beta_N \sim 6$ have been obtained on START in these regimes. The preliminary ideal ballooning stability analysis shows that a monotonic $q(r)$ plasma is unstable for these high β_N values, however NCS profiles are stable in the second stability zone. Note that in

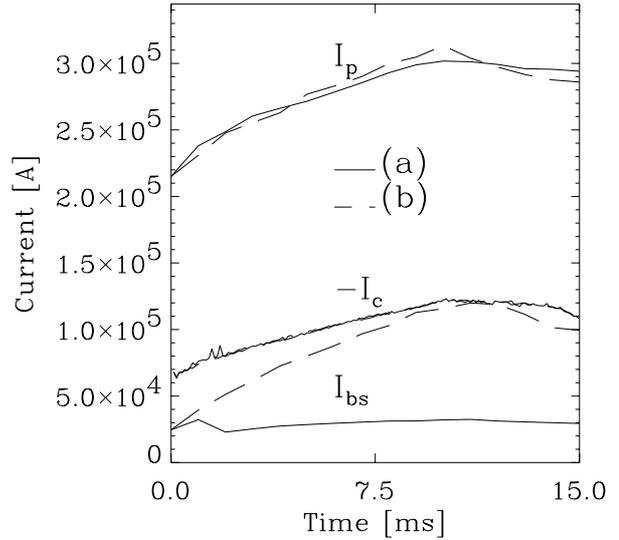


Fig. 2. Time dependence of total plasma current I_p , total bootstrap current I_{bs} and PF coil current I_c , obtained with SCoPE.

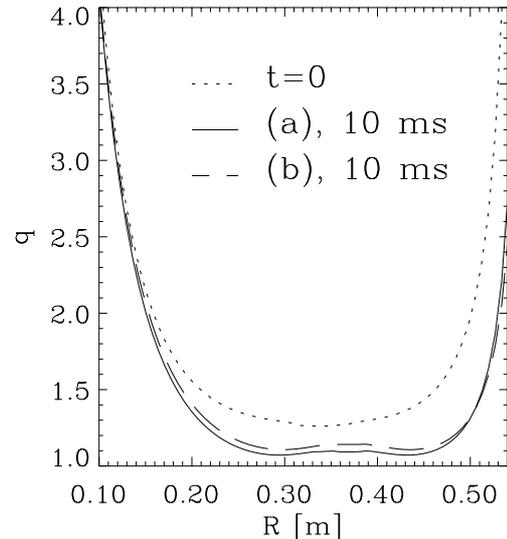


Fig. 3. Safety factor profile $q(R)$ at different moments of time, obtained with SCoPE. Case (c) gives a curve very close to (a).

the experiments, as in most of the simulations, the plasma is collisional and the bootstrap current low - in high temperature plasmas, e.g. on MAST, the off-axis bootstrap current should make accessing these $q(r)$ profiles easier. Indeed calculations have shown that stable spherical tokamak equilibria with very high bootstrap fractions may be possible [e.g. 12].

5. Conclusion

Calculations show that at high pressures in tight aspect ratio plasmas, an optimised shear regime can be achieved and sustained. This is in qualitative agreement with equilibrium reconstruction of high β plasmas on START. For START this does not rely on the bootstrap current, which should increase this effect in hotter, collisionless spherical tokamaks, such as MAST, with the potential for steady-state operation of an ST fusion device.

Acknowledgement

The authors thank Dr. L.C. Appel for the START equilibrium reconstruction. The MSU work was partly funded by the Russian Foundation for Basic Research, grants Nos. 96-01-01171a, 96-15-96205. The UKAEA work was funded by the UK Department of Trade and Industry and by Euratom.

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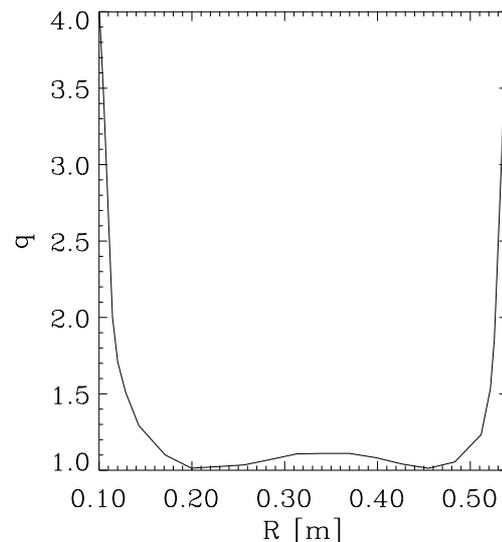


Fig. 4. EFIT reconstruction of q -profile for shot 36544, $\beta_T=39\%$, $\beta_N=4.7$.