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RESEARCH REPORT

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Destruction of Magnetic Surfaces near a Separatrix of a Stellarator Attributed to Perturbations of Magnetic Fields

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ABSTRACT

The destruction of magnetic surfaces in the vicinity of a separatrix of a stellarator and a torsatron is analized. Unperturbed magnetic surfaces formed by a straight helical current and a uniform magnetic field are assumed. Destruction of magnetic surfaces is attributed to perturbations of magnetic fields, which are assumed to be brought from toroidal effects of magnetic fields or discrete structure of magnetic coils, respectively. Analysis is based on "Stochasticity" and a spread of a stochastic layer in the vicinity of the separatrix is calculated.

§.1 Introduction

In the confinement of the plasma with closed magnetic fields, the effects of magnetic perturbations to equilibrium magnetic surfaces are important. Such magnetic surfaces are known to exist exactly in cases of certain symmetry, for example, translational, axial or helical symmetry. However magnetic perturbations which break this symmetry produce magnetic islands and then destroy equilibrium magnetic surfaces in certain circumstances. The destruction of equilibrium magnetic surfaces is discussed by Rosenbluth et al.[1] on the basis of overlapping of adjacent islands. This phenomena surely occur in the vicinity of the separatrix of magnetic fields. Similar and detailed discussions have been also given in references.[2-7] Particularly a linear stellarator has a helical symmetry, so equilibrium magnetic surfaces exist and the destruction of magnetic surfaces due to the toroidal effects is analized near the magnetic axis by Filonenko, Sagdeev and Zaslavsky.[2]

In this paper, we consider the system which has a separatrix formed by a straight helical coil and a uniform magnetic field. The toroidal effects of helical coils and the effects of discrete structure of toroidal coils are taken account of. Analysis is based on "Stochasticity"[8], and a spread of a stochastic layer in the vicinity of the separatrix, in which equilibrium magnetic surfaces are destroyed, is calculated in the case of a stellarator and torsatron.

In a linear stellarator, equations for the magnetic lines of force are given and action-angle variables are introduced, so these equations are transformed to a simpler canonical form. The magnetic perturbations act as external forces on these canonical equations for the magnetic lines of force, and resonate with the rotational transform of the unperturbed magnetic fields in certain circumstances. The condition for this resonance is obtained and formation of magnetic islands around each resonance is analized. Finally, the stochastic condition is studied and the stochastic layer is calculated.

§.2 Unperturbed System

We consider an unperturbed system constituted of a straight helical coil of l turns with a constant pitch L_h $(=2\pi/\alpha)$ and an external uniform magnetic field B_{t0} (Fig.1). A field of this kind exhibits helical symmetry, so equilibrium magnetic surfaces are performed ; in the cylindrical coordinates (r,ϕ,ζ) normalized by $1/\alpha$, the magnetic field depends only on the coordinates r and $\theta = \phi + \zeta$. The magnetic field of this system is expressed by the scalar potential:

$$\Phi = B_0 \zeta + \sum_{k=1}^{\infty} b_k I_{lk}(lkr) \sin lk\theta \quad , \tag{2.1}$$

where $I_{lk}(lkr)$ is the modified Bessel function of the first kind and $B_0 = B_{to} + B_{h0}$. The magnetic fields B_{h0} and b_k formed by a straight helical coil are given by

$$B_{h0} = \frac{1+\sigma}{2} \frac{l\mu_0 I}{\pi\sqrt{r_0^2+1}} ,$$

$$b_k = -\frac{1+\sigma^{k-1}}{2} \frac{2l\mu_0 r_0 I}{\pi\sqrt{r_0^2+1}} K_{lk}'(lkr_0) , \tag{2.2}$$

where $\sigma = \pm 1$, the upper sign is refered to a torsatron and the lower sign to a stellarator , r_0 and I are a radius and a current of a straight helical coil respectively, $K_{lk}(lkr)$ is the modified Bessel function of the second kind, and the prime denotes a derivative with respect to its argument. Then we obtain the components of the unperturbed magnetic field in the following form:

$$B_r^0 = \frac{\partial\Phi}{\partial r} = l\sum_k kb_k I_{lk}'(lkr) \sin lk\theta ,$$

$$B_\phi^0 = \frac{1}{r}\frac{\partial\Phi}{\partial\phi} = \frac{l}{r}\sum_k k\, b_k\, I_{lk}(lkr) \cos lk\theta , \tag{2.3}$$

$$B_\zeta^0 = \frac{\partial\Phi}{\partial\zeta} = B_0 + l\sum_k kb_k I_{lk}(lkr) \cos lk\theta ,$$

and the magnetic lines of force are given by

$$B_\zeta^0 \frac{dr}{d\zeta} = B_r^0 ,$$

$$B_\zeta^0\, r\frac{d\theta}{d\zeta} = B_\phi^0 + rB_\zeta^0 . \tag{2.4}$$

Following to the scheme employed in ref.8 , we will introduce a new variable t by the relation :

$$dt \equiv \frac{B_0}{B_\zeta^0} d\zeta , \tag{2.5}$$

then the eq.(2.4) of the magnetic lines of force is rewritten in the following form :

$$\frac{dr}{dt} = \frac{B_r^{\,0}}{B_0} = l \sum_k k\beta_k \, I_{lk}{}'(lkr) \sin lk\theta \;,$$

$$\frac{d\theta}{dt} = \frac{1}{B_0}\left(\frac{B_\phi^{\,0}}{r} + B_\zeta^{\,0} \right) \tag{2.6}$$

$$= 1 + l \left(1 + \frac{1}{r^2} \right) \sum_k k\beta_k \, I_{lk}(lkr) \cos lk\theta \;,$$

where $\beta_k = b_k / B_0$. Eq. (2.6) has the obvious integral

$$H = \frac{r^2}{2} + r \sum_k \beta_k \, I_{lk}{}'(lkr) \cos lk\theta \;, \tag{2.7}$$

so that using this integral H we can obtain the equations of the magnetic line of force in the following canonical form :

$$\frac{d(r^2/2)}{dt} = -\frac{\partial H}{\partial \theta} \;,$$

$$\frac{d\theta}{dt} = \frac{\partial H}{\partial (r^2/2)} \;. \tag{2.8}$$

Accordingly one can presume that H is the Hamiltonian of the motion and correspondingly $r^2/2$ and θ are the canonical variables. The variable t plays the role of time. Since the Hamiltonian H does not involve t explicitely, that is a constant of motion. Namely, the value $H(r,\theta)$ is constant along the magnetic line of force or on a magnetic surface.

An introduction of the action-angle variables (ξ,η) by the definition :

$$\xi \equiv \frac{1}{2\pi} \int_0^{2\pi} \frac{r^2(\theta,H)}{2}\, d\theta \quad ,$$
$$\eta \equiv \frac{\partial S(\theta,\xi)}{\partial \xi} \quad , \tag{2.9}$$

where the generating function $S(\theta,\xi)$ is defined by

$$S(\theta,\xi) \equiv \int^{\theta} \frac{r^2(\theta,H)}{2}\, d\theta \quad , \tag{2.10}$$

leads to a simpler form of the equations :

$$\frac{d\xi}{dt} = 0 \quad ,$$
$$\frac{d\eta}{dt} = \omega(\xi) \quad , \tag{2.11}$$

where

$$\omega(\xi) \equiv \frac{dH(\xi)}{d\xi} \quad . \tag{2.12}$$

The physical meanings of these quantities are clear : ξ represents a magnetic surface , i.e., area enclosed by a magnetic surface, and η is the angle of rotation of the magnetic line of force. The quantity $\omega(\xi)$ is the frequency of this rotation and related to the"rotational transform", i.e., a rotational transform angle $d\phi/d\zeta$ is expressed in terms of the value $\omega(\xi)$ and $d\eta/d\theta$ by the relation :

$$\frac{d\phi}{d\zeta} = 1 - \frac{B_0}{B_\zeta^0} \frac{\omega}{\frac{d\eta}{d\theta}} \quad . \tag{2.13}$$

An altitude chart of $\xi(r,\theta)$ and $\eta(r,\theta)$, for example, in the case of a stellarator with $l=2$, is given in Fig.2 and the frequency $\omega(\xi)$ is demonstrated in Fig.3.

§ .3 Perturbations

Under the circumstance where a perturbation of magnetic fields (εB^1) acts on the equilibrium system, the equation of motion (2.11) must be modified in the form :

$$\frac{d\xi}{dt} = \frac{d\xi}{dH}\left[\frac{\partial H}{\partial(r^2/2)}\frac{d(r^2/2)}{dt} + \frac{\partial H}{\partial\theta}\frac{d\theta}{dt}\right] \equiv \Gamma(\xi,\eta,t) \quad , \tag{3.1}$$

$$\frac{d\eta}{dt} = \omega(\xi) + O(\varepsilon) \quad , \tag{3.2}$$

where the small value ε denotes a inverse aspect ratio in the case of the perturbation due to toroidal effects and the ripple of toroidal magnetic fields in the case of effects of the discrete structure of toroidal coils. Since the r.h.s. of eq.(3.1) is composed of the perturbation of magnetic fields as a function of (r,θ,ζ), it needs to be expressed by the variables (ξ,η,t). It is accomplished by eqs.(2.7) and (2.9) for the variables (r,θ), and the perturbation $\Gamma(\xi,\eta,t)$ can be expressed in a Fourier series with respsct to η and ζ ;

$$\Gamma(\xi,\eta,t) = \sum_{m',n} \Gamma_{m',n}(\xi)\exp[\,i(m'\eta - n\lambda\zeta)] \quad , \tag{3.3}$$

where the value λ is unity in the case of the perturbation due to toroidal effects and L_h / L_t in the case of effects of discrete structure of toroidal coils , L_t is the pitch length of toroidal coils. Using eq.(2.5), the variable ζ can be written in the following form :

$$\zeta = \int \frac{B_\zeta^0}{B_0}\,dt = \Omega(\xi)t + \tau(\xi,\eta) \tag{3.4}$$

, for example, in the case of a stellarator with $l=2$, the frequency $\Omega(\xi)$ is given in Fig.4 where the frequency $\omega(\xi)$ is also demonstrated. Finally the perturbation $\Gamma(\xi,\eta,t)$ can be deduced in the following Fourier series :

$$\Gamma(\xi,\eta,t) = \sum_{m,n} \Gamma_{m,n}(\xi) \exp[\, i(m\eta - n\lambda\Omega(\xi)t)] \quad . \tag{3.5}$$

In due consideration of the integral of eq.(3.2), $\eta = \omega(\xi)\, t + \Delta\eta + O(\varepsilon)$, the magnetic island contours are formed on every magnetic surface the resonance condition $m\,\omega(\xi) - n\,\lambda\,\Omega(\xi) = 0$ is satisfied. It is found that the extent of the magnetic island is

$$(\Delta\xi)_j = 4\left(\frac{2\,|\Gamma_{m_j,n_j}(\xi_j)|}{m_j\,|d\omega(\xi_j)/d\xi|}\right)^{1/2} , \tag{3.6}$$

or the frequency spread, corresponding to eq.(3.6), of the magnetic island is

$$\Delta\omega(\xi_j) = \left|\frac{d\omega(\xi_j)}{d\xi}\right| (\Delta\xi)_j$$

$$= 4\left(\frac{2\,|\Gamma_{m_j,n_j}(\xi_j)|\,|d\omega(\xi_j)/d\xi|}{m_j}\right)^{1/2} , \tag{3.7}$$

where m_j and ξ_j is denoted the harmonic number and its position of the j-th resonance respectively, i.e., defined by the equation $m_j\,\omega(\xi_j) - n_j\,\Omega(\xi_j) = 0$.

On the other hand, the spacing of adjacent resonance is

$$\delta\omega_{j,j+1} = |\omega(\xi_j) - \omega(\xi_{j+1})|$$

$$= \left| \frac{n_j \lambda \Omega(\xi_j)}{m_j} - \frac{n_{j+1} \lambda \Omega(\xi_{j+1})}{m_{j+1}} \right| . \quad (3.8)$$

If the frequency spacing of the resonances is much smaller than the extent of the magnetic island so that several harmonics of the perturbation simultaneously occur in resonance :

$$\Delta\omega(\xi_j) \gg \delta\omega_{j,j+1} , \quad (3.9)$$

then the magnetic line of force will oscillate as though a " random force " is acting on it. This special type of trajectory is known as " stochasticity " and may be evaluated by a stochastic parameter $K = | \Delta\omega / \delta\omega |$. A condition $K = 1$ gives a stochastic boundary and the region enclosed by this boundary $(K > 1)$ forms the stochastic layer.

Due to the toroidal effects of this system, the perturbation of magnetic field is generated. The magnitude of this perturbation is with an accuracy of the order r/R :

$$\varepsilon B_r^1 = - \frac{r}{2R} \sum_k b_k \sin lk\theta \cos(\theta-\zeta) [kl I_{lk}'(lkr) + \frac{1}{r} I_{lk}(lkr)],$$

$$\varepsilon B_\phi^1 = - \frac{r}{2R} \sum_k \frac{b_k}{r} I_{lk}(lkr)[\sin(\theta-\zeta) \sin lk\theta - lk\cos(\theta-\zeta)\cos lk\theta],$$

$$\varepsilon B_\zeta^1 = - \frac{r}{R} \sum_k [B_0 + \frac{3}{2} lkb_k I_{lk}(lkr) \cos lk\theta] \cos(\theta-\zeta), \quad (3.10)$$

where R is the major radius normalized by $1/\alpha$. The perturbation $\Gamma(\xi,\eta,t)$ is written in the following form :

$$\Gamma(\xi,\eta,t) = -\frac{1}{2R\omega(\xi)}[\gamma_c(\xi,\eta)\cos\Omega(\xi)t + \gamma_s(\xi,\eta)\sin\Omega(\xi)t], \quad (3.11)$$

where

$$\gamma_c(\xi,\eta) = F_1(\xi,\eta)\cos[\theta-\tau(\xi,\eta)] + F_2(\xi,\eta)\sin[\theta-\tau(\xi,\eta)],$$

$$\gamma_s(\xi,\eta) = F_1(\xi,\eta)\sin[\theta-\tau(\xi,\eta)] - F_2(\xi,\eta)\cos[\theta-\tau(\xi,\eta)],$$

$$\begin{aligned} F_1(\xi,\eta) = {} & r\{\sum_k \beta_k\left[I_{lk}(lkr) - 3lkr\, I'_{lk}(lkr)\right]\sin lk\theta + \\ & + \sum_k lk\beta_k I_{lk}(lkr)\cos lk\theta \sum_m \beta_m[(1+\frac{1}{r^2})I_{lm}(lmr) - \\ & - 4lmr\, I'_{lm}(lmr)]\sin lm\theta\}, \end{aligned} \quad (3.12)$$

$$F_2(\xi,\eta) = \sum_k lk\beta_k I'_{lk}(lkr)\sin lk\theta \sum_m \beta_m I_{lm}(lmr)\sin lm\theta.$$

The r.h.s. of eq.(3.12) is numerically transformed to the variables (ξ,η) using eqs.(2.7) and (2.9). Note that the perturbation of the order r/R has only the fundamental mode ($n = 1$) with respect to t. Then the magnitude of the perturbation is written in the following form :

$$|\Gamma_m(\xi)| = \frac{1}{8R\,\omega(\xi)}[G^2_{1m}(\xi) + G^2_{2m}(\xi)]^{1/2},$$

$$G_{1m}(\xi) = \frac{1}{\pi}\int_0^{2\pi}[\gamma_c(\xi,\eta)\cos m\eta + \gamma_s(\xi,\eta)\sin m\eta]\, d\eta, \quad (3.13)$$

$$G_{2m}(\xi) = \frac{1}{\pi}\int_0^{2\pi}[\gamma_c(\xi,\eta)\sin m\eta - \gamma_s(\xi,\eta)\cos m\eta]\, d\eta.$$

On the other hand, the discrete structure of toroidal coils brings a ripple of magnetic fields (εB^1). The ripple of the magnetic fields near the axis of toroidal coils may be approximately written by

$$
\begin{aligned}
\varepsilon B_r^1 &= \frac{1}{2}\,\varepsilon\, B_{to}\, k_t r \,\sin k_t \zeta , \\
\varepsilon B_\phi^1 &= 0 , \\
\varepsilon B_\zeta^1 &= \varepsilon B_{t0} \cos k_t \zeta ,
\end{aligned}
\tag{3.14}
$$

where ε stands for the ripple of the magnetic field on the axis of the coil, k_t is the ratio of the pitch length of helical coils (L_h) to the pitch length of toroidal coils (L_t). Using this expression (3.14), the perturbation $\Gamma(\xi,\eta,t)$ is written in the form, corresponding to the previous procedure,

$$
\Gamma(\xi,\eta,t) = \frac{\varepsilon}{\omega(\xi)} \frac{B_{t0}}{B_0} [\gamma_c^t(\xi,\eta) \cos k_t \Omega(\xi) t + \gamma_s^t(\xi,\eta) \sin k_t \Omega(\xi) t],
\tag{3.15}
$$

where

$$
\begin{aligned}
\gamma_c^t(\xi,\eta) &= F_1^t(\xi,\eta) \sin k_t \tau(\xi,\eta) - F_2^t(\xi,\eta) \cos k_t \tau(\xi,\eta) , \\
\gamma_s^t(\xi,\eta) &= F_1^t(\xi,\eta) \cos k_t \tau(\xi,\eta) + F_2^t(\xi,\eta) \sin k_t \tau(\xi,\eta) , \\
F_1^t(\xi,\eta) &= \frac{1}{2}\, k_t\, r^2\, [1 + l(1 + \frac{1}{r^2}) \sum_k k\beta_k\, I_{lk}(lkr) \cos lk\theta] , \\
F_2^t(\xi,\eta) &= lr \sum_k k\beta_k\, I'_{lk}(lkr) \sin lk\theta .
\end{aligned}
\tag{3.16}
$$

The r.h.s. of eq.(3.16) is expressed by the variables (ξ,η)

same as the previous procedure. Then the magnitude of the perturbation is written in the following form :

$$|\Gamma_m(\xi)| = \frac{\varepsilon}{4\omega(\xi)} \left[G_{1m}^{t\,2}(\xi) + G_{2m}^{t\,2}(\xi) \right]^{1/2} ,$$

$$G_{1m}^t(\xi) = \frac{1}{\pi} \int_0^{2\pi} [\gamma_c^t(\xi,\eta) \cos m\eta + \gamma_s^t(\xi,\eta) \sin m\eta] \, d\eta , \qquad (3.17)$$

$$G_{2m}^t(\xi) = \frac{1}{\pi} \int_0^{2\pi} [\gamma_s^t(\xi,\eta) \sin m\eta - \gamma_s^t(\xi,\eta) \cos m\eta] \, d\eta .$$

Together with the relation eq.(3.7) these eqs.(3.13) or (3.17) form a basis of the calculation of the frequency spread $\Delta\omega(\xi)$, and finally together with eq.(3.8), make it possible to find out a stochastic layer near a separatrix of a stellarator. These will be discussed in section 4.

§.4 Stochastic Layer

In the unperturbed system, magnetic fields are expressed as a function of a normalized radius of helical coil r_0 and a normalized helical field β_1 . A typical value of r_0 is unity. In eq.(2.7) the higher harmonics of helical field are considered up to tenth, corresponding to 20° width in the azimuthal direction of helical coils. The stochastic layer is calculated for the case of a stellarstor or a torsatron. In a latter case, helical coils produce a toroidal magnetic field, and auxiliary toroidal magnetic field is applied in the opposite direction (torsatron I) or in the same direction (torsatron II) to it. One can numerically calculate the stochastic parameter K as a function of ξ using eqs.(3.7) and (3.8). Where, magnitudes of perturbations are calculated by means of eqs.(3.13) or (3.17) numerically for the case of toroidal effects or the discrete structure of toroidal coils, respectively.

In the case of toroidal effects of magnetic fields, the spread of magnetic islands due to the lowest mode of magnetic perturbations is very large, i.e., the stochastic parameter K is much larger than unity, so the outer region of its resonant magnetic surface is destroyed. Accordingly the region between this resonant magnetic surface, which is shown in Fig.5(a) and (b), and separatrix can be considered as a stochastic region. A torsatron II type has much wider stochstic regions than other two types. The typical value of β_1 is $0.1 \sim 1.0$ in a present stellarator. Suppose a system with $l=2$ and $\beta_1=0.8$, for example, one can see in Fig.5(a) that the stochastic layer occupies the area 4.0% of the separatrix area for a torsatron II type, and 1.5% for a stellarator and/or a torsatron I type.

The stochastic layer due to the effects of the discrete structure of toroidal coils is also calculated for a value $\lambda = 2$ and $\lambda = 5$. Results are shown in Fig.6(a) and (b) in the case of a stellarator. It is noted the ripple of magnetic fields ε is 10^{-3} for the typical case. The stochastic layer of a torsatron II type is extended much more than that of other two types in same measure with toroidal effects. Suppose $\beta_1 = 0.4$, $\varepsilon = 10^{-3}$ and $\lambda = 5$, for example, one can see that only a small area $\sim 0.15\%$ of the separatrix area are destroyed for a stellarator and/or torsatron I type in the case of $l = 2$ and the area $\sim 0.10\%$ is destroyed in the case of $l = 3$.

Our analysis is limited in the case of the vacuum magnetic fields. Effects of the plasma in the separatrix region are future problems.

Acknowledgements

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Figure captions

Fig.1. An illustration of the unperturbed system: a stellarator constituted of a straight helical coil of $l=2$ turns with a constant pitch L_h and a uniform magnetic field B_{t0} . Magnetic surfaces are also illustrated.

Fig.2. Altitude chart of $\xi(r,\theta)$ and $\eta(r,\theta)$ in the case of a stellarator with $l=2$. The line $\xi=o.251$ is the separatrix.

Fig.3. The frequency of rotation of a magnetic line of force as a function of ξ , in the case of a stellarator with $l=2$.

Fig.4. The frequency of rotation of a magnetic perturbation as a function of ξ , in the case of a stellarator with $l=2$. The frequency $\omega(\xi)$ is also demonstrated.

Fig.5. A stochastic layer due to toroidal effects of magnetic fields in the case of a stellarator and a torsatron II with (a) $l=2$ and (b) $l=3$. A value ξ_r denotes a resonant magnetic surface and ξ_s refers a separatrix. A parameter β_1 is defined by b_1/B_0 and independent of perturbations.

Fig.6. A stochastic layer attributed to a discrete structure of toroidal coils in the case of a stellarator with (a) $l=2$ and (b) $l=3$. The stochastic region is obtained for a value $\lambda=2$ and 5 and a ripple $\varepsilon=10^{-3}$ for a typical value.

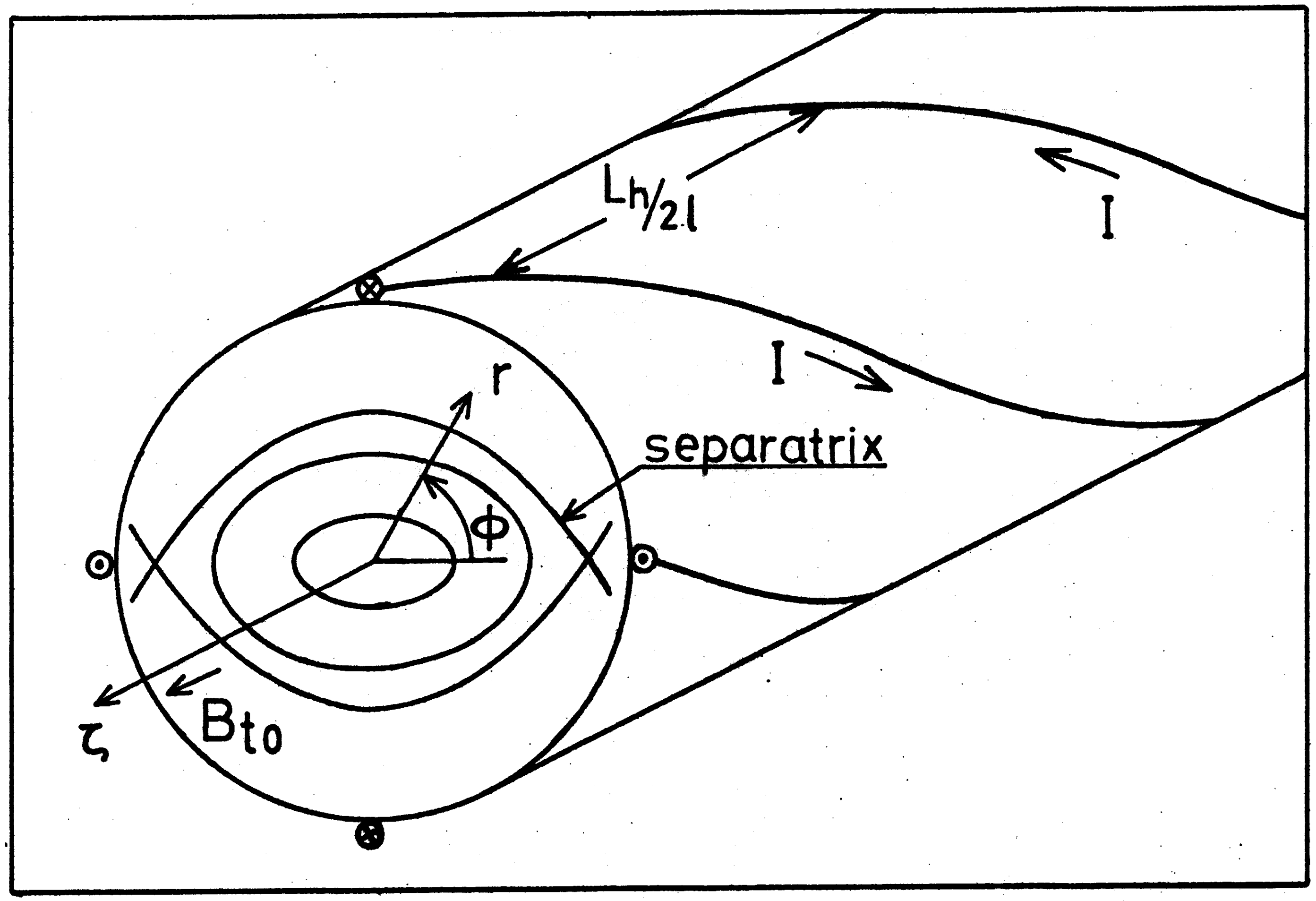


Fig.1

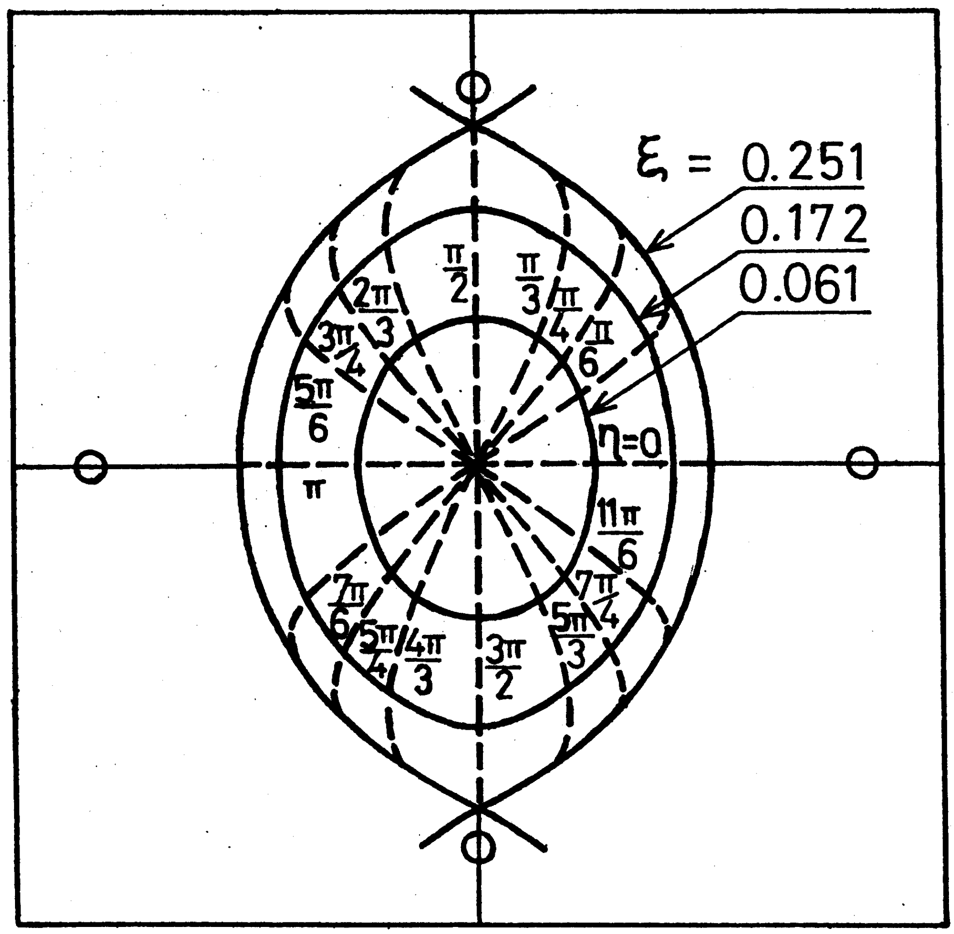

ξ = 0.251
0.172
0.061
π/2
π/3
π/4
π/6
2π/3
3π/4
5π/6
η=0
π
11π/6
7π/4
5π/3
3π/2
4π/3
5π/4
7π/6

Fig.2

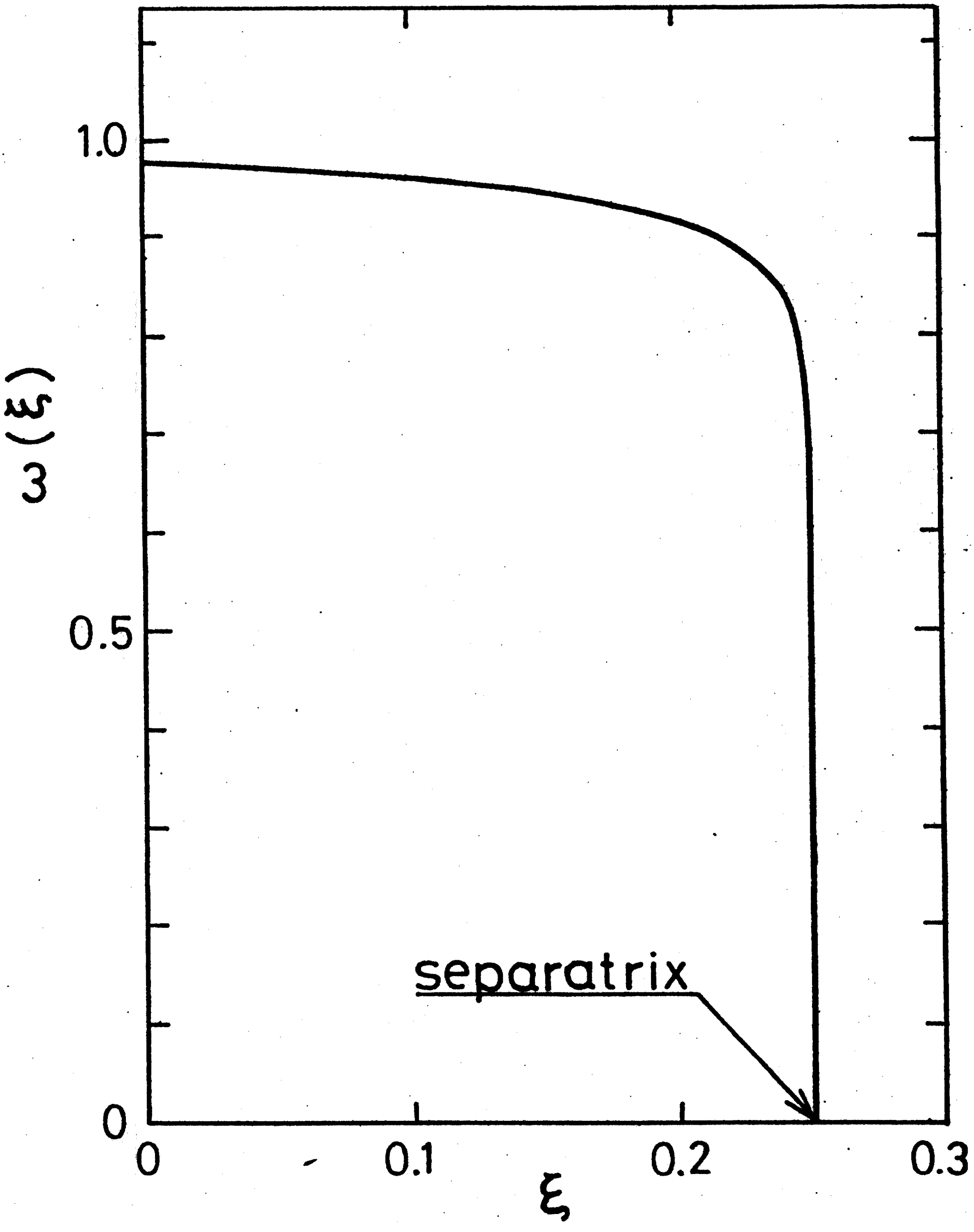


Fig.3

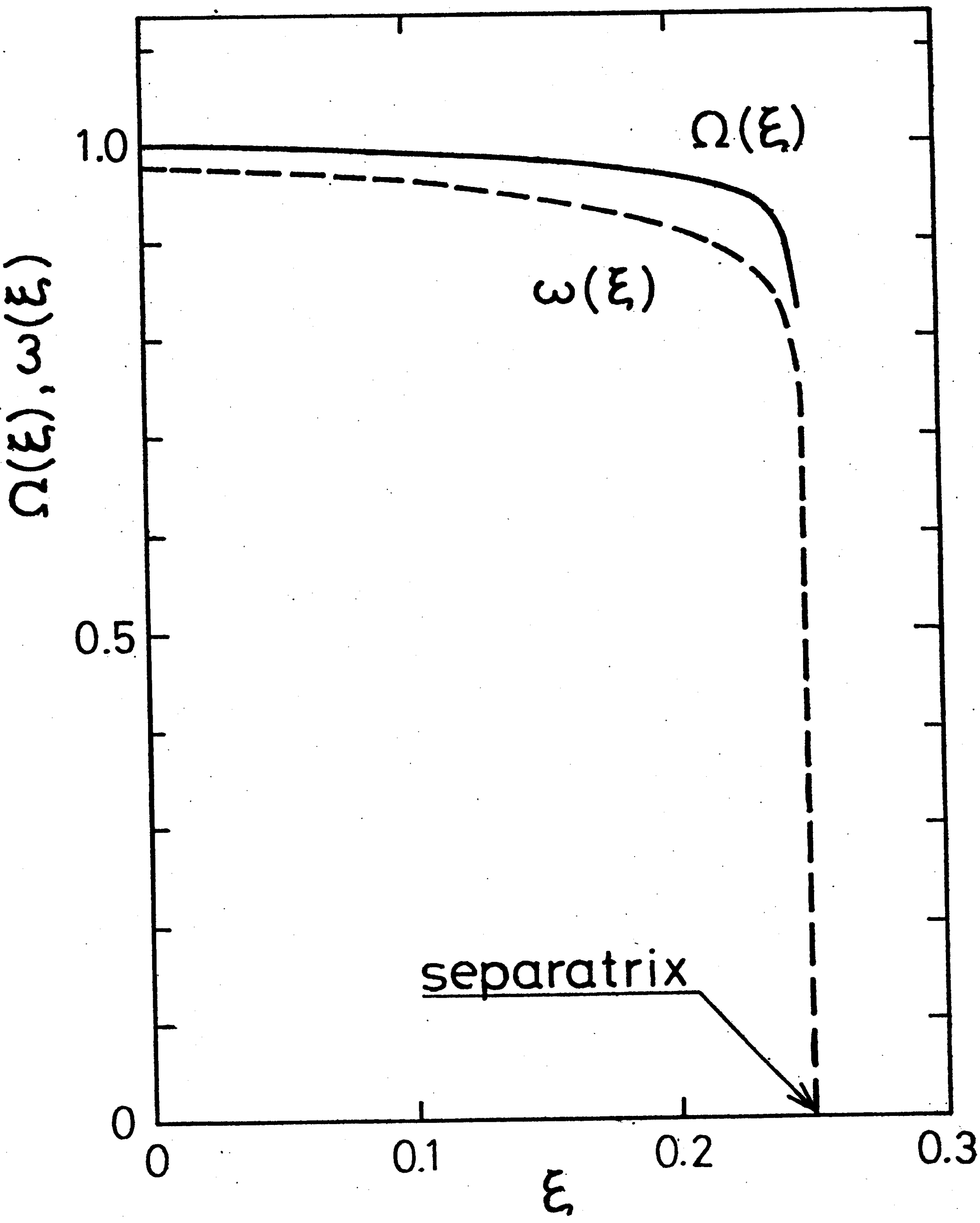


Fig.4

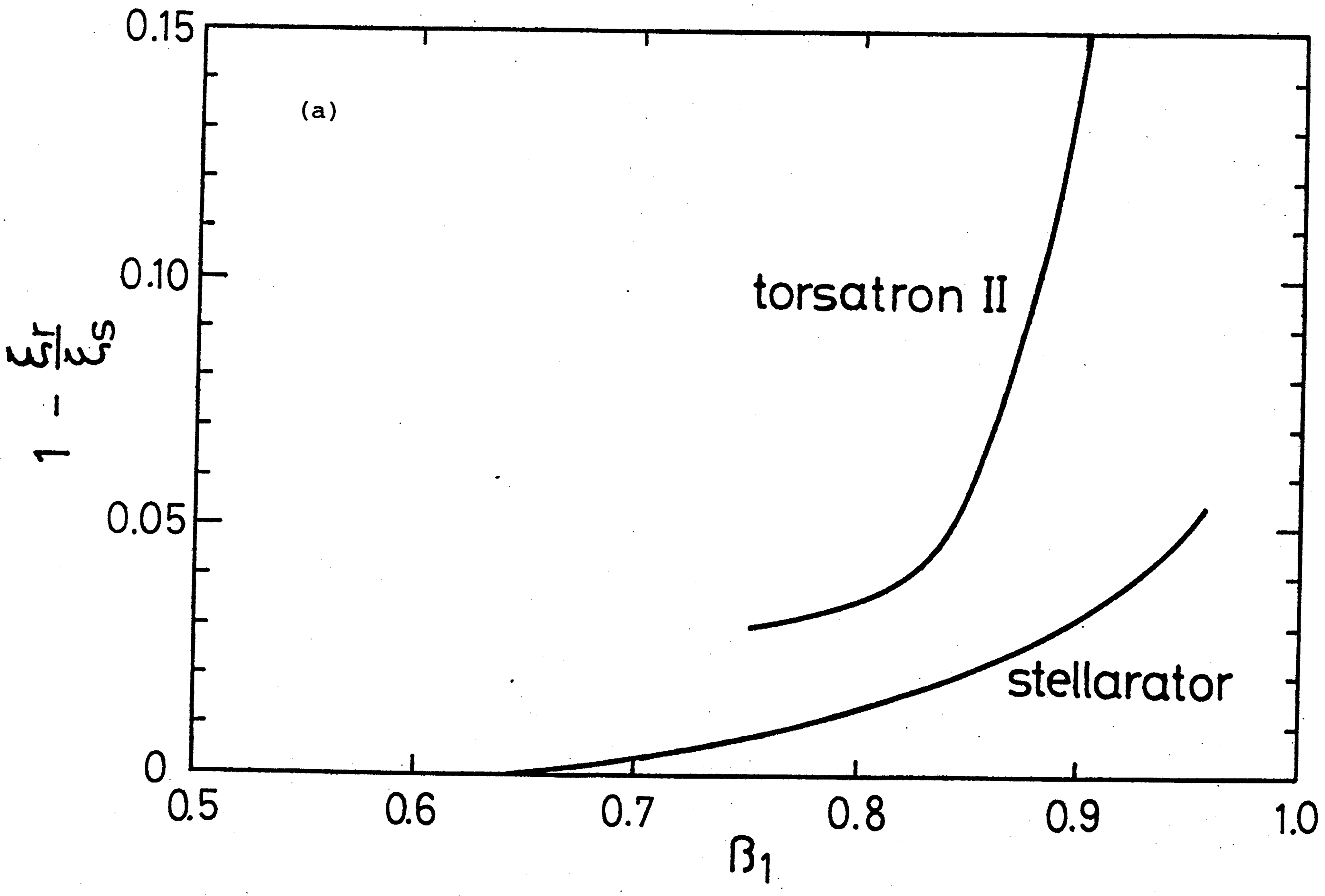
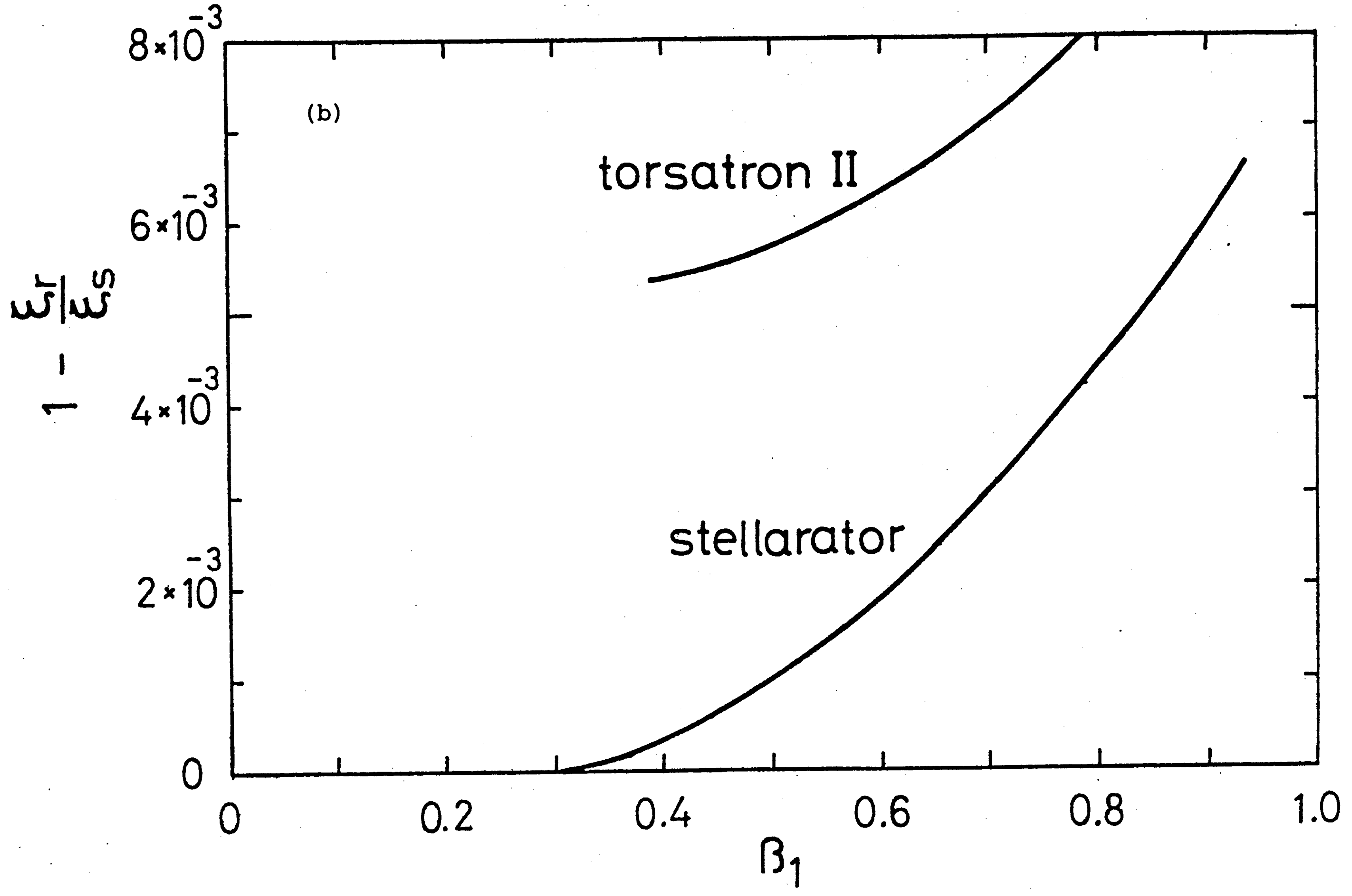

0.15
0.10
0.05
0
0.5
0.6
0.7
0.8
0.9
1.0
$1 - \frac{\bar{\omega}_T}{\bar{\omega}_S}$
β_1
(a)
torsatron II
stellarator

Fig.5(a)



(b)
torsatron II
stellarator
$1 - \bar{\omega}_r/\bar{\omega}_s$
8×10^{-3}
6×10^{-3}
4×10^{-3}
2×10^{-3}
0
0
0.2
0.4
0.6
0.8
1.0
β_1

Fig.5(b)

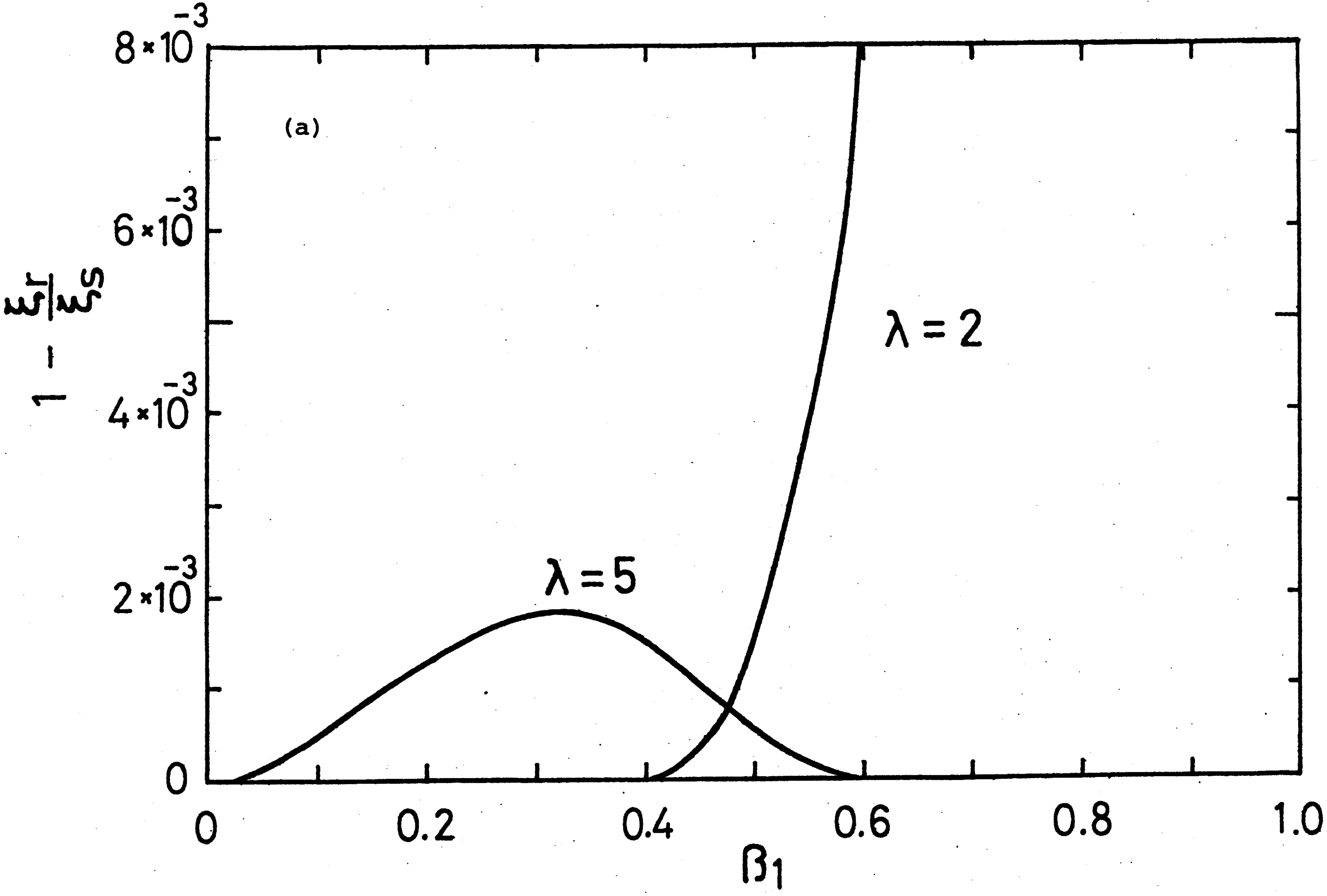

(a)
8×10^{-3}
6×10^{-3}
4×10^{-3}
2×10^{-3}
0
$1-\frac{\xi_r}{\xi_s}$
$\lambda=2$
$\lambda=5$
0
0.2
0.4
0.6
0.8
1.0
β_1

Fig.6(a)

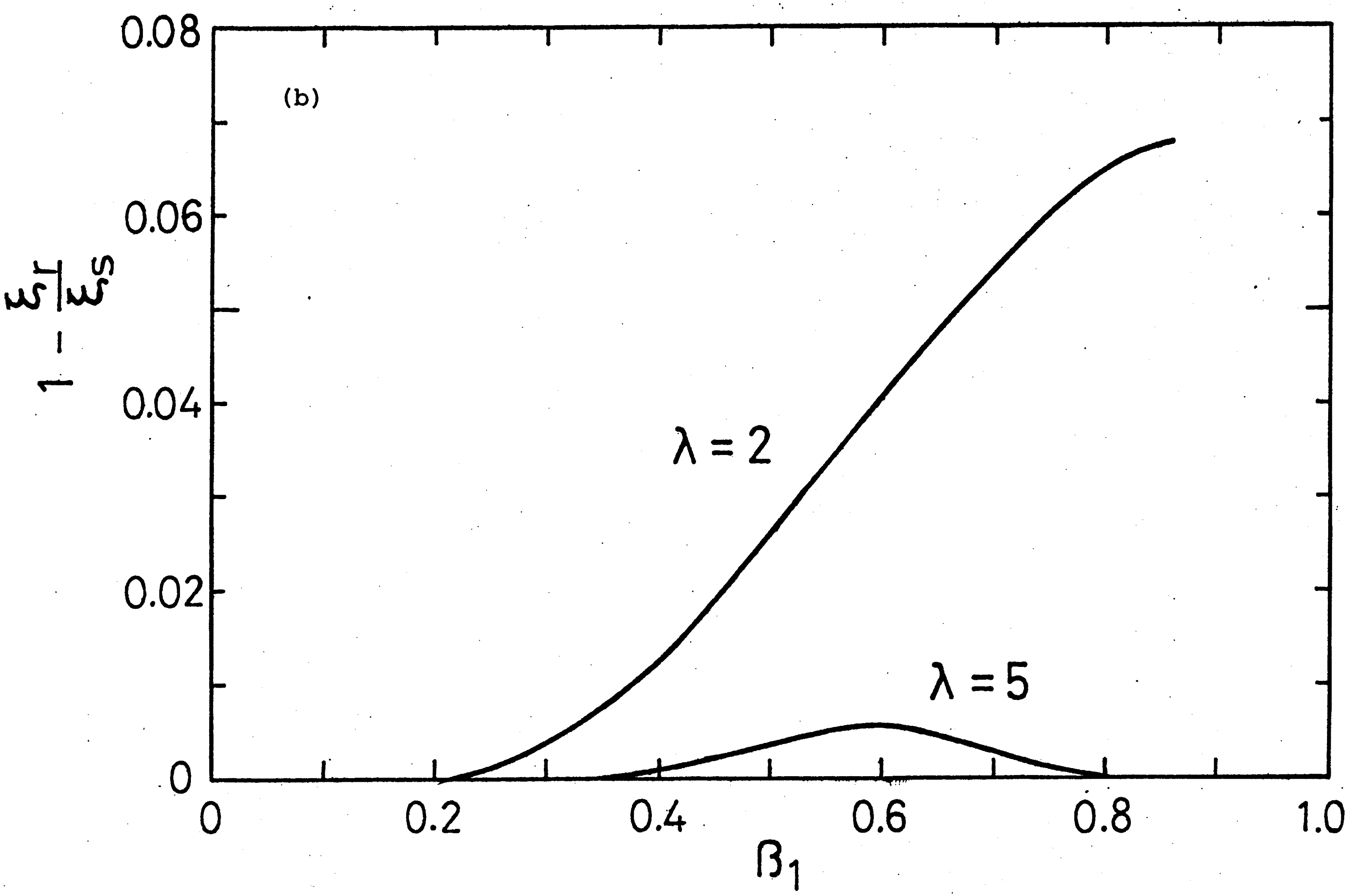

(b)
0.08
0.06
0.04
0.02
0
$1-\frac{\xi_r}{\xi_s}$
$\lambda = 2$
$\lambda = 5$
0
0.2
0.4
0.6
0.8
1.0
β_1

Fig.6(b)