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TOROIDAL EQUILIBRIUM OF REVERSED FIELD PINCH

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TOROIDAL EQUILIBRIUM OF REVERSED FIELD PINCH

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SYNOPSIS

An analytical expression for the toroidal equilibrium of a reversed field pinch is derived in which the radial distribution of the plasma pressure is variable from a convex to a concave one near the magnetic axis. Using this expression, the marginal condition satisfying the Suydam's criterion for stability is found in the limiting case of large aspect ratio. The fraction of trapped particles in this configuration decreases near the periphery as the value of β becomes larger.

1. INTRODUCTION

Up to date the reversed field pinch (RFP) has been proved to have large potential to confine high β plasma.[1)2)] The essential feature of this configuration is its high magnetic shear. There is no restriction on the choice of large aspect ratio owing to the stabilising effect of the high magnetic shear. However, in general the toroidal magnetic configuration is apt to be deformed by the finite β of the confined plasma. In order to discuss the change of the configuration of the RFP due to the toroidicity and the finite β, a suitable and simple analytical expression would be preferred, in which the pressure gradient of the plasma should be adjustable since it is an essential variable for discussions of the stability of plasma.[3)] Experiments in ZETA and HBTX-I[1)2)] have shown that the stable configuration of the RFP is situated close to the state of the force free Bessel function model of the linear cylindrical geometry.[4)5)] Also this stable state satisfies Suydam's necessary condition[6)] for the plasma stability.[1)2)] The marginal condition of this criterion has been found numerically by using a relaxation method.[7)]

In this report, an analytical expression of the toroidal equilibrium of the RFP is presented, where the profile of the pressure can be changed widely. The Suydam criterion and the fraction of trapped particles in this model are also given.

2. EXPRESSION OF EQUILIBRIUM STATE

The equation of the magnetohydrostatic equilibrium for axisymmetric toroidal plasma is written in the quasi-toroidal coordinates (ρ,θ,ϕ) depicted in Fig.1 as

$$\frac{\partial^2\psi}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial\psi}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial^2\psi}{\partial\theta^2} + \frac{1}{2}\frac{d}{d\psi} f^2 + \mu_o R \frac{dp}{d\psi}$$

$$= \frac{1}{R} \left[\frac{\partial\psi}{\partial\rho}\cos\theta - \frac{1}{\rho}\frac{\partial\psi}{\partial\theta}\sin\theta \right] - 2\mu_o R\rho \frac{dp}{d\psi}\cos\theta \qquad (1)$$

to the order of the inverse aspect ratio ρ/R, where R is the major radius of the torus and ψ the magnetic flux function. The scalar plasma pressure p and the current stream function f are arbitrary function of ψ. Using the normalisations

$$\psi = B_o Ra\Phi \ , \ p = p_o P(\Phi), \ f^2 = B_o{}^2 R^2 F^2(\Phi), \ \rho = ar, \ \varepsilon = a/R,$$

we have a dimensionless form of Eq.(1)

$$\frac{\partial^2\Phi}{\partial r^2} + \frac{1}{r}\frac{\partial\Phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\Phi}{\partial\theta^2} + \frac{1}{2}\frac{d}{d\Phi}(F^2 + \alpha P)$$

$$= \varepsilon \left[\frac{\partial\Phi}{\partial r}\cos\theta - \frac{1}{r}\frac{\partial\Phi}{\partial\theta}\sin\theta - \alpha r\frac{dP}{d\Phi}\cos\theta \right], \qquad (2)$$

where

$$\alpha = p_o / (B_o{}^2/2\mu_o)$$

is a parameter concerning the beta of the plasma. In this case, the magnetic field $\vec{B} = B_o\vec{b}$ and the current $\vec{J} = (B_o/a\mu_o)\vec{j}$ are

$$\vec{b} = (b_r, b_\theta, b_\phi) = \frac{1}{1+\varepsilon r\cos\theta}\left(\frac{1}{r}\frac{\partial\Phi}{\partial\theta}, -\frac{\partial\Phi}{\partial r}, F\right), \qquad (3)$$

and

$$\vec{j} = (j_r, j_\theta, j_\phi)$$

$$= \left(\frac{1}{2F}\frac{dF^2}{d\Phi} b_r,\ \frac{1}{2F}\frac{dF^2}{d\Phi} b_\theta,\ \frac{1}{2}\left\{(1+\varepsilon r\cos\theta)\alpha\frac{dP}{d\Phi} + \frac{1}{1+\varepsilon r\cos\theta}\frac{dF^2}{d\Phi}\right\}\right). \qquad (4)$$

The radial profile of the plasma pressure is an essential variable for discussing the stability, so that an expression for the profile is desired which can be varied.
Equation(3) means that the function $F(\Phi)$ should be reversed to express the RFP configuration. For these reasons, we choose the following forms of F and P

$$F(\Phi) = \mu(\Phi + A),$$

$$P(\Phi) = \mu^2(\{\Phi + D\} - \eta\{\Phi + D\}^2),$$

where μ is a parameter of the configuration, and A and D are constants decided by the boundary condition. The pressure profile can be changed by the parameter η. The case $\eta = 0$ has been discussed in ref[8]. We consider the boundary condition that the pressure P vanishes at $r = 1$. Then, the solution of Eq.(2) where magnetic surfaces are circular can be found to the order of ε as

$$\Phi = J_0(\mu k r) + \varepsilon S\cos\theta, \qquad (5)$$

where

$$S = \frac{1}{2}\left[rJ_0(\mu kr) - \frac{J_0(\mu k)}{J_1(\mu k)} J_1(\mu kr)\right]$$
$$+ \frac{\alpha}{k^2}\left[\{1+2\eta J_0(\mu k)\}\left\{\frac{J_1(\mu kr)}{J_1(\mu k)} - r\right\} + \frac{1}{2}\eta\mu k(r^2-1)J_1(\mu kr)\right], \qquad (6)$$

$$k^2 = 1 - \alpha\eta. \qquad (7)$$

Also we have

$$F = \mu[J_o(\mu kr) - \tfrac{1}{2}\alpha\{1 + 2\eta J_o(\mu k)\} + \varepsilon S\cos\theta], \tag{8}$$

$$P = \mu^2[J_o(\mu kr)-J_o(\mu k)+\varepsilon S\cos\theta][1-\eta\{(J_o(\mu kr)-J_o(\mu k)+\varepsilon S\cos\theta\}]. \tag{9}$$

The boundary condition of the plasma pressure is satisfied since the function S vanishes at r = 1. The magnetic field outside the plasma can easily be found by connecting analytically the internal field with the outer vacuum field on the intersurface r = 1. The toroidal effect $\varepsilon S\cos\theta$ in Eq.(5) includes in itself the influence of finite plasma pressure (or finite α) as is seen in Eq.(6). The function F is also changed by α and η so that the condition of the field reversal is modified by them.

Parameters which are frequently used in the linear configuration $\varepsilon = 0$ are easily derived from Eqs.(3) and (5) to (9). 'Pinch ratio' defined by $\Theta \equiv B_\theta\ (\rho = a)/\langle B_\phi\rangle$, where $\langle X\rangle$ means the average of X over the cross section of the plasma, is

$$\Theta = \frac{b_\theta(r=1)}{\langle b_\phi\rangle} = \frac{\mu}{2}\, k^2[1 - \frac{\mu kC}{2J_1(\mu k)}]^{-1}, \tag{10}$$

where

$$C = \frac{\alpha}{2}\ [1 + 2\eta J_o(\mu k)].$$

'Field parameter' defined by $B_\phi(\rho = a)/\langle B_\phi\rangle$ is

$$\lambda = \frac{b_\phi(r=1)}{\langle b_\phi\rangle} = \frac{\mu k[J_o(\mu k) - C]}{2J_1(\mu k) - \mu kC}\ . \tag{11}$$

The value of β at the centre r = 0 for $\varepsilon = 0$, β_o , and the average of β, $\overline{\beta}$, are related with α such that

$$\beta_o = \alpha \cdot \frac{[1-J_o(\mu k)]\cdot[1-\eta\{1-J_o(\mu k)\}]}{[1 - C]^2} \tag{12}$$

and

$$\overline{\beta} = \frac{<p>}{<\frac{B^2}{2\mu_o}>} = \alpha \frac{<p>}{<b^2>} = \alpha \cdot \frac{[\frac{2J_1(\mu k)}{\mu k} - J_o(\mu k)][1+2\eta J_o(\mu k)] - \eta J_1^2(\mu k)}{(k^2+1)[J_1^2(\mu k)+J_o^2(\mu k)]+C^2 - \frac{2}{\mu k}[2C+k^2J_o(\mu k)]J_1(\mu k).} \tag{13}$$

The average poloidal β is also found to be

$$\overline{\beta}_p \equiv \frac{<p>}{\frac{B_\theta^2(r=1)}{2\mu_o}} = \frac{<P>}{b_\theta^2(r=1)}$$

$$= \frac{\alpha}{k^2J_1^2(\mu k)} [\{2 \frac{J_1(\mu k)}{\mu k} - J_o(\mu k)\}\cdot\{1+2\eta J_o(\mu k)\}-\eta J_1^2(\mu k)]. \tag{14}$$

The pitch of a field line s is

$$s \equiv \frac{\rho B_\phi}{B_\theta} = \frac{rb_\phi}{b_\theta} = \frac{\mu kr[J_o(\mu kr) - C]}{k^2J_1(\mu kr)} \tag{15}$$

In the case of the linear force-free state ($\varepsilon = 0$, $\alpha = 0$), θ and λ are reduced to the Bessel function model of J.B.Taylor; i.e. $\theta = \frac{1}{2}\mu$ and $\lambda = \frac{1}{2}\mu J_0(\mu)/J_1(\mu)$. Θ, λ and β_o for $\eta = 0$ are all in agreement with the results in ref.[8].

3. DEPENDENCE OF THE CONFIGURATION ON PARAMETERS

Let us define a critical value of η:

$$\eta_c = \frac{1}{2}\frac{1}{1 - J_o(\mu k)}, \tag{16}$$

then the radial profile of the pressure for $\varepsilon \to 0$ becomes

$$\text{convex for } \eta < \eta_c$$

and

$$\text{concave for } \eta > \eta_c \text{ near the centre axis.}$$

At $\eta = \eta_c$ the profile becomes flat at the centre $r = 0$ where $d^2P/dr^2 = 0$, and the pressure vanishes at the centre if $\eta = 2\eta_c$. In the range $\eta_c < \eta < 2\eta_c$ the position of the peak of the pressure r_0 is related to η as

$$\eta = \frac{1}{2} \frac{1}{J_o(\mu k r_o) - J_o(\mu k)}$$

The toroidal field at the boundary $r = 1$ is

$$B_\phi(r=1) = [J_o(\mu k) - C]/(1 + \varepsilon\cos\theta)$$

so that the field reversal of the toroidal magnetic field occurs if

$$J_o(\mu k) \leq \frac{\alpha}{2(1 - \alpha\eta)} \ . \qquad (17)$$

The necessary value of μ for the field reversal becomes smaller as α and/or η increases.

Profiles of B_ϕ, B_θ, p and s for different α and η in the case $\varepsilon = 0$ are presented in Fig.2 where the maxima of B_ϕ, p and s are normalised to unity and B_θ is shown relative to the maximum of B_ϕ. The value of μk is fixed at $\mu k = 2.2$. The toroidal magnetic field is not reversed in the force-free state $\alpha = 0$ in which the field parameter $\lambda = +0.218$ and $\Theta = 1.1$ (see Fig.2(a)). The field parameter decreases as α(i.e. β) becomes higher and then the field reversal occurs at higher α satisfying the inequality (17). Figure 2(b) and (c) show this RFP state where $\eta = \eta_c = 0.562$. Examples of the case $\eta_c < \eta < 2\eta$ are also shown in Fig.2(d) and (e).

The (usual) magnetic axis relative to the geometrical axis r = 0 is shifted by

$$\Delta r = \frac{\varepsilon}{(\mu k)^2}\left[1 - \frac{\mu k J_0(\mu k)}{2J_1(\mu k)} + \frac{2\alpha}{k^2}\left\{ \frac{\mu k}{2J_1(\mu k)} - 1 + 2\eta\left(\frac{\mu k}{2J_1(\mu k)} - 1\right) J_0(\mu k) - \frac{\mu^2 k^2}{8} \right\}\right], \tag{18}$$

toward the outside of the torus from r = 0. Figure 3 shows the dependence of this shift on μ, β_0 and η. In the force-free case the shift monotonically increases as the parameter μk becomes larger, while it turns to have a minimum with appropriate higher values of β_0 and/or η.

The second magnetic axis closed by extraordinary magnetic surfaces appears on the inside of the torus ($\theta = \pi$) if the following condition is attained;

$$\alpha \geq k^2 \frac{\left(\frac{1}{\varepsilon} - \frac{1}{2}\right)J_1^{\,2}(\mu k) + \frac{1}{2} J_0(\mu k) J_2(\mu k)}{J_2(\mu k) + \eta\{2J_0(\mu k)J_2(\mu k) - J_1(\mu k)\}} \ . \tag{19}$$

The appearance of the second magnetic axis would limit the available region of the RFP operation within the frame of this model as the problem of large β_p in tokamak.[9)10)] However, the condition (19) is only satisfied on high μ side where the field parameter λ becomes very large.[8)] For this reason, the problem is not serious in the usual operation of the RFP.

From Eqs. (3),(4),(8) and (9) we have

$$\left.\begin{aligned} j_r &= \mu b_r, \\ j_\theta &= \mu b_\theta, \\ j_\phi &= \frac{1}{2}(1 + \varepsilon r\cos\theta)\alpha\frac{dP}{d\Phi} + b_\phi\cdot\frac{dF}{d\Phi} \ . \end{aligned}\right\} \tag{20}$$

Therefore, it is sufficient to show b_ϕ, b_θ, P and j_ϕ in order to see the toroidal effect. These components on the median plane of the torus ($\theta = 0$, π) are shown in Fig. 4 for several sets of the parameters. The aspect ratio $1/\varepsilon$ is set to 3 which is the planning value of HBTX-II[9], and the parameter μ is 2.6. In the force-free state $\alpha = 0$ (Fig. 4(a)), the toroidal field b_ϕ and the toroidal current j_ϕ become zero at the same radius, but these zero-crossing points separate as α increases (Fig. 4(b) and 4(c)). A striking toroidal effect can be seen in the profile of b_θ; b_θ on the inside of the torus is larger than that on the outside. However, as α or β becomes higher, b_θ decreases on the inside of the torus and it rises at the periphery on the outside. This change of b_θ with α affects the fraction of trapped particles, especially near the periphery.

4. TRAPPED PARTICLES

The absolute value of the magnetic field is found from Eqs. (3),(5) ∿ (8) as

$$b^2 = (F^2 + R'^2) + 2\varepsilon[R'S' - r(F^2 + R'^2)]\cos\theta,$$

where $R = J_0(\mu k r)$ and X' means dX/dr. By using the average radius of any magnetic surface $\bar{r}$, the absolute value of the magnetic field on any $\bar{r}$ magnetic surface is found after some algebra to be

$$|b| = H^{1/2}(\bar{r})\left[1 + \varepsilon \frac{K(\bar{r})}{H(\bar{r})}\cos\theta\right], \qquad (21)$$

where

$$H(\bar{r}) = \mu^2[J_o{}^2(\bar{x}) + k^2 J_1{}^2(\bar{x}) - C\cdot\{2J_o(x) - C\}], \qquad (22)$$

$$K(\bar{r}) = -(\mu k)[J_o(\bar{x})J_1(\bar{x}) + \frac{1}{2}\bar{x}\{J_1{}^2(\bar{x}) + \frac{1+\alpha\eta}{k^2} J_o{}^2(\bar{x})\}]$$
$$+ \frac{\alpha(\mu k)}{k^2}[2J_1(\bar{x}) - \frac{\alpha}{4}\bar{x} - \eta\{x(J_1{}^2(\bar{x}) + \alpha J_o(\bar{x}) + \alpha\eta J_o{}^2(\mu k) - xJ_1{}^2(\bar{x})\}], \qquad (23)$$

$$\bar{x} = \mu k \bar{r}.$$

Then, the fraction of trapped particles on $\bar{r}$ magnetic surface is given by

$$\Omega(\bar{r}) = \sqrt{2\varepsilon}\left|\frac{K(\bar{r})}{H(\bar{r})}\right|^{\frac{1}{2}} \qquad (24)$$

The second term on the right hand side of Eq. (23) is an increasing function of α (up to $\alpha = 4J_1(\mu k)/(\mu k)$ for $\eta=0$), while the first term is negative. Therefore, finite α works to decrease the fraction of trapped particles. For $K \geq 0$ trapped particles on the inside of the torus come out.[2)10)11)8)] Figure 5 shows this effect of α for the case $\mu = 2.6$ and $\eta = \eta_c = 0.456$. The fraction decreases as β_o becomes higher. The dotted curve $\Omega/\sqrt{2\varepsilon} = \bar{r}^{1/2}$ roughly corresponds to the case of tokamak. In the inner region the fraction is close to this $\bar{r}^{1/2}$ curve. The remarkable change of Ω near the periphery in the RFP mainly orignates in the large dependences of b_ϕ and b_θ on finite β.

5. CONFIGURATION SATISFYING SUYDAM'S CRITERION AT THE LIMIT OF LARGE ASPECT RATIO

Most of stable states obtained in ZETA lie in the region of $\lambda - \Theta$ space which is surrounded by Taylor's force-free state[5)] and the curve from a high β model.[7] This high β model was used to find numerically the configuration of the RFP which marginally satisfies the Suydam's criterion everywhere inside the plasma region. The marginal condition is analytically given for the model used here.

The Suydam's necessary condition for stability[6] is written in our normalisation by

$$\alpha \frac{dP}{dr} + \frac{r}{4} b_\phi{}^2 \left(\frac{1}{s} \frac{ds}{dr} \right)^2 \geq 0 \tag{25}$$

where s is the pitch given by Eq. (15). Using Eqs. (3),(5),(8), (9) and (15),we rewrite Eq. (25) as

$$[\{J_o(x) - C\}\{2 - \frac{xJ_o(x)}{J_1(x)} - xJ_1(x)]^2$$
$$\geq 4\alpha x J_1(x)[1 - 2\eta\{J_o(x) - J_o(\mu k)\}], \tag{26}$$

where $x = \mu kr$ and $C = \frac{1}{2}\alpha\{1 + 2\eta J_o(\mu k)\}$.

The approximate form of the condition (26) for small x is

$$\frac{1}{64} (C^2 + 10C + 1 -24\alpha\eta)x^2 \geq C - \alpha\eta. \tag{27}$$

Above inequality is always satisfied if

$$\left.\begin{array}{l} C - \alpha\eta \leq 0 \quad \text{or} \quad \eta \geq \eta_c = \frac{1}{2}\frac{1}{1 - J_o(\mu k)}, \\ \text{and} \\ (C^2 + 10C + 1 - 24\alpha\eta) \geq 0. \end{array}\right\} \tag{28}$$

Thus, the marginal condition for small x is $\eta = \eta_c$ where the pressure profile is flat at the centre $x = 0$ as shown in Section 3. The requirement (28) also leads to the limit on α

$$\alpha \leq \alpha_s \equiv 0.0718/\eta_c \tag{29}$$

whence

$$k^2 = k_s^2 \equiv 1 - \alpha_s \eta_c = 0.9282.$$

Therefore, once the parameter μ is given, the associated parameters in this marginal case can be found from

$$\eta = \eta_c = \frac{1}{2}\frac{1}{1 - J_o(\mu k_s)} ,$$

$$\theta = \theta_s \equiv \frac{0.481(\mu k_s)}{1 - 0.0359\dfrac{(\mu k_s)}{J_1(\mu k_s)}}$$

$$\lambda = \lambda_s \equiv \frac{(\mu k_s)[J_o(\mu k_s) - 0.0718]}{2J_1(\mu k_s)[1 - 0.0359\dfrac{(\mu k_s)}{J_1(\mu k_s)}]} \qquad (30)$$

$$\beta_o = \beta_{os} \equiv 4.04\alpha_c^2 .$$

It is numerically shown that the condition (26) is satisfied all over the region $0 \leq r \leq 1$ if above marginal condition $\eta = \eta_c$ and $\alpha = \alpha_s$ for small x is used. In Fig. 6(a), the marginal curve on $\lambda - \Theta$ space is shown and the numerical result from the high β model[7] is also drawn for comparison. The region between this analytical curve and the curve of the force-free Bessel function model is narrow compared with the case of the high β model. This shrinkage of the region is due to the modest pressure gradient near the periphery in our case. Figure 6(b) shows the relation of β_{os} with θ_s. At $\mu = 3.2$, β_{os} becomes 0.13.

The requirement that there is 'no pitch minimum' inside the plasma region leads to the condition

$$c \geq \frac{2J_o(x)J_1(x) - x\{J_o^2(x) + J_1^2(x)\}}{2J_1(x) - xJ_o(x)}$$

Since the right hand side is always negative and $C \gtrsim 0$, the requirement is always satisfied in our case. The variation of the pitch s is shown in Fig. 2.

Another stability criterion concerning the magnetic shear on the axis[12)] is

$$\gamma = \frac{1}{2} s \left. \frac{d^2 s}{dr^2} \right|_{r \to 0} < -\frac{4}{9} = -0.444 \qquad (31)$$

In our model

$$\gamma = -\frac{1 - C^2}{2k^3} \qquad (32)$$

and in the marginal case for the Suydam's criterion we have

$$\gamma = -\frac{1 + \alpha_s \eta_c}{2(1 - \alpha_s \eta_c)^2} = -0.622.$$

Therefore, the criterion (31) is satisfied.

6. SUMMARY

An analytical expression for the toroidal equilibrium of the RFP has been presented. The profile of the plasma pressure in this model is variable from a peaked profile to a hollow one, and the configuration tends to the force-free Bessel function model as β tends to zero. With this expression, toroidal effects have been demonstrated in the profiles of the magnetic field and the pressure. The fraction of trapped particles is also found. The marginal condition for the Suydam's criterion has been given in this model and compared with the numerical result using the relaxation method.

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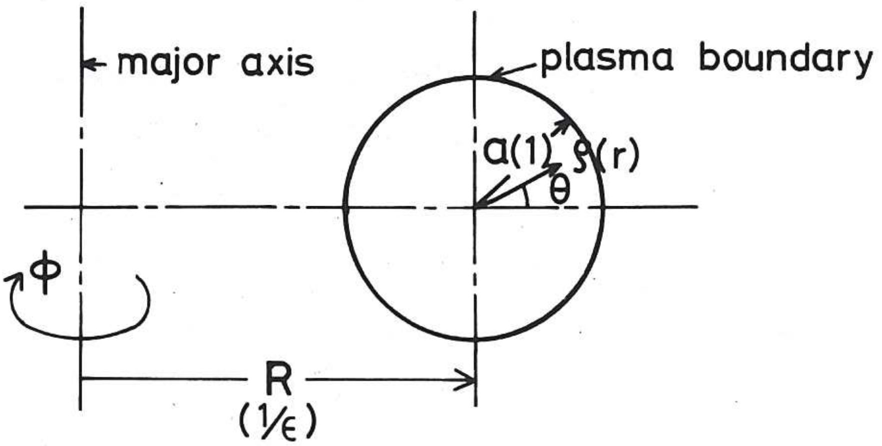

Fig.1 Quasi-toroidal coordinates (ρ,θ,ϕ). In the parentheses their normalised coordinates are given.

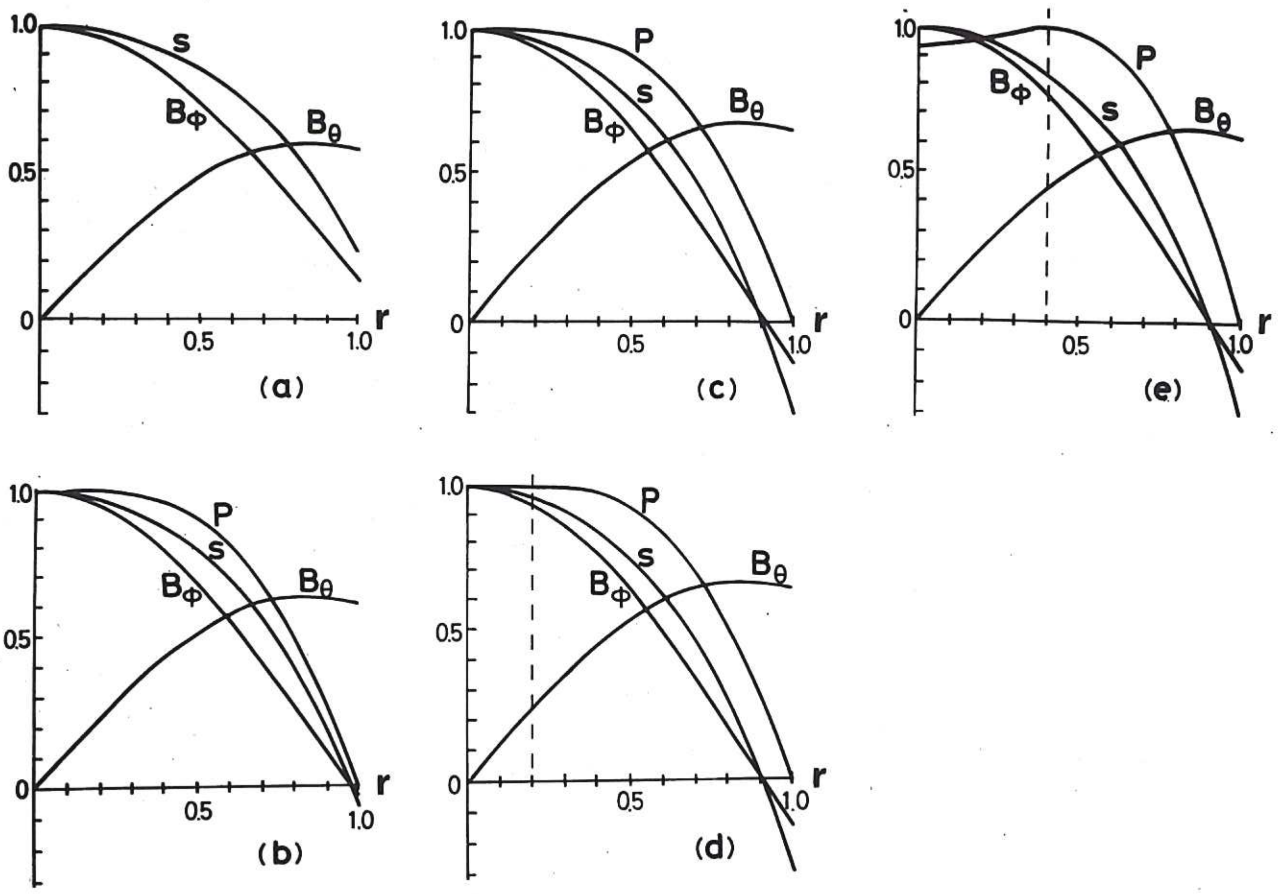

Fig.2 Radial distributions of the toroidal field B_ϕ, the poloidal field B_θ and the pitch s at the limit of the large aspect ratio ($\epsilon = 0$). B_ϕ and s are normalised to be 1.0 at the centre and B_θ is relative value to B_ϕ at the centre. The parameter μ is set to be 2.2 for all cases. (a) $a = 0, \eta = 0, \theta = 1.1, \lambda = 0.218, \beta_o = 0$. (b) $a = 0.25, \eta = \eta_c = 0.562, \theta = 1.41, \lambda = -0.083, \beta_o = 0.15$. (c) $a = 0.4, \eta = \eta_c = 0.562, \theta = 1.74, \lambda = -0.40, \beta_o = 0.30$. (d) $a = 0.4, \eta = 1.06\eta_c = 0.594, \theta = 1.74, \lambda = -0.415, \beta_o = 0.28$. (e) $a = 0.4, \eta = 1.26\eta_c = 0.709, \theta = 1.72, \lambda = -0.441, \beta_o = 0.22$.

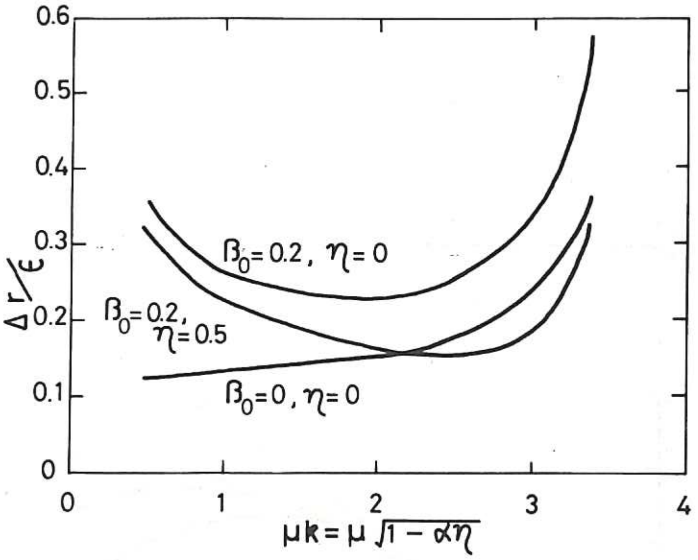

Fig.3 Shift of the magnetic axis Δr as a function of μk for different values of β_o and η.

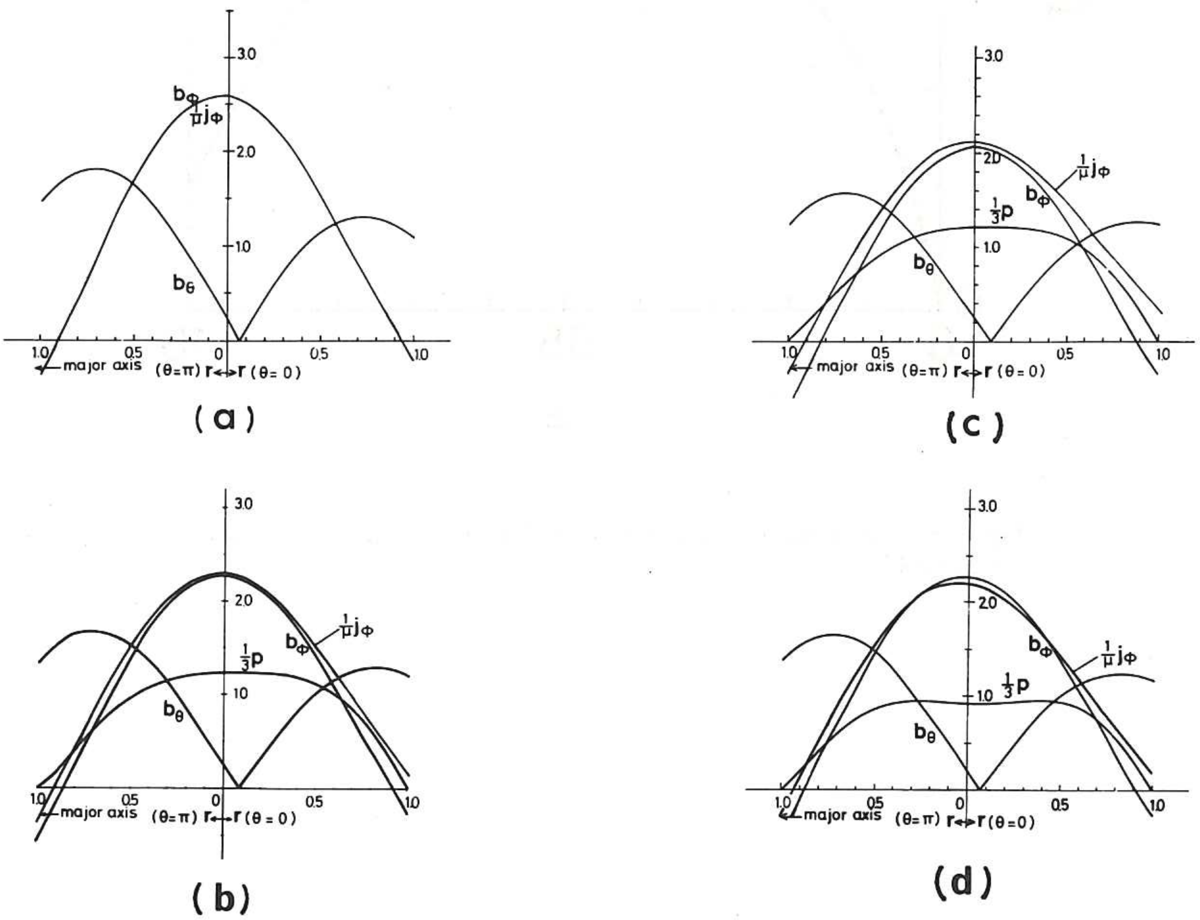

Fig.4 Profiles of the toroidal field b_ϕ, the poloidal field b_θ the pressure P and the toroidal current j_ϕ on the median plane of the torus for $\epsilon = 1/3$ and $\mu = 2.6$. (a) $a = 0, \eta = 0, \theta = 1.3, \lambda = -0.267, \beta_o = 0, \beta_p = 0$. (b) $a = 0.25, \eta = \eta_c = 0.456, \theta = 2.08, \lambda = -0.49, \beta_o = 0.177, \beta_p = 0.338$. (c) $a = 0.4, \eta = \eta_c = 0.456, \theta = 2.92, \lambda = -0.71, \beta_o = 0.343, \beta_p = 0.532$. (d) $a = 0.25, \eta = 1.3\eta_c = 0.592, \theta = 2.15, \lambda = -0.399, \beta_o = 0.134, \beta_p = 0.295$.

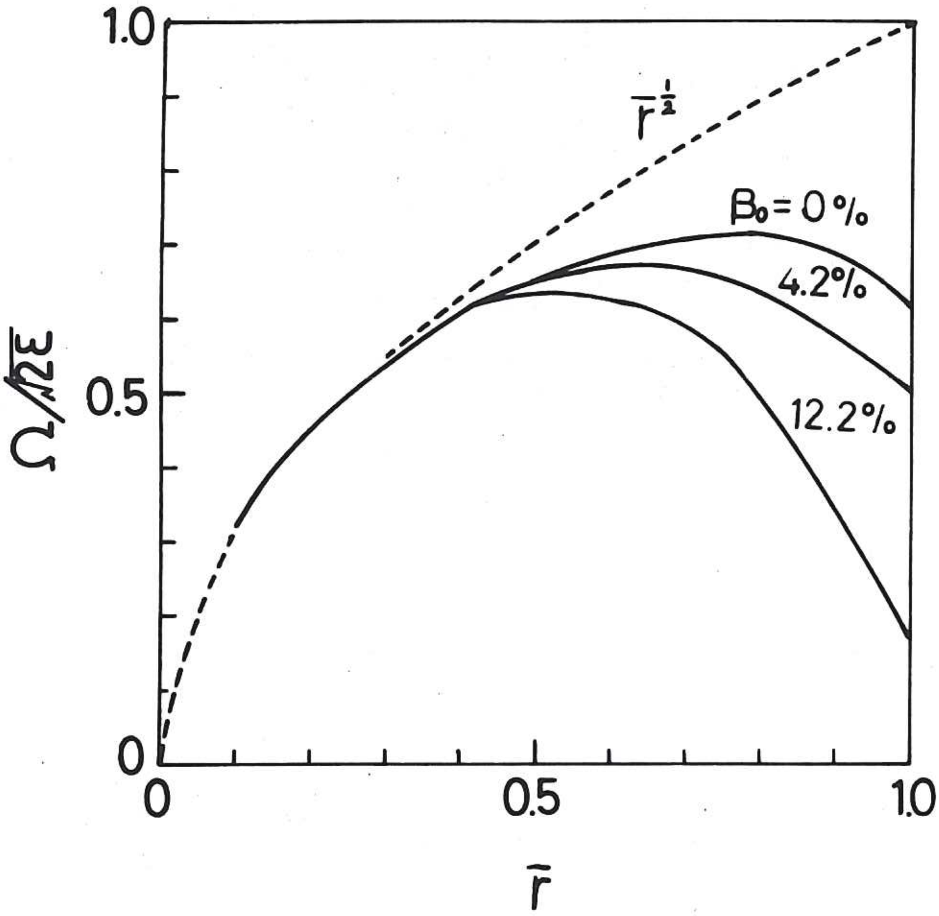

Fig.5 Fractions of trapped particles in the RFP configuration for $\mu = 26$ and $\eta = \eta_c = 0.456$.

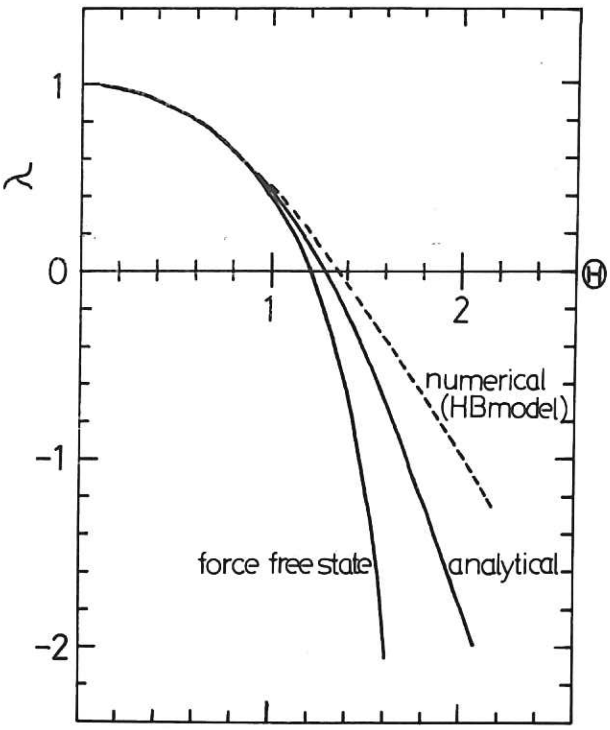

Fig.6 (a) Marginal curve of the Suydam's necessary condition for stability. The dotted line is the numerical result by the relaxation method (ref.7).

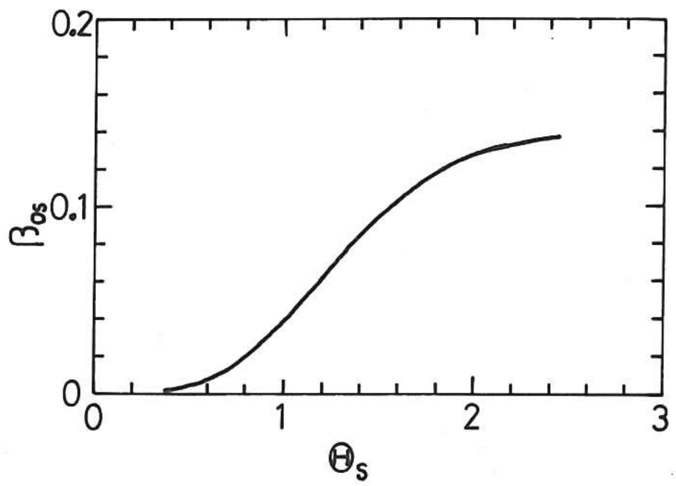

Fig.6 (b) Relation between β_{os} and θ_s in the marginal condition.

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