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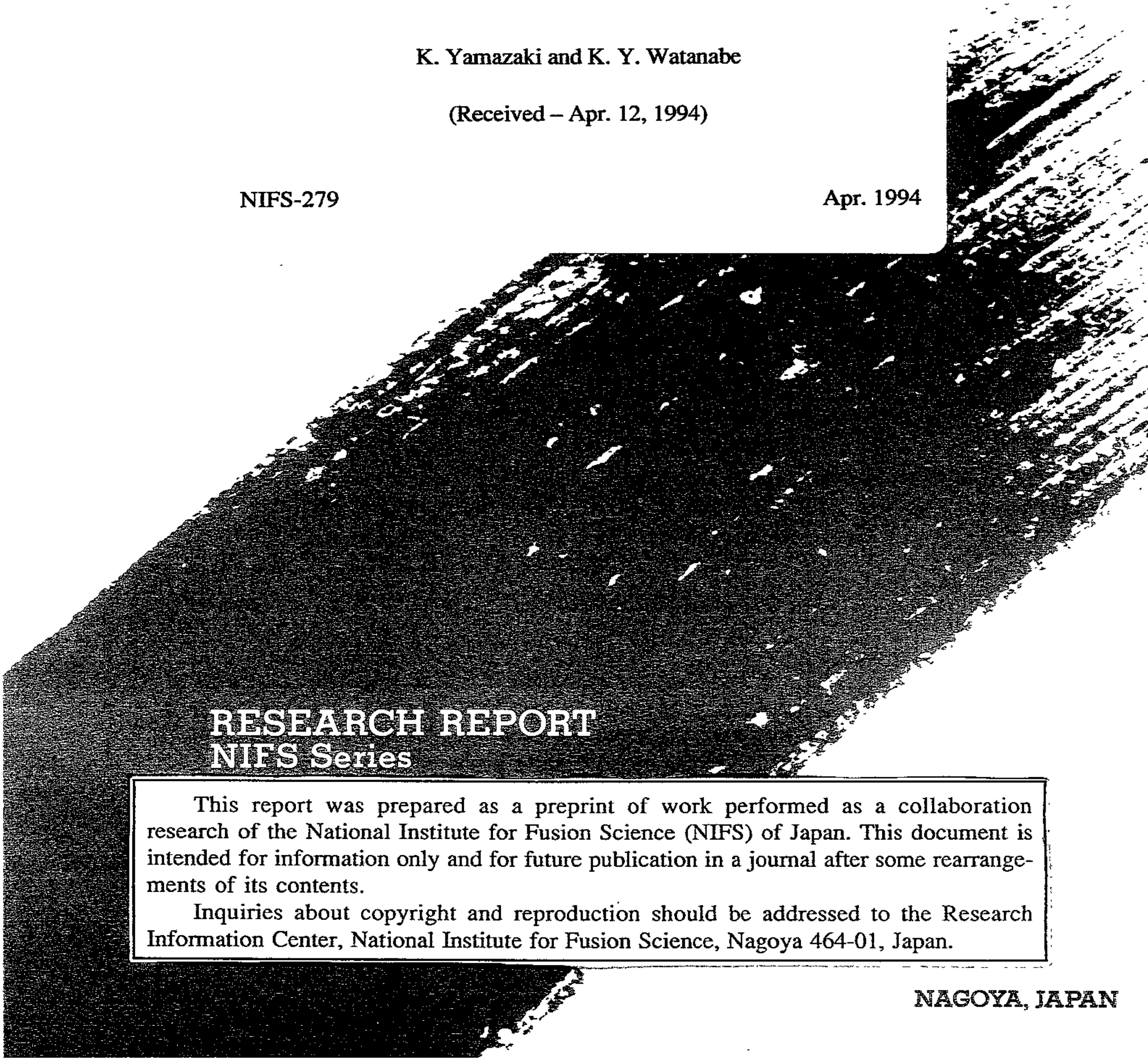

RESEARCH REPORT
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New Modular Heliotron System Compatible with Closed Helical Divertor and Good Plasma Confinement

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ABSTRACT

A new helical system ("Modular Heliotron") with improved modular coils compatible with efficient closed helical divertor and good plasma confinement property is proposed based on a Heliotron system with continuous helical coils and one pair of poloidal coils.

The physics optimization of this system as a function of the gap angle between adjacent modular coils has been carried out by means of vacuum magnetic surface calculations and finite-beta plasma analyses, and a new improved coil system is invented by combining sectored helical field coils with sectored returning poloidal field coils.

The Modular Heliotron with standard coil winding law (reference Modular Heliotron) was previously proposed, but it is found that this is not appropriate to keep clean helical divertor and high beta configuration when the coil gap becomes large. By modulating the modular coil winding with outside-plus and inside-minus pitch modulation, almost the same good magnetic configuration as that of a conventional Heliotron can be produced. The optimal gap angle is determined as a function of the modulation parameter. This improved Modular Heliotron permits larger gap angle between adjacent modules and produces more clean helical divertor configuration than the reference Modular Heliotron. All these helical system are created by only modular coils without poloidal coils.

Keywords: modular coils, helical system, high beta,
trapped particle confinement, helical divertor,
magnetic surface, heliotron/torsatron, stellarator

1. INTRODUCTION

Helical fusion reactor is an attractive system for demonstrating steady-state reactor concept. For its steady-state operation the efficient divertor functions are required, and the modularization of helical coils is requested for easy maintenance of the reactor. The compatibility between the coil modularity and the helical divertor configuration is one of urgent issues to be solved. For this purpose, a new concept ("Modular Heliotron", Fig. 1) has already been proposed and its vacuum magnetic surfaces were analyzed [1].

Helical system with continuous helical coils such as LHD (Large Helical Device) [2] provides with large space for divertor pumping, however it is difficult to make the system modularized for easy maintenance of the reactor system. On the other hand, the present modular stellarator represented by W7-X [3] is designed to optimize the core magnetic confinement, but is not optimized on the edge and separatrix configuration. Especially, in this system it is very difficult to keep enough divertor space for heat load reduction and helium ash exhaust. One of the most important issues for helical system is to search for good confinement configuration compatible with the coil modularity and closed divertor. In the actual plasma experiments, the improvement of the confinement requires the closed divertor configuration and the sharp boundary plasma structure, as found in tokamaks.

Until now, various modular coil concepts have been proposed[4-8], however, they cannot get good compatibility between above two issues. The present proposal of improved Modular Heliotron (Fig.1) is a unique system satisfying coil modularity and closed divertor configuration, and is a configuration extended from the LHD (Large Helical Device) concept [9,10].

In this paper, we improved Modular Heliotron configuration with new winding law, which make it possible to attain high beta value and helical divertor configuration. In chapter 2, the modular coil configuration and its optimization are described. The optimization of magnetic surfaces are given in chapter 3, and the finite beta analyses using VMEC code [11] are presented in chapter 4. In the final chapter, the summary and discussions are shown.

2. COIL CONFIGURATIONS

A variety of helical system configurations have been proposed so far by many researchers. Among these configurations, the LHD project adopted an $\ell=2$, m=10 continuous coil systems to produce optimized plasmas [9] and to create clean helical divertor [10], where ℓ and m are the poloidal and toroidal multipolarity numbers of the helical coil systems, respectively. One of the basic reasons why the $\ell=2$ system was adopted instead of $\ell=1$ or 3 is because the database for $\ell=2$ machines are more sufficient and reliable than those of other configurations.

On the basis of the LHD configuration, we can innovate a modular heliotron as described in Figs. 2 & 3. In this paper we focused on the helical coil system with the major radius R_0 of 4m and the minor radius r_0 of 1m. Figure 2 shows the coil systems with coil gap angle Δ_{gap} for the conventional Heliotron ($\alpha=0$), the reference Modular Heliotron ($\alpha_{in}=\alpha_{out}=0$, $\Delta_{gap}=4°$) and the improved Modular Heliotron($\alpha_{in}=-0.3, \alpha_{out}=0.3$, $\Delta_{gap}=8°$). Here, the following helical winding law is adopted,

$$\theta = (m/\ell)\phi + \alpha \sin\{(m/\ell)\phi\}\,, \tag{1}$$

where

$$\begin{aligned} \alpha &= \alpha_{out} \quad (\Delta_{gap}/2 < (m/\ell)\phi < \pi/2-\Delta_{gap}/2, \\ &\qquad\qquad 3\pi/2+\Delta_{gap}/2 < (m/\ell)\phi < 2\pi-\Delta_{gap}/2\,)\,, \qquad (2) \\ &= \alpha_{in} \quad (\,\pi/2+\Delta_{gap}/2 < (m/\ell)\phi < 3\pi/2-\Delta_{gap}/2\,)\,. \end{aligned}$$

This is the same definition of the continuous coil winding law when $\alpha=\alpha_{in}=\alpha_{out}$ and $\Delta_{gap}=0$, where θ and ϕ are poloidal and toroidal angles, respectively. In this modular coil system it is possible to use different pitch parameters; an inside-coil modulation (α_{in}) and an outside-coil modulation (α_{out}).

The schematic diagrams of the winding law for these three systems are given in Fig.3(a)(b) and (c), where the bolded lines denote the part of helical coil wounded on the one quasi-toroidal plane, and the dashed line denotes the part of poloidal coil and the connection part wounded on the different quasi-toroidal plane.

As a starting point of our design analyses, the conventional Heliotron (Fig.2(a) & Fig.3(a)) based on the LHD-like configuration is defined with only one pair of poloidal coils. The location of one pair of poloidal field coils of conventional Heliotron was determined by the optimization scheme of vacuum magnetic surfaces using the constraint that the poloidal coil current is equal to the helical coil current [1].

The coil system of the reference Modular Heliotron without one-turn poloidal-field coils (Fig.2(b) & Fig.3(b)) was constructed based on the above-mentioned conventional Heliotron by combining the sectored helical field coils with the sectored returning poloidal field coils. Here, the connection current feeders were arranged to avoid the destroy of the divertor layer and to keep large space of the divertor chamber. This reference configuration has been analyzed in Ref.[1] in details.

A new and improved configuration with outside-plus and inside-minus pitch modulated windings (Fig.2(c) & Fig.3(c)) is proposed in this paper. This system is characterized by the capability of keeping large space of divertor chamber, the adoption of new coil winding with plus/minus modulation, and the formation of magnetic configuration by only modular coils without poloidal coils. The confinement properties obtained by this improved coil system is nearly equal to the optimized configuration [9] of the LHD-type continuous coil system as shown later.

3. MAGNETIC SURFACE OPTIMIZATION

In order to search for the above-stated optimized modular helical system, physics analysis has been done taking the following parameters into account;

(1) the gap angle between adjacent modular coils
(index of coil modularity),
(2) the branching-off of divertor separatrix layers
(index of closed divertor) and
(3) the magnetic properties such as plasma radius, rotational transform, beta limit, particle confinement etc.
(index of good confinement).

Based on the LHD-type configuration with $\ell=2$, m=10 and γ (pitch parameter)=1.25, parametric variations of plasma radius, rotational transform, magnetic well, equilibrium beta limit, minimum mod-B contours and so on, are evaluated as a function of the gap angle between adjacent modular coils.

Figure 4 shows the vacuum magnetic surfaces of three systems on different toroidal angles, 0°, 9°, and 18°. In the conventional Heliotron (Fig.4(a)), the position of magnetic axis is adjusted to about 15 cm inward shift of 4 meter system for the optimization of equilibrium/stability beta achievement and particle orbit confinement [9]. Different from the magnetic surfaces of this conventional Heliotron, the cross-sectional shape of vacuum magnetic surfaces of reference Modular Heliotrons (pitch modulation parameter α =0) with 4° gap (Fig.4(b)) is deformed to the rectangular shape, and the equilibrium beta limit and the trapped particle confinement are deteriorated as shown in the next chapter. It is difficult to re-construct the LHD-type configuration by this reference coil system especially in the case of larger coil gap. Even by applying the conventional pitch modulations ($\alpha_{out}=\alpha_{in}=0.15$ or -0.15, $\Delta_{gap}=4°$) or elliptical, triangle shaping of winding support structure, it was impossible to get good magnetic surfaces and good plasma properties. On the other hand, the improved Modular Heliotron coil system with the outside-plus and inside-minus pitch modulation ($\alpha_{out}=-\alpha_{in}=0.15$, $\Delta_{gap}=4°$) leads to the reproduction of conventional Heliotron configurations (Fig.4(c)), and gives rise to the better configuration with larger plasma volume and higher rotational transform. Since these vacuum magnetic surfaces are almost similar, confinement properties of this improved Modular Heliotron are supposed to be nearly equal to those of optimized conventional Heliotron.

The divertor layer configuration is compared in Fig.5. In the conventional Heliotron a clean divertor layer is created (Fig.5(a)), however, in the reference Modular Heliotron the deformation of divertor traces is marginally tolerable (Fig.5(a)) only in the case of the coil gap angle less than 4 degree. A new winding system with outside-plus and inside-minus modulation is effective to re-produce the good magnetic surfaces (Fig.5(c)) by adopting optimum modulation as a function of gap ($\alpha_{out}=-\alpha_{in}=0.1$ at $\Delta_{gap}=2°$, $\alpha_{out}=-\alpha_{in}=0.15$, at $\Delta_{gap}=4°$), and good magnetic divertor configurations are obtained even in the case of a large increase in gap angle Δ_{gap}.

4. PROPERTIES OF EQUILIBRIUM BETA AND PARTICLE ORBIT

The configuration properties of Modular Heliotron are analyzed by using three-dimensional equilibrium code VMEC [11]. In this paper, we adopted the fixed boundary assumption with pressure profile $P=P_0(1-\psi)^2$, where ψ is the toroidal flux. The central beta value β_0 defined by the external field strength at the machine center R_0 is used in this paper.

Figure 6 shows the comparisons of the finite beta deformation of magnetic surfaces at $\phi=0°$ and the rotational transform among three systems. Each upper figures of magnetic surfaces are at low beta and the lower figures are at marginal beta limit for equilibrium. These equilibrium beta values are determined by the criteria on the conversion of VMEC calculation or the large outward shift of plasma axis (beyond 0.6 of normalized plasma minor radius). The conventional Heliotron (Fig.6(a)) is well optimized by the inward shift of 15 cm which is the results of LHD optimizations. The equilibrium beta limit is about 10%. The magnetic surface of reference Modular Heliotron is deformed to the rectangular shape instead of the elliptical shape, which reduces the equilibrium beta limit to ~4% (Fig.6(b)). One of the reasons on the decrease in the equilibrium beta limit is the existence of the wide shear-less region in the plasma core. As for improved Modular Heliotron, the beta limit is greater than 10% (Fig.6(c)). The change in the rotational transform due to finite beta effects is almost same as that of the conventional Heliotron.

Figure 7 denotes minimum-B contour (dashed curves) on averaged vacuum magnetic surfaces (solid contours) for estimating the confinement of deeply trapped particles. The conventional Heliotron has good particle confinement properties as shown in Fig.7(a). On the other hand , the magnetic surfaces do not coincide with the minimum mod-B contours in the reference Modular Heliotron (Fig. 7(b)). In the improved Modular Heliotron, the outer magnetic surface nearly agrees with outer contour of minimum B. However, different from the conventional Heliotron, the central minimum-B contour is deformed due to the bumpy component of magnetic field (Fig.7(c)). Aside from $m=0/n=10$ bumpy field components, other field components are almost same between the conventional Heliotron and the improved Modular Heliotron. It is concluded that this improved Heliotron with +/-0.15 pitch modulation and 4° gap angle is satisfactory for deeply trapped particle confinement.

Figure 8 summarizes the results of the finite beta calculations; (a) equilibrium central beta limit and (b) the confinement fraction estimated by minimum-B contours as a function of coil gap. In this figure the improvement of the equilibrium beta and particle confinement by the plus/minus pitch modulation technique is clarified. The strong dependence of gap angle Δ_{gap} on plus/minus α are found and even in the case of 10°

gap, α=+/-0.4 (α_{out}=+0.4/α_{in}=-0.4) modulation improves the configuration. This larger gap may allow the easier engineering design of modularization of the helical reactor system. Generally speaking, the optimal plus-minus pitch modulation is given by the continuity condition of helical coil on the gap; $\alpha_{out} = - \alpha_{in} \sim (m/4\ell)\, \Delta_{gap}$(radian) as a function of gap angle Δ_{gap}. In the present analysis based on LHD configuration, pitch modulation parameters are given by $\alpha_{out} = - \alpha_{in} \sim - 0.04\Delta_{gap}(°)$.

By changing the absolute value of modulations inside and outside, for example, α_{out}=0 and α_{in}=-0.3 at Δ_{gap}=4°, we can reproduce an transport-optimized helical configuration with respect to the neoclassical confinement theory. On the other hand, in the case of α_{out}=0.3 and α_{in}=0 at Δ_{gap}=4°, the helically symmetric divertor configuration is created which is almost same as the continuous coil configuration with α=0.15. In this case the anomalous transport might be improved by the clean closed divertor of this system. Detailed analysis will be published somewhere in the near future.

5. SUMMARY AND DISCUSSIONS

In summary, we proposed and analyzed new modular helical coil systems as an extension of the present continuous coil concept of the LHD design. We clarified the following items,

(1) New modular coil system with outer plus and inner minus modulation parameters is very effective to produce good magnetic surfaces equivalent to those of LHD.

(2) Optimal value of this modulation parameter is strongly related to the gap angle between the adjacent cols.

(3) By means of this coil modularization the compatibility among the coil modularity, the closed helical divertor operations and good plasma confinement are attained without using additional poloidal coils.

(4) By using unbalanced plus-minus modulation, we can produce a variety of configuration system.

In this paper, single filament coils are used to calculate magnetic surfaces. A model of finite-sized coils should be used in the near future. The free-boundary equilibrium and stability analyses should be also carried out, whose results are supposed to nearly same as those of conventional

Heliotron configuration because the plasma shape and the rotational transform profile are almost same between these two configurations. In addition to deeply trapped particles, detailed particle orbit analysis is required to confirm the good confinement property of the improved Modular Heliotron. The detailed engineering design is also required to check this modular coil system, especially stress analysis and fabricability check of the modular coil. These issues are now under investigation and will be published somewhere in the near future.

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FIGURE CAPTIONS

Fig. 1 Schematic drawing of Modular Heliotron concept , (a) one module and (b) total coil system.

Fig. 2 Coil systems of (a) conventional Heliotron, (b) reference Modular Heliotron (Δ=4°, α_{out}=α_{in}=0) and (c) improved Modular Heliotron (Δ=8°, α_{out}=0.3,α_{in}=-0.3).

Fig. 3 Schematic diagrams of coil winding for (a) conventional Heliotron, (b) reference Modular Heliotron (Δ=4°, α_{out}=α_{in}=0) and (c) improved Modular Heliotron (Δ=4°, α_{out}=0.15,α_{in}=-0.15).

Fig. 4 Vacuum magnetic surfaces for (a) conventional Heliotron, (b) reference Modular Heliotron (Δ=4°, α_{out}=α_{in}=0) and (c) improved Modular Heliotron (Δ=4°, α_{out}=0.15,α_{in}=-0.15).

Fig. 5 Divertor layers for (a) conventional Heliotron, (b) reference Modular Heliotron (Δ=4°, α_{out}=α_{in}=0) and (c) improved Modular Heliotron (Δ=4°, α_{out}=0.15,α_{in}=-0.15).

Fig. 6 Magnetic surfaces at low beta and nearly equilibrium beta limit for (a) conventional Heliotron (β=10%), (b) reference Modular Heliotron (β=4%) and (c) improved Modular Heliotron (β=10%).

Fig. 7 Minimum-B contour at low β of (a) conventional Heliotron, (b) reference Modular Heliotron (Δ=4°, α_{out}=α_{in}=0) and (c) improved Modular Heliotron (Δ=4°, α_{out}=0.15,α_{in}=-0.15).

Fig. 8 Effects of coil gap on (a) equilibrium beta limit and (b) trapped particle confinement fraction.

Table. 1 Comparisons among Helical Coil Configurations

	Improved Modular Heliotron (Present Proposal)	Reference Modular Heliotron [1]	Conventional LHD-type Continuous Coil	W7X-type Modular Coil
Coil Modularity	○	○	△ (SC Joint)	○
Helical Divertor	○	○	○	△ (Island Divertor)
Good Confinement	○	△ (Low β-limit)	○	○

Table 1
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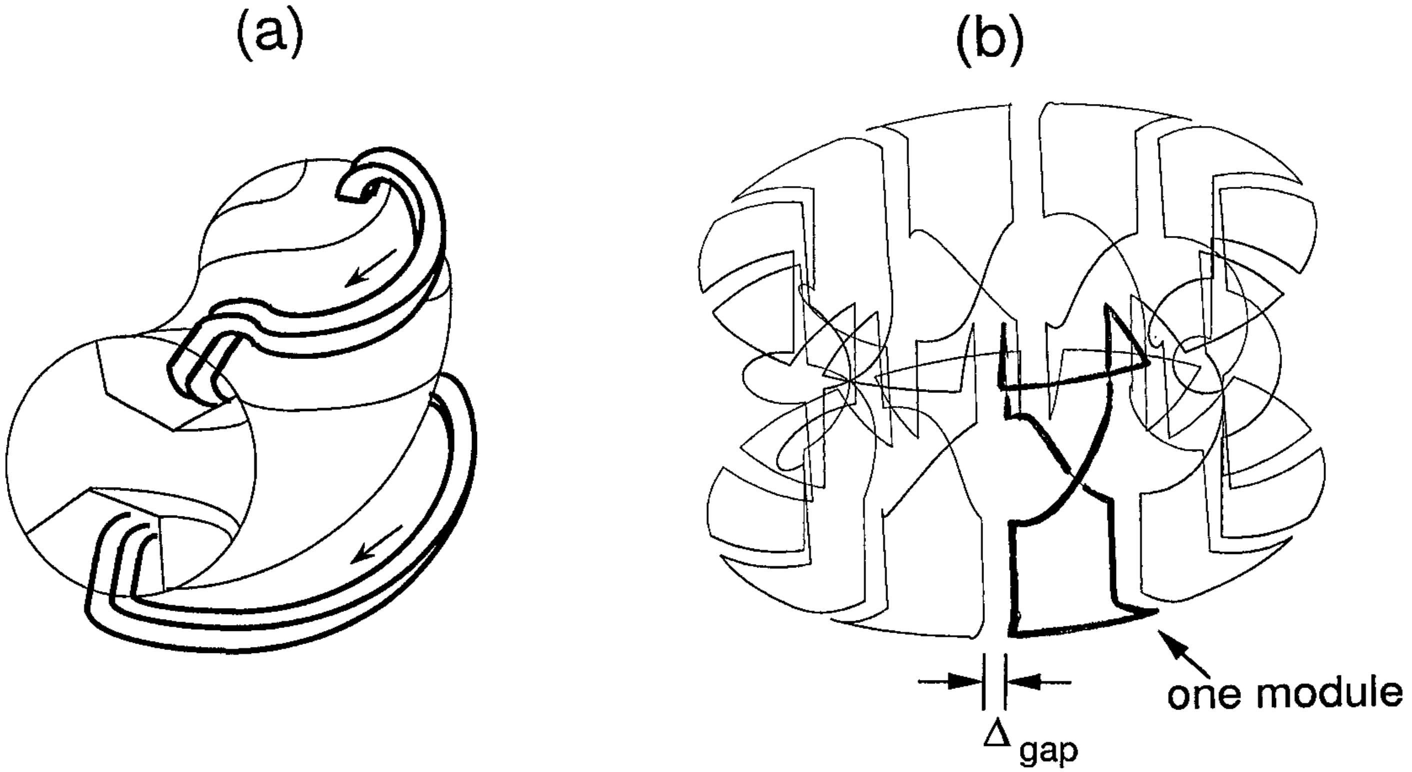

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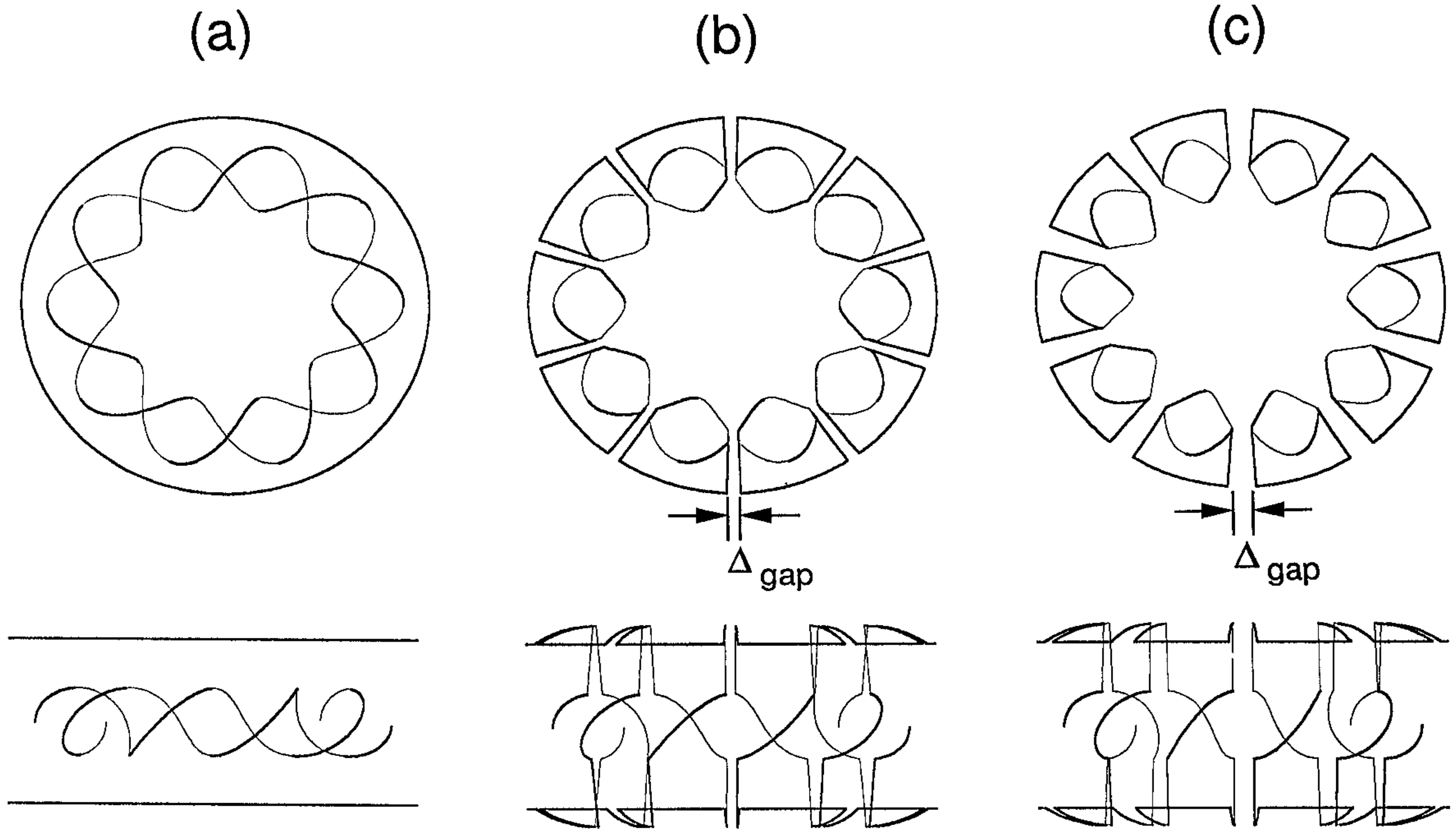

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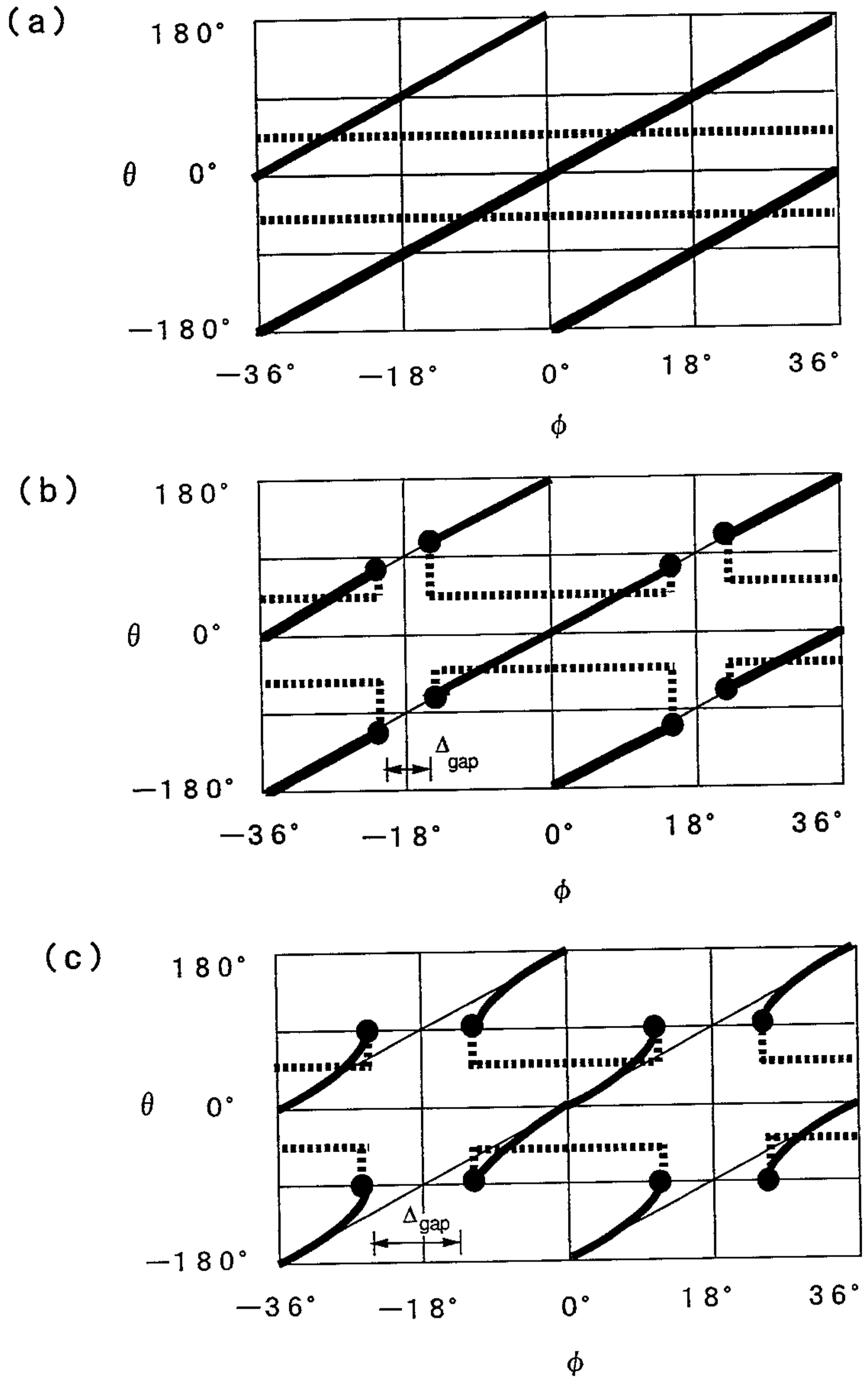

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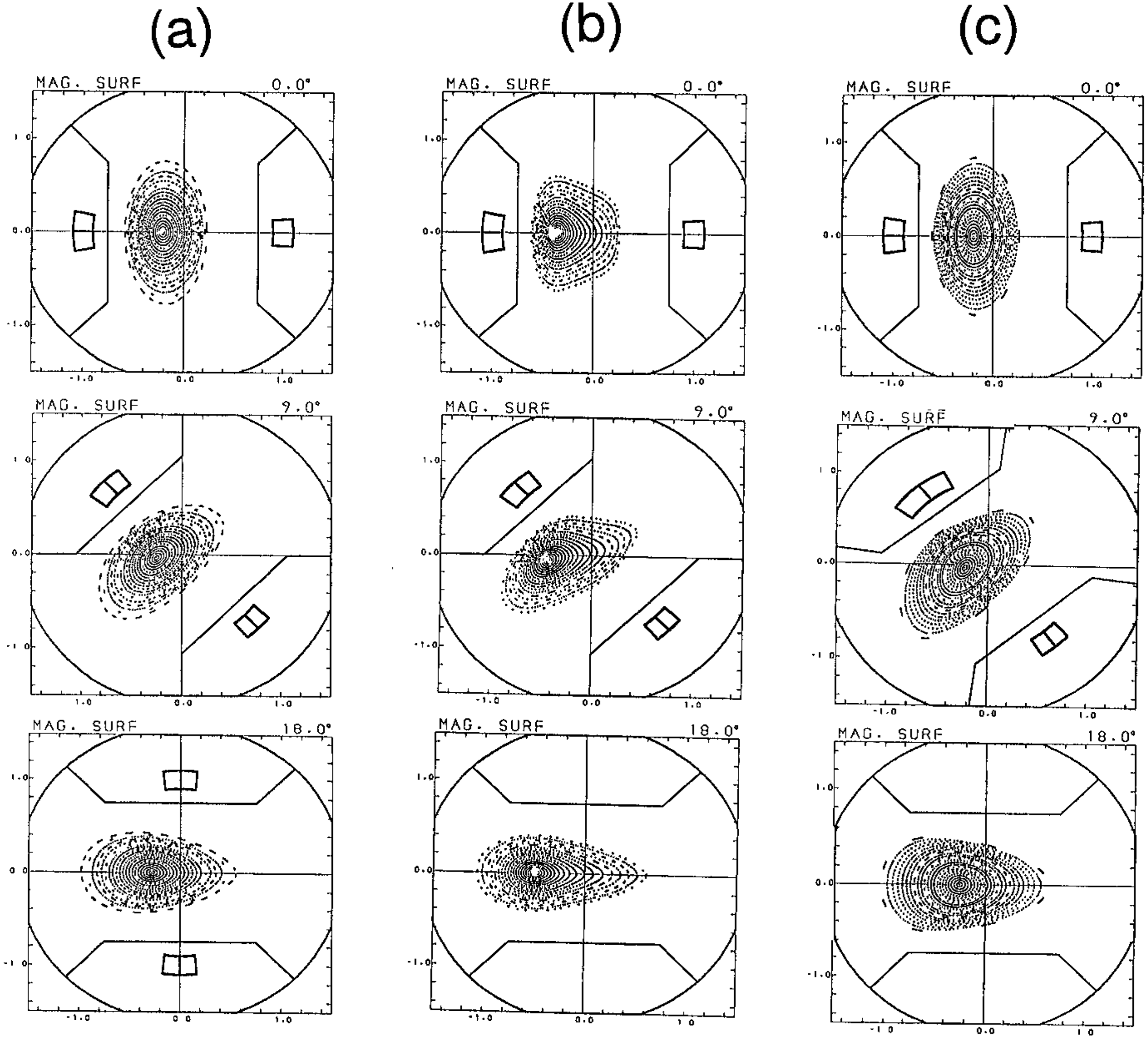

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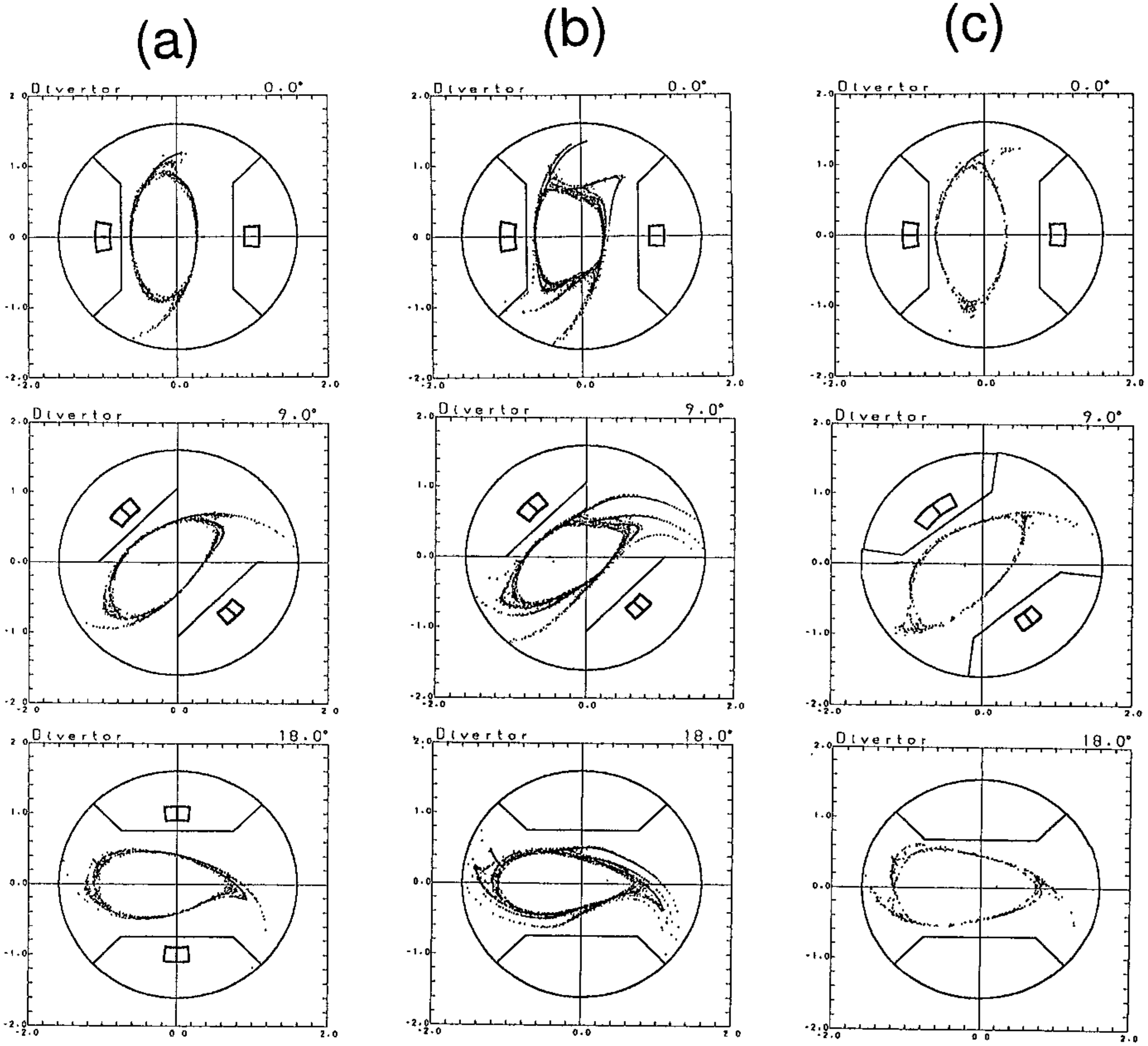

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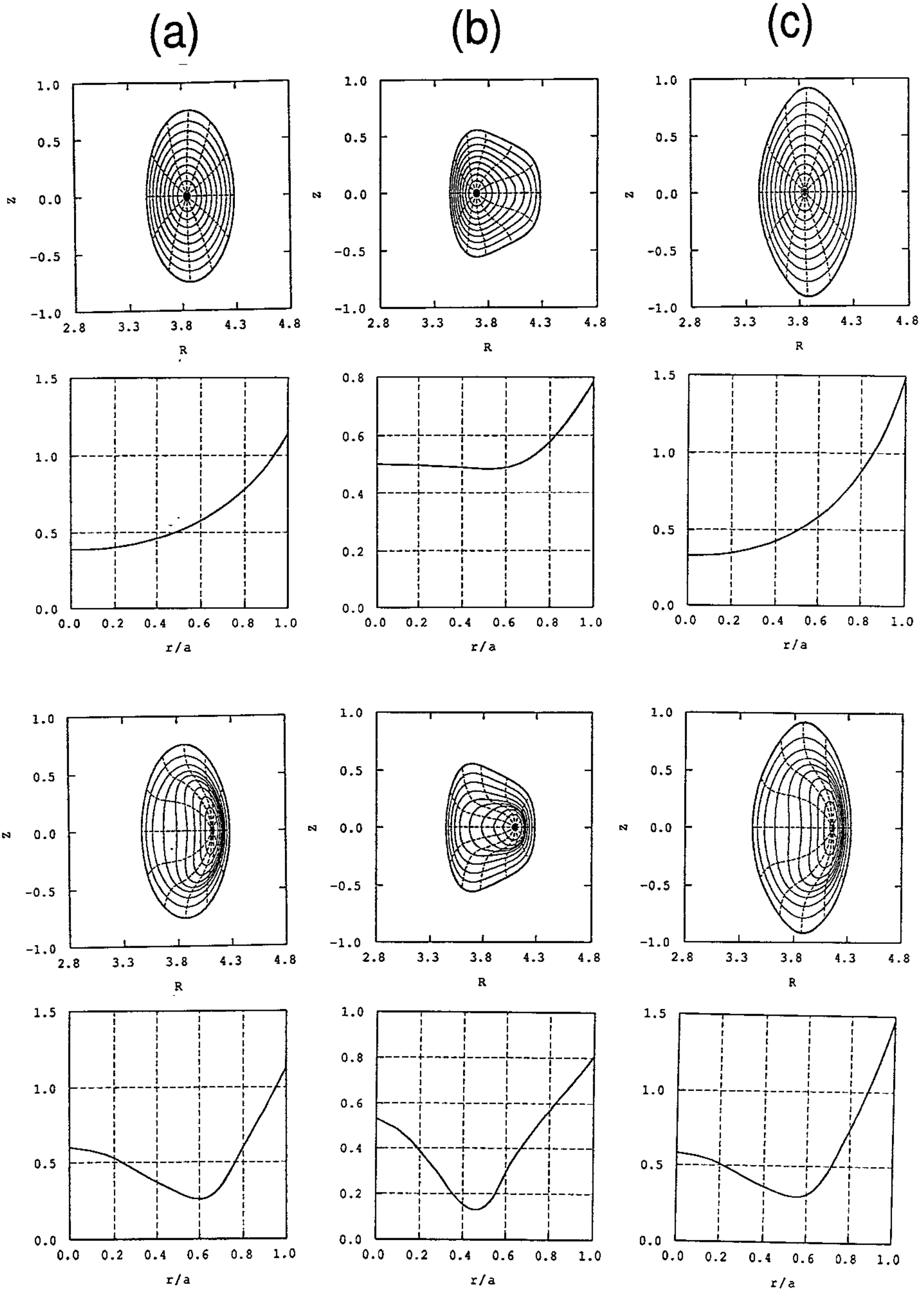

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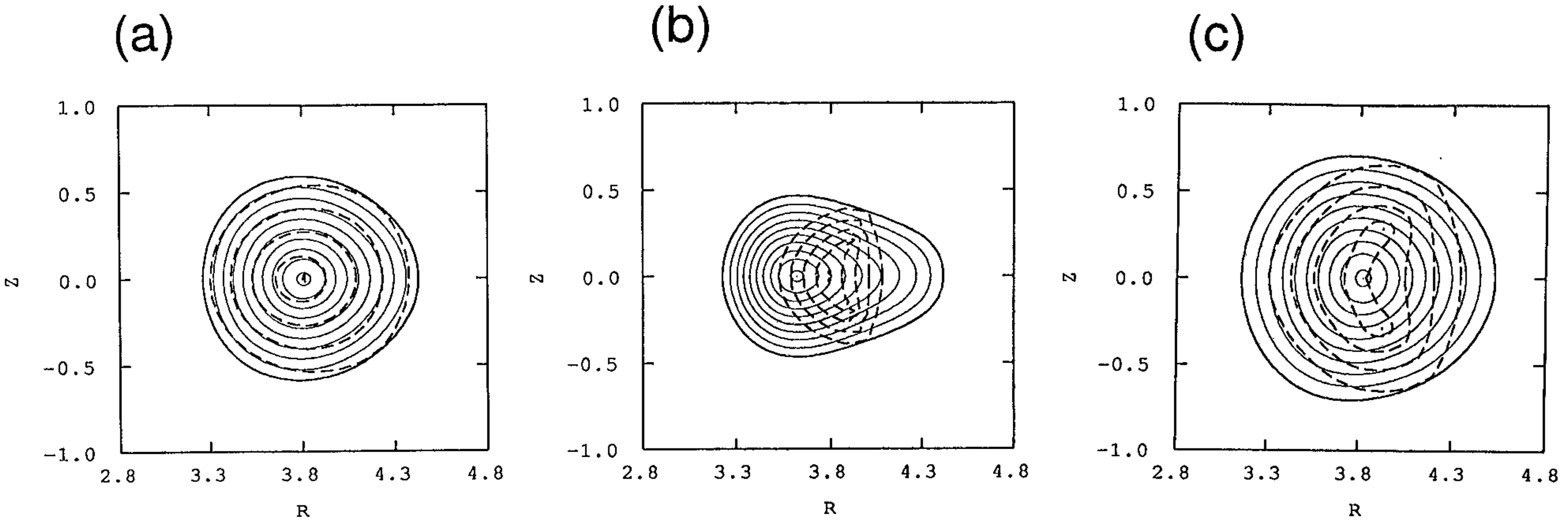

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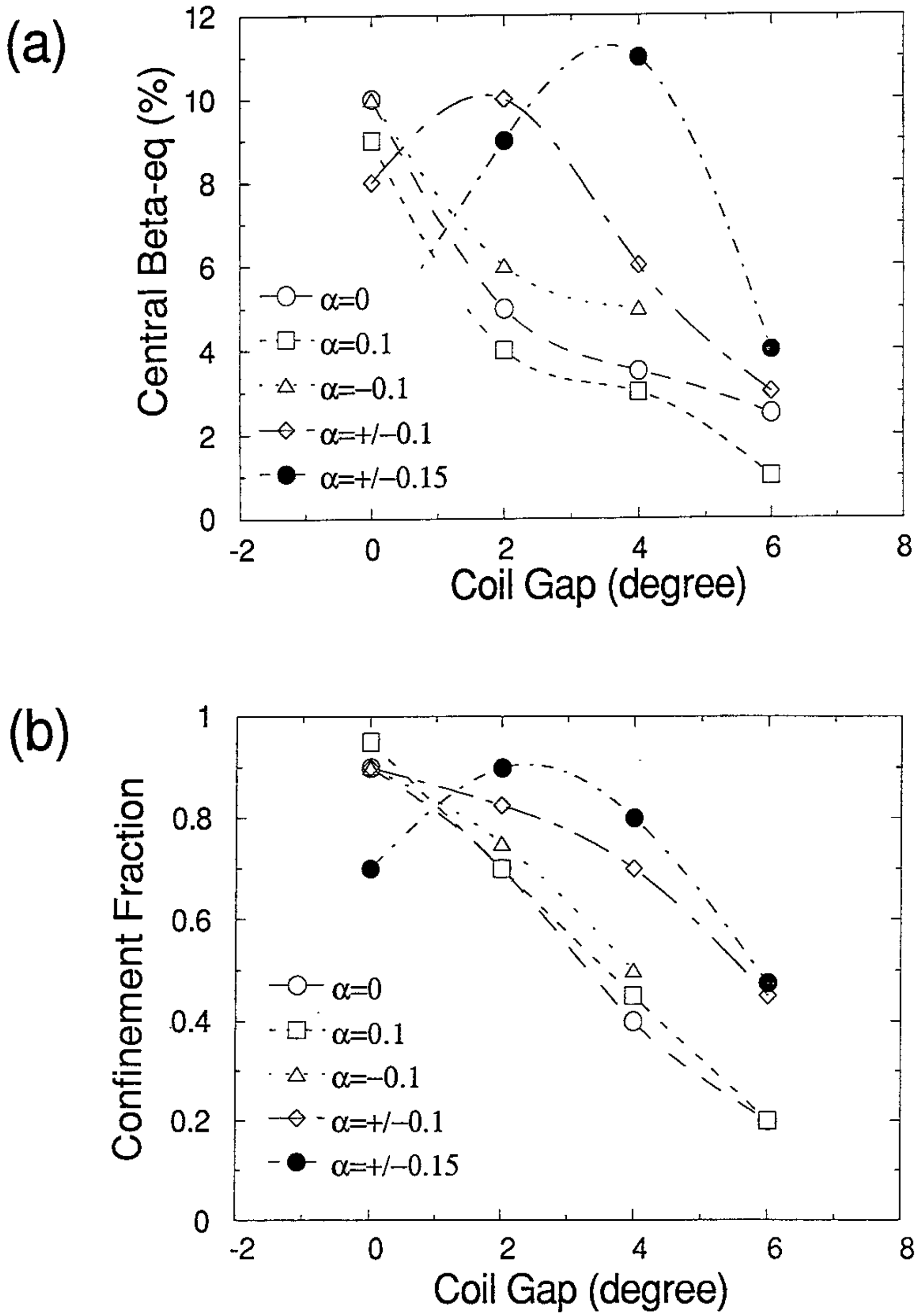

Fig. 8

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