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STABILITY AND CONFINEMENT PROPERTIES OF SMALL-ASPECT-RATIO TOKAMAK

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Stability and Confinement Properties of Small-Aspect-Ratio Tokamak

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Abstract

The stability of compact magnetic confinement configurations with axial symmetry is investigated with respect to ballooning modes using equilibrium profiles characteristic of high-beta discharges produced in large tokamaks. It is shown that average beta values $\langle\beta\rangle \approx 0.10$ are readily obtained for configurations with a substantial paramagnetic effect. The stability to trapped particle modes in the collisioness regime can also be achieved by reversal of single particle drifts caused by toroidal effects.

1. Introduction

Small-aspect-ratio tokamaks have been proposed to enhance the average value of the parameter beta from a maximum around 5%, in current devices to 10% or more needed for economical fusion reactors[1]. Here we define the average beta as $\langle\beta\rangle = 2\mu_0\langle p\rangle/B_0^2$, where $\langle p\rangle$ is the average value of the plasma pressure and B_0 is the value of the toroidal magnetic field B_T in the vacuum at the center of the plasma cross-section. Theoretical results indicate that the strong toroidicity associated with small aspect-ratio has a beneficial effect on the stability of ideal magnetohydrodynamic modes[2]. However, the performance of compact configurations with respect to linear resistive modes, saturated magnetic islands, disruptions, and neoclassical and anomalous transport remains to be thoroughly investigated.

The maximum value of $\langle\beta\rangle$ that a given confinement configuration can sustain is usually calculated using the so-called Troyon scaling $\langle\beta\rangle_{max} = cI_p(MA)/a(m)B_0(T)$, where I_p is the plasma current,a is the half-width of the plasma column, and c is a constant[3]. This expression results from a profile optimization procedure in which the profile of the safety factor q is chosen rather flat in the central plasma region and the pressure profile is made marginally stable to ballooning modes on every flux surface[3,4]. The value of the constant c depends somewhat on the choice of the q profile; a currently accepted value is $c \approx 0.028$.

Detailed analysis of high-beta discharges produced in large devices have indicated, however, that the value of beta can saturate at levels below that predicted by the Troyon scaling even with strong additional heating[5]. This saturation is usually followed by an increase in the magnetohydrodynamic activity and a relaxation of the discharge to lower values of $\langle\beta\rangle$. Numerical simulations show that the magnetohydrodynamic activity can be associated with local instabilities in the region of the plasma with highest pressure gradient[5]. We have then carried out a stability analysis of small-aspect-ratio configurations using fixed profiles characteristic of high-beta discharges produced in JET instead of optimized ones. The results are presented in the next section.

The stability of trapped-particle modes is directly related to the sign of the bounce average drift frequency $\omega_D = (m/e\tau_b)dJ/d\psi$, when m and e are respectively the mass and charge of the particle, τ_b is the bouncing time in the banana orbits, ψ is the poloidal flux, and J is the adiabatic invariant

$$J = \oint V_{\parallel} dl, \tag{1}$$

where $V_{\parallel}$ is the velocity parallel to the magnetic field and dl is a line element along the field line. For the collisionless trapped-particle mode, complete stabilization requires $(\partial J/\partial\psi)(dp/d\psi) > 0$[6]. Since the pressure profile is peaked at the magnetic axis and J, to lowest order, is proportional to the fraction of trapped particles, $\partial J/\partial\psi$ and $dp/d\psi$ have opposite signs in low-beta large aspect-ratio tokamaks. However, it has been shown that particle drift reversal ($\partial J/\partial\psi < 0$) can be obtained by elongating or suitable shaping the cross-section of the plasma column[7,8]. Actually, drift reversal can be achieved even with circular cross-section in high-beta discharges[9]. In section 3 we use the simple model of Ref. 9 to show that decreasing the aspect ratio has a favourable effect on drift reversal.

2. Ballooning Stability

The stability analysis has been carried out following the procedure of Kerner et al[2]. For fixed profile functions and for fixed value of the parameter $\epsilon\beta_p$, the value of the parameter q^* is varied until the maximum value of $\langle\beta\rangle$ is reached at the stability boundary. Here $\epsilon = a/R_0$ is the inverse aspect ratio, $\beta_p = 8\pi S\langle p\rangle/\mu_0 I_p^2$, where S is the area of the cross-section of the plasma column, and q^* is the so-called cylindrical safety factor, which is related of $\langle\beta\rangle$ and $\epsilon\beta_p$ through the equation

$$\frac{\langle\beta\rangle}{\epsilon} = \frac{C^2}{4\pi S}\frac{\epsilon\beta_p}{q^{*2}}, \tag{2}$$

where C is the length of the perimeter of the cross-section of the plasma column. The usual profile functions $p(\psi)$ and $F(\psi) = RB_T$, where R is the distance from the axis of symmetry, are given by

$$\frac{dp}{d\psi} = \left(\frac{dp}{d\psi}\right)_0 [1 + 2.51\psi - 3.51\psi^2 + 12\psi^3 - 11\psi^4] \tag{3}$$

and

$$\frac{dF^2}{d\psi} = \left(\frac{dF^2}{d\psi}\right)_0 [1+0.04\psi-0.8\psi^2-0.2\psi^3-0.04\psi^4-\alpha(2.47\psi-2.7\psi^2+11.8\psi^3-10.96\psi^4)], \tag{4}$$

where $\alpha = (dp/d\psi)_0/(dF^2/d\psi)_0$ and ψ is normalized to run from zero at the magnetic axis to one at the plasma boundary[5]. The maximum value of $\langle\beta\rangle$ is shown as a function of ϵ in Fig. 1. The curve does not follow the Troyon scaling at large valves of ϵ; instead it is well fitted by the polynominal approximation $\langle\beta\rangle = 0.013 + 0.089\epsilon + 0.116^2 - 0.046\epsilon^3$ in the range $0.1 \leq \epsilon \leq 0.6$.

The tokamak PROTO-ETA, currently being designed at "Instituto de Pesquisas Espaciais", has a quite tight aspect-ratio, i.e., $\epsilon \approx 0.66$. In Fig. 2 we show the p, q and B_T profiles for a stable configuration with $\langle\beta\rangle = 0.12$. We note that the q profile is quite flat in the central plasma region with strong shear at the edge and that there is a substantial paramagnetic effect indicated by a larger value of the toroidal field in the plasma (full line) than in the vacuum (dotted line).

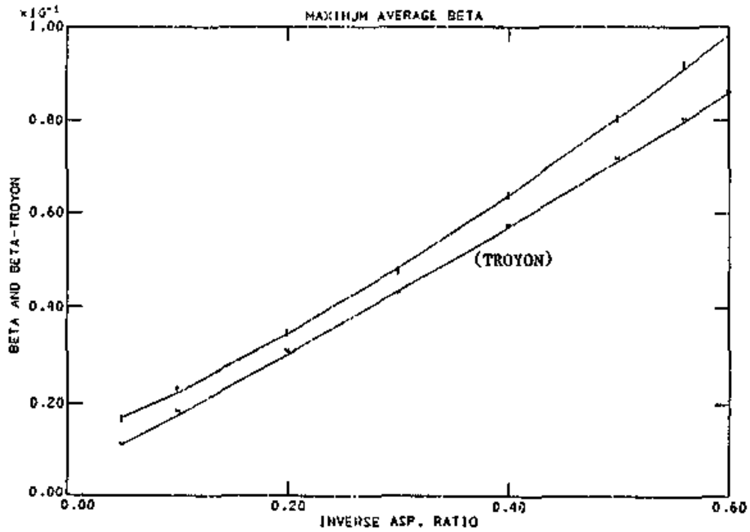

Figure 1. Maximum value of $\langle\beta\rangle$ obtained with the profile given by Eqs. (3) and (4) as a function of ϵ. The curve in somewhat above that obtained with the Troyon scaling with $c \approx 0.028$ and also rises faster with ϵ.

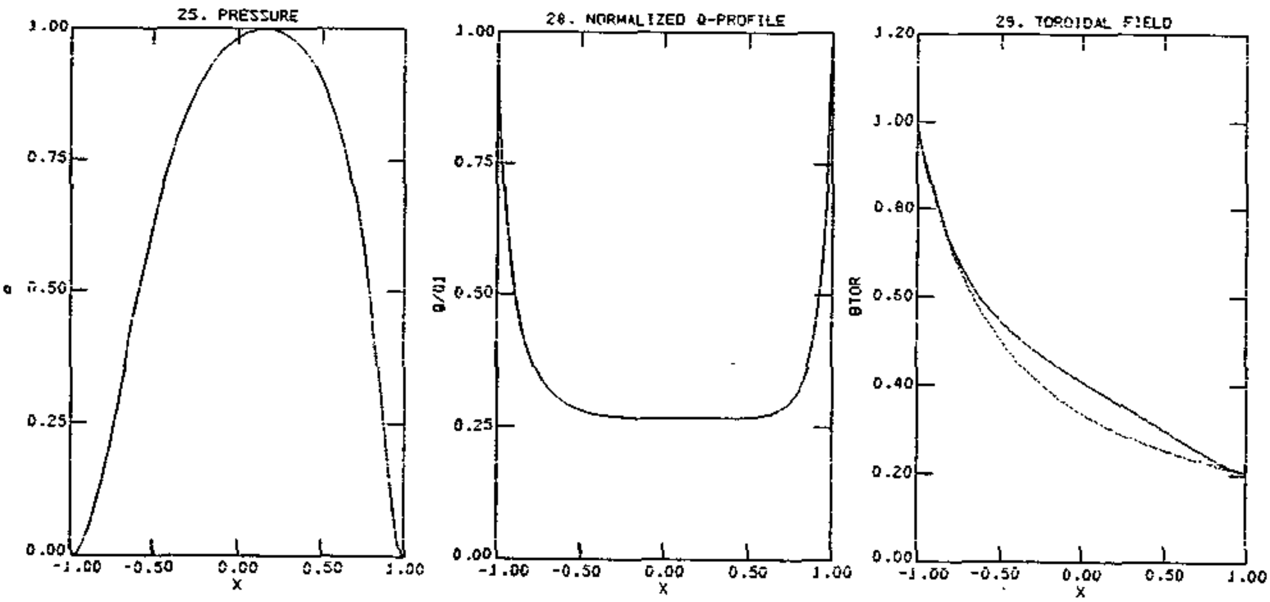

Figure 2. Pressure, p, safety factor, q, and toroidal magnetic field, B_T, profiles along the equatorial plane of a PROTO-ETA equilibrium with profiles given by Eqs.(3) and (4). $\epsilon = 0.66$, $\epsilon\beta_T = 0.23$,$\langle\beta\rangle = 0.12$, $q^\star = 1.2$ and $K = 1.75$, where K is the plasma elongation.

3. Drift Reversal

The paramagnetic increase of B_T works against whereas the large outward shift of the magnetics axis favours drift reversal at small aspect-ratios. To find out the winning effect, we have carried out a simple calculation of the adiabatic invariant J as a function of ϵ using the equilibrium model described in Ref. 9. In order to concentrate only on the variation of ϵ, we have kept the shape of the plasma boundary circular. In Fig. 3 we show the adiabatic invariant J as a function of the flux function for different valves of ϵ. Both the pressure and current profiles are of the form $p/p_0 \approx 1 + \psi^2 - 2\psi^4$. We see that substantial drift reversal is obtained for $\epsilon > 0.5$, i.e., $R/a < 2$. If anomalous transport is associated with satured trapped particle modes, this result indicates that small-aspect-ratio tokamaks should present enhanced confinement even without substantial shape optimization[8].

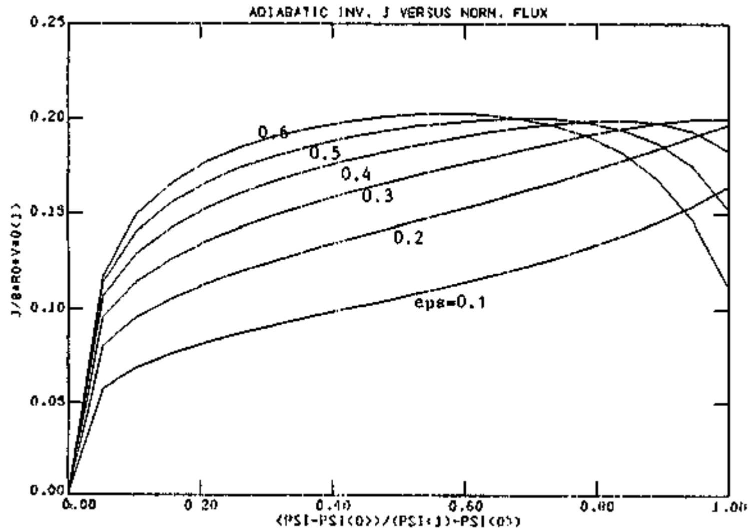

Figure 3. Normalized adiabatic invariant J as a function of the normalized flux function for $\beta_p = 0.7$ and different valves of ϵ. In the normalization of J, R_0 is the major radius, v is the thermal speed of trapped particles, and $q(1)$ is the value of the safety factor at the plasma boundary.

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