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INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

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VERTICAL FIELD AND EQUILIBRIUM CALCULATION IN ETE

Antonio Montes
Carlos Shinya Shibata

Trabalho aceito para apresentação no Encontro Brasileiro de Física de Plasmas, 3., Águas de Lindóia, 04-06 de dez. 1995

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VERTICAL FIELD AND EQUILIBRIUM CALCULATION IN ETE

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ABSTRACT - The free-boundary MHD equilibrium code HEQ is used to study the plasma behaviour in the tokamak ETE, with optimized compensation coils and vertical field coils. The changes on the equilibrium parameters for different plasma current values are also investigated.

INTRODUCTION

The investigation of the plasma equilibrium state is an important topic to be taken into account in a tokamak design. For the tokamak ETE [1], in its final design phase, the free-boundary code HEQ [2,3] is used to define the best settings of some of the machine's parameters. This is done by a careful analysis of the influences of the external constraints, such as the vertical field coils specification, or of the internal plasma characteristics, such as the pressure profile broadening factor, on the resulting equilibrium configuration.

Considering axisymmetric plasma configurations, the HEQ code essentially solves the Grad-Shafranov equation,

$$\Delta^* \psi = -\mu_o R J_\phi$$

where Δ^* is the well-known Grad-Shafranov operator, and $\psi(R, Z)$ and J_ϕ are respectively the poloidal flux and the toroidal current density. The latter is defined by means of the derivatives of the given profiles for the kinetic pressure and the toroidal flux, P and F, as functions of the poloidal flux ψ. The Grad-Shafranov equation is then solved by using an iteractive process of the form

$$\Delta^* \psi^{(n+1)} = -\mu_o R[\alpha J_\phi^n + (1-\alpha) J_\phi^{(n+1)}]$$

where the convergence of the solution is controlled by the parameter α.

EXTERNAL COIL SYSTEM

The MHD equilibrium in ETE is produced by a central Ohmic solenoid, 2 pairs of error field compensation coils, and a single pair of vertical equilibrium coils, as summarized in Table 1. The central inductive solenoid in ETE is a 2-layers, 130-turns, 1.3m-height Ohmic coil, supporting a current of $I_\Omega = 20kA$/turn. The leakage of the field generated by this solenoid into the vacuum chamber is compensated by 2 pairs of correction coils, placed symmetrically with respect to the equatorial plane and assuring a quite reasonable field null: an averaged poloidal field $<B> \leq 2.0$ G on the central plasma region, and $B_m \simeq 0.85$ G on the expected magnetic axis position [4].

In order to prevent against displacements of the plasma column, a vertical coil system is also used. According to the stability theory, this system is to be designed in order to produce a vertical field whose curvature provides the decay index $n = -(R/B_v)(\partial B_v/\partial R)$ in the interval $0 \leq n \leq 3/2$. Nevertheless, extended studies on elongated cross-section plasmas have shown that these configurations are naturally related to negative values for the decay index, and so stability is only achievable by using some rapid feedback control system [5]. In view of this, vertical field position and current were fixed just considering the desired plasma geometry, in special an elongation as high as possible. The impossibility in obtaining an elongated plasma fully stable against vertical displacements is illustrated in Figure 1, which shows a quite large part of the plasma column immersed in the unstable region (above and below the curve labeled as 2) when it is elongated (κ=1.4), compared to a reduced area for almost circular plasmas (κ=1.0).

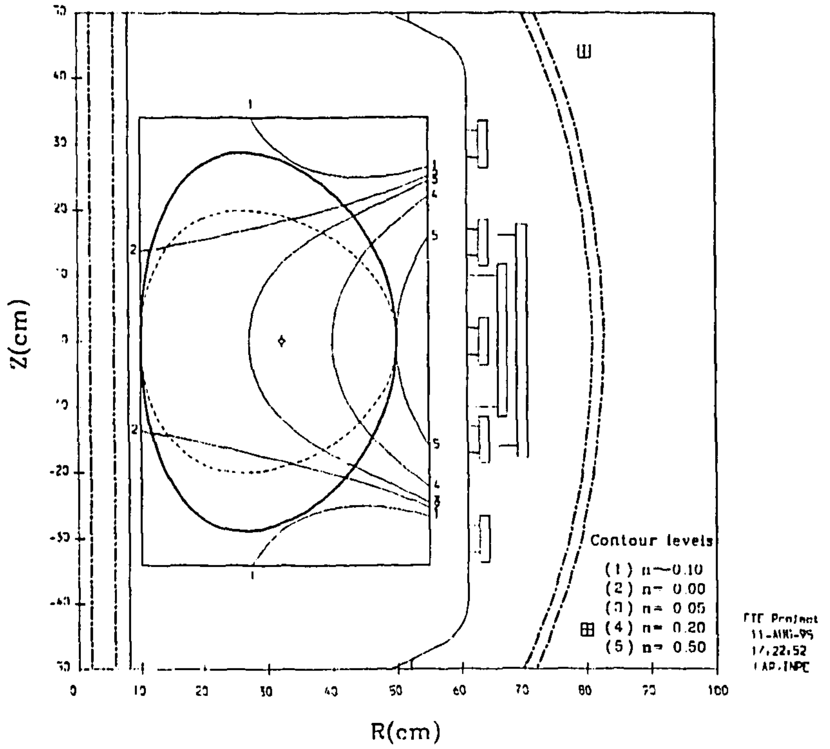

Figure 1. Constant decay index contours for the verfical field coils ♯4, showing a larger unstable region ($n < 0$, above and below the curve 2) for an elongated plasma (bold contour), compared to the nearly circular plasma (dashed contour). Dash-dotted lines represents the toroidal coil legs.

Coil	Rc(cm)	Zc(cm)	Nr × Nz	I_{loop}(kA)	I_{total}(kA)
Ohmic (♯1)	7.2	0.0	2×130	20	5200
Compensation (♯2)	10.0	±66.7	2 × 8	20	320
Compensation (♯3)	66.0	±84.9	2 × 1	20	40
Vertical (♯4)	80.0	±44.0	2 × 2	20	80

Table 1 - Poloidal coil system in ETE.

RESULTS AND COMMENTS

The main equilibrium parameters obtained for the configuration resulting from the coil system given in Table 1 are listed in Table 2, together with some input data values. For a plasma current $I_p = 200kA$ and toroidal magnetic induction of $B_o = 0.4T$, an equilibrium configuration with $\kappa = 1.44$ and $q_o = 1.20$ was obtained.

Major radius,	R_o	=	30.0	cm	Safety factor (on axis),	q_o	=	1.20	
Aspect ratio,	A	=	1.49		Safety factor (at edge),	q_a	=	4.97	
Elongation,	κ	=	1.44		Poloidal beta,	β_p	=	4.50	%
Triangularity,	δ	=	0.20		Engineering beta,	β_e	=	0.70	%
Toroidal magnetic field,	B_o	=	0.40	T	Plasma current,	I_p	=	200	kA

Table 2 - Main equilibrium parameters in ETE.

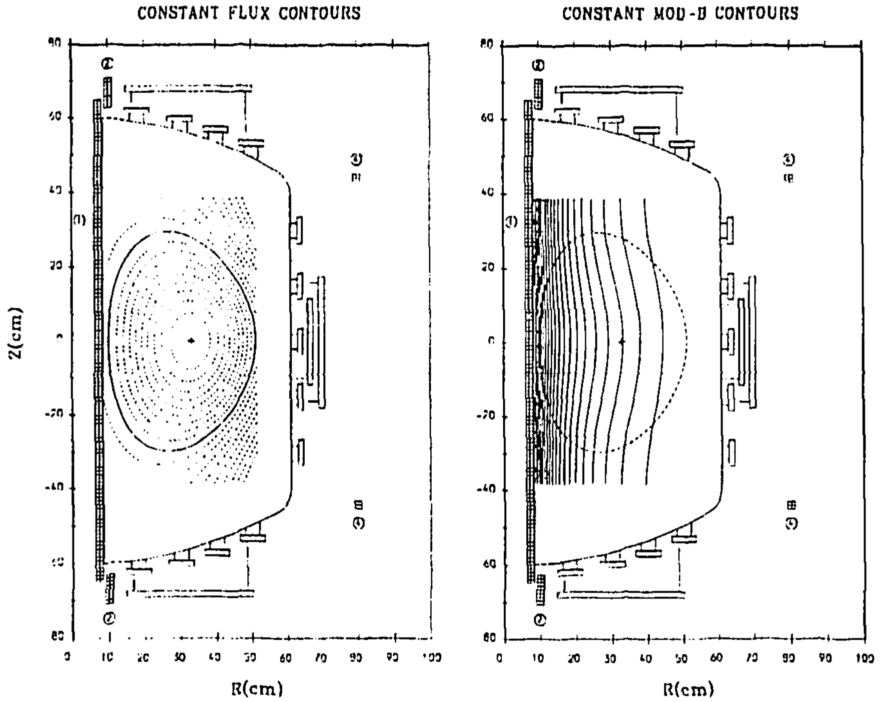

Figure 2. Constant poloidal flux (left) and constant-$|\vec{B}|$ (right) contours corresponding to the equilibrium given in Tab.2.

The constant poloidal flux and constant-$|\vec{B}|$ contours are shown in Figure 2. Notice that compensation coils ♯3 at $r = 66.0cm, z = \pm 84.9cm$ do not appear. The safety factor profile against the normalized poloidal flux and the normalized pressure (peaked on the magnetic axis) and current density radial profiles on the $z = 0$ plane are given in Figure 3.

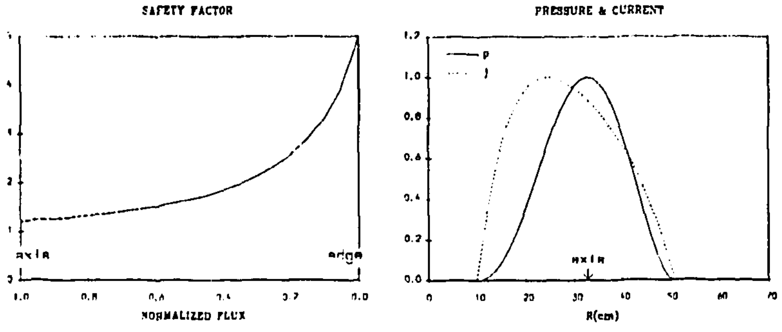

Figure 3. Safety factor q profile *vs* poloidal flux (left), and normalized pressure and current density radial profiles on the equatorial plane (right).

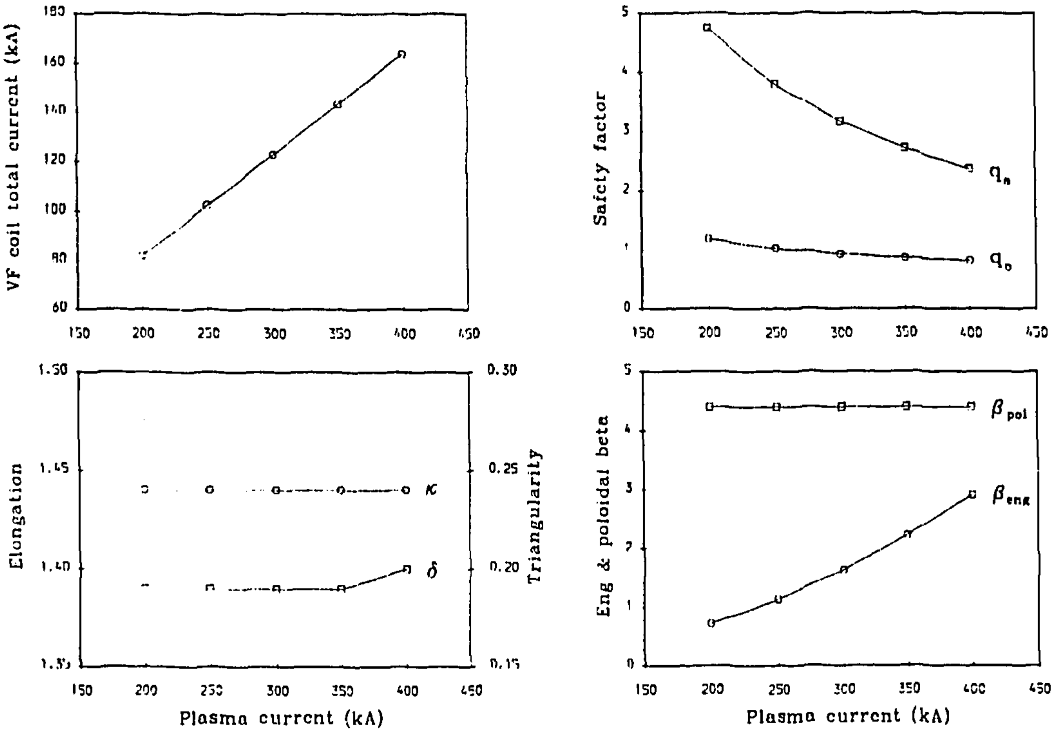

Figure 4. Equilibrium parameters for different values of the plasma current.

Finally, the effects of the plasma current on the equilibrium was studied by running the code for several values of I_p, and the results are shown in Figure 4. In the top-left frame, the current in the vertical field coils necessary for the achievement of MHD equilibrium is calculated for different values of the plasma current I_p, showing the expected linear variation. From the elongation and triangularity profiles, we conclude that the plasma current value do not affects the plasma geometry at all, whereas the q-profiles tell us that high-I_p phases may endanger the plasma stability. The last frame show a quite different behaviour for the poloidal and engineering-β values.

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[4] Shibata, C.S. and Montes,A. *"Poloidal field leakage optimization in ETE"*, this proceedings.

[5] Rosenbluth, M.N. and Rutherford, P.H. *"Tokamak Plasma Stability"*, in: **Fusion**, E.Teller (editor), Academic Press, New York, 1981, Vol. 1, Part A, chap. 2.

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FREE-BOUNDARY EQUILIBRIUM PROBLEM

- ALGORITHM

The HEQ code solves the Grad-Shafranov equation

$$\Delta^* \psi = -\mu_o R J_\phi$$

by using an iteractive process of the form

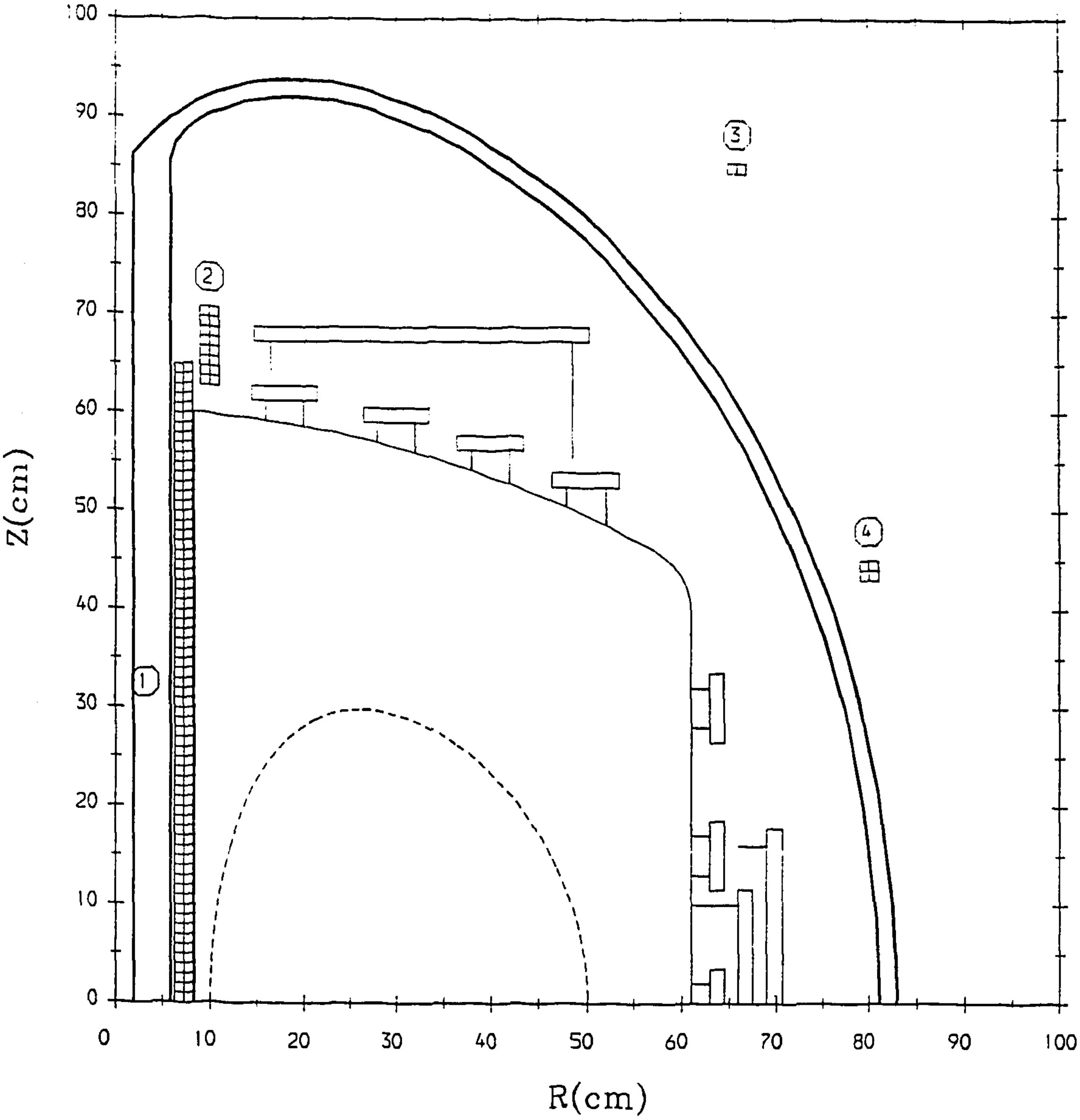
$$\Delta^* \psi^{(n+1)} = -\mu_o R[\alpha J_\phi^n + (1-\alpha) J_\phi^{(n+1)}]$$

where the parameter α controls the convergence of the solution.

- CONSTRAINTS

Parameter	Fixed *a priori*	Set by the code
Coils	- Ohmic solenoid - compensation coils - v-field coil position	- v-field coil current
Plasma	- major radius - aspect ratio	- elongation - triangularity

POLOIDAL COIL SYSTEM



Coil	Rc(cm)	Zc(cm)	Nr × Nz	I_{loop}(kA)	I_{total}(kA)
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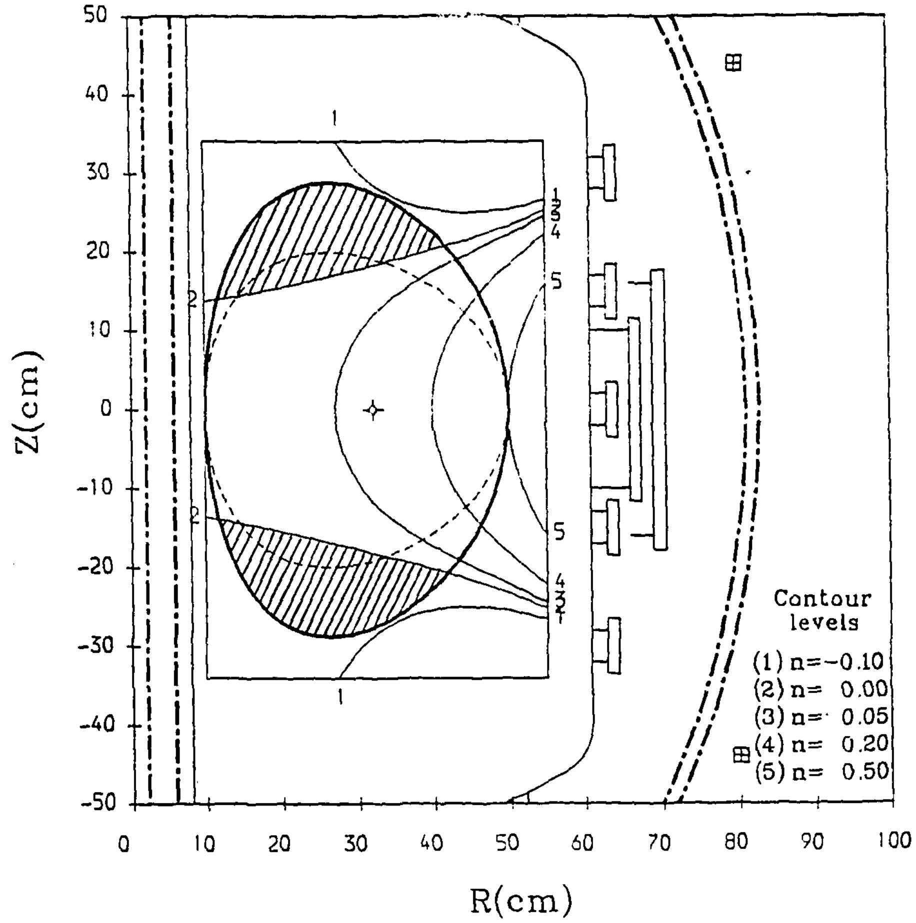
VERTICAL FIELD

- V-FIELD DECAY INDEX

$$n = -\frac{R}{B_v}\frac{\partial B_v}{\partial R}$$

- STABILITY REQUIREMENTS

$$0 \leq n \leq \frac{3}{2}$$



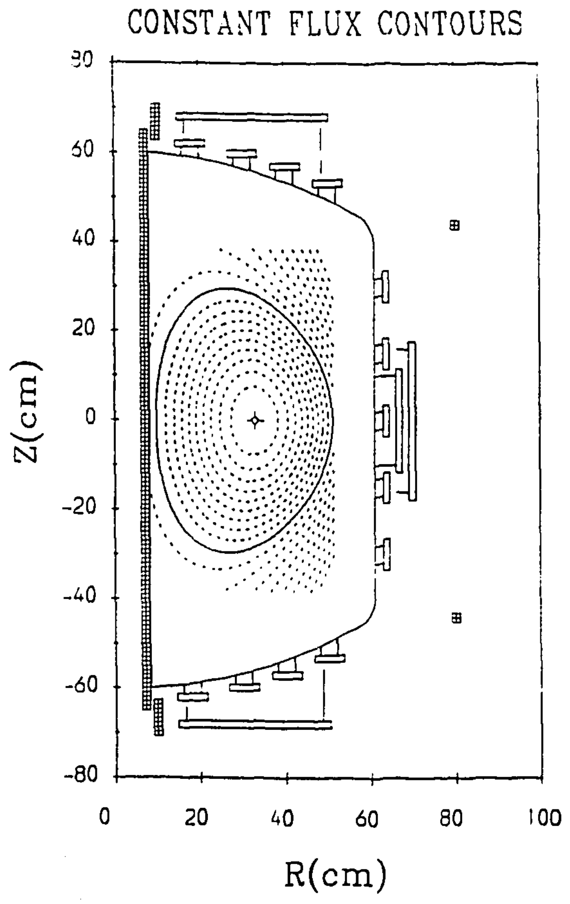
Constant decay index contours: dashed regions ($n < 0$) are unstable against vertical displacements.

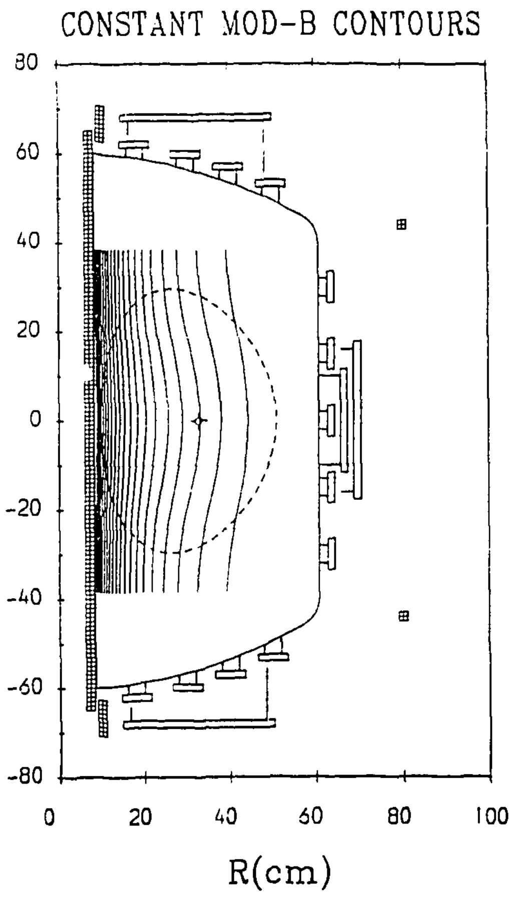
RESULTS

• MAIN EQUILIBRIUM PARAMETERS

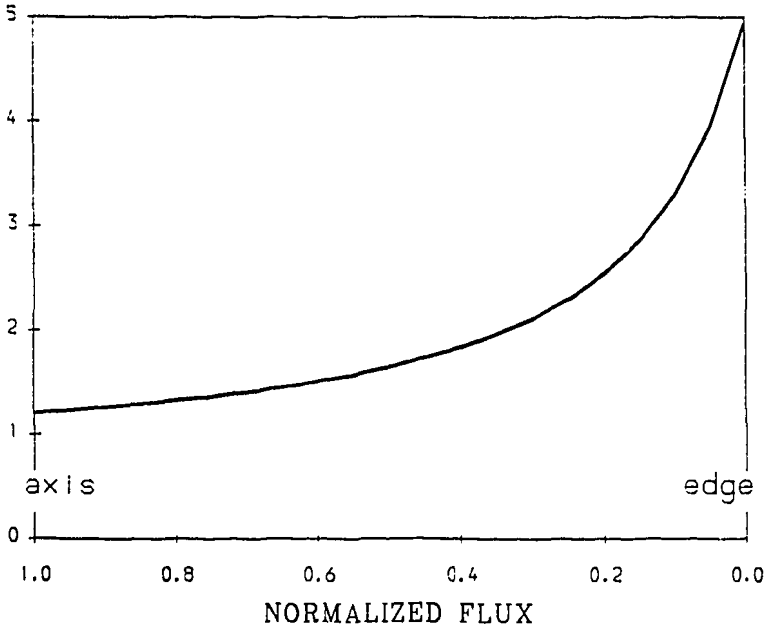
Plasma half-width,	$a =$	$20,55$	cm
Major radius,	$R_o =$	$30,55$	cm
Aspect ratio,	$A =$	$1,49$	
Elongation,	$\kappa =$	$1,44$	
Triangularity,	$\delta =$	$0,20$	
Plasma current,	$I_p =$	$200,00$	kA
Toroidal magnetic field,	$B_o =$	$4,00$	kG
Safety factor (on axis),	$q_o =$	$1,20$	
Safety factor (at edge),	$q_a =$	$4,97$	
Engineering beta,	$\beta_e =$	$0,70$	%
Poloidal Beta,	$\beta_p =$	$4,50$	%

- CONSTANT FLUX AND $|\vec{B}|$ CONTOURS

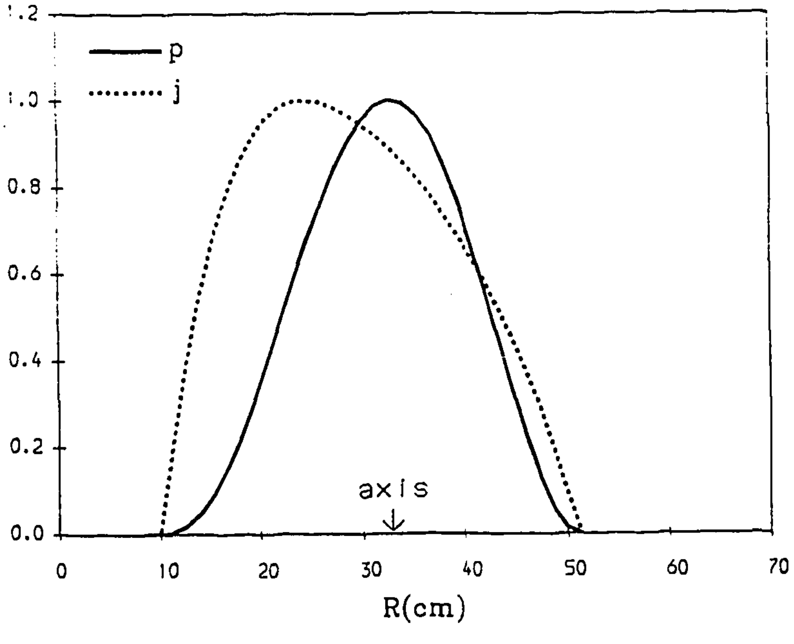

CONSTANT FLUX CONTOURS


CONSTANT MOD-B CONTOURS

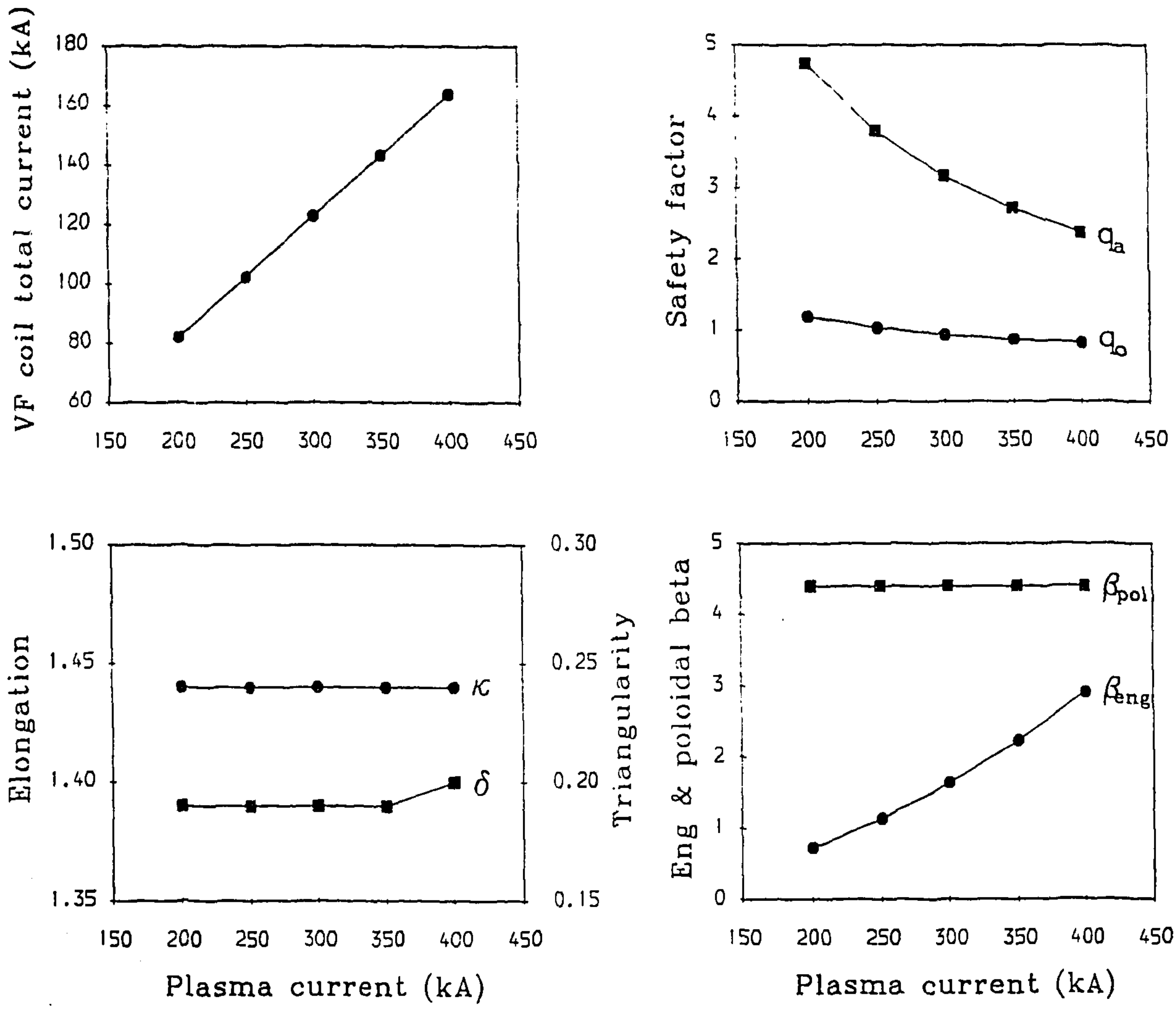
• SAFETY FACTOR PROFILE



• PRESSURE AND CURRENT DENSITY PROFILES



• EQUILIBRIUM DEPENDENCE ON I_p



CONCLUDING REMARKS

- A midium-elongated equilibrium configuration ($\kappa = 1.4$) was obtained by a relatively simple coil arrangement. Resulting safety factor profile shows acceptable values both on axis and at the plasma edge, in addition to a quite broad current profile.

- Nevertheless, vertical field decay index map shows that the configuration has unstable regions against vertical displacements. According to former works [see, e.g., Rosenbluth & Rutherford, *"Tokamak Plasma Stability"*, in: "Fusion", E.Teller (Editor), Academic Press, 1981], this is just due to the moderate plasma elongation value ($\kappa \geq 1.3$).

- Hence, a highly elongated plasma expected in ETE ($\kappa \sim 1.8$) seems to be possible only with the use of some feedback control system for the vertical field coils.

- Attempts to increase the plasma elongation (even unstable) by inclusion of more vertical field coils were not succesful with HEQ. Some other equilibrium code will be used for this purpose.

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