INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

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K. Yamazaki and W.T. Reiersen

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RESEARCH REPORT

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Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan.

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* Plasma Physics Laboratory, Princeton University, Princeton, NJ 08544, U.S.A.

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FOR COMPACT IGNITION

K. YAMAZAKI
Institute of Plasma Physics
Nagoya University, Chikusa-Ku, Nagoya 464 JAPAN
and
W. T. REIERSEN
Plasma Physics Laboratory
Princeton University, Princeton, NJ 08544 U.S.A

ABSTRACT

A compact high beta tokamak configuration with "crescent"-shaped (or "boomerang"-shaped cross-section is proposed as a next-generation ignition machine. This configuration with a small indentation but a large triangularity is more compact than the normal dee-shaped design because of its high beta characteristics in the first-second transition regime of stability. This may also be a more reliable next-generation compact device than the bean-shaped design with large indentation and small triangularity, because this design dose not rely on the second stability and is easily extendable from the present dee-shaped design.

1. INTRODUCTION

Before the construction of the Engineering Test Reactor (for instance INTOR, FER, NET or TFCX), it is important to clarify stability and confinement properties of "burning plasmas" by using compact ignition devices[1-2].

To make tokamak devices rather compact, several high-field approaches and high-beta approaches have been considered (Table 1). High field compact ignition devices having moderately dee-shaped configuration with medium beta value, like Ignitor[3] or ISP (Ignition Studies Project) device, is now being extensively studied. As another approach, medium-field, high-beta designs like ST (Spherical Tokamak), ET (Elongated Tokamak) and BT (Bean-Shaped Tokamak) are also being studied, but do not seem to be considered as a prime candidate for the next-generation compact ignition device, because ST and ET have no enough experimental data-base and BT relies on the so called "second stability" characteristics, which was not experimentally varified yet. Roughly speaking, high-field moderate-β (normally dee-shaped) compact designs give rise to the difficulty of the TF coil design. On the other hand, as for high-β ignitions, a low-aspect-ratio device suffers from the difficulty of the OH coil design, high-elongation leads to the violent vertical instabilities and beta-saturation, and high-indentation requires sophisticated pushing coil design.

Different from these high-beta configurations, the "CRESCENT"-Shaped Tokamak (CT) considered here may be a reasonable step from the present data-base to the ignition device, because it is easily extendable from the dee-shaping and does not rely on the second stability property.

2. BETA SCALINGS FOR CRESCENT SHAPE VS. KIDNEY SHAPE

Firstly we should clarify the difference between kidney-bean shaping[4] and our crescent shaping[5]. By the following definition of the plasma shape (see Fig.1(a));

$$\left[\frac{R-R_0^*}{a^*} + \delta^* \cdot \left(\frac{Z}{\kappa^* a^*} \right)^2 \right]^2 + \left(\frac{Z}{\kappa^* a^*} \right)^{2\lambda} = 1 \quad , \qquad (1)$$

that is

$$R - R_0^* = a^* \left(\cos\theta - \delta^* \sqrt[\lambda]{\sin^2\theta} \right) \ , \qquad (2a)$$

$$Z = \pm \kappa^* a^* \sqrt[\lambda]{\left| \sin\theta \right|} \ . \qquad (2b)$$

where, asterisk (*) means the quantity relevant to the plasma size on the horizontal plane, and the global size parameters are shown without asterisk. We can obtain the sharp-chip indented shape (crescent shape) with $\lambda = 1$ and $\delta^* \sim 1$, while the round-chip indented shape (kidney-bean shape) is obtained with $\lambda \geqq 2$ and $\delta^* \sim 1$ (Fig.1(b)). The latter shape is almost similar to the PPPL bean configuration with small indentation. It should be noted that previous bean shaping is characterized mainly by the strong indentation, while this crescent shaping is given by the small indentation but large triangurality.

The expected maximum beta value for the bean-shaped tokamak is supposed to be be described by the Troyon-type scaling[6-7]

$$\beta \ (\%) = 4.0 \ I_N^* \tag{3}$$

where

$$I_N^* = \frac{I_p(MA)}{a^*(m)B_{t0}(T)} \ , \tag{3a}$$

or new scaling [5] .

$$\beta \ (\%) = 4.7 I_N \ (1 - b I_N) \tag{4}$$

where

$$I_N = \frac{I_p(MA)}{a(m)B_{t0}(T)} \ , \tag{4a}$$

$$b = 0.065 \frac{A}{\sqrt{\kappa}} \{ 1$$

$$- \frac{(\kappa - 1 + 0.05\delta^*)}{\sqrt{\kappa}} \left(\frac{1 + 1.5\delta^*}{\kappa} \right)^{2.5} \} . \tag{4b}$$

It should be noted that the Troyon-type scaling overestimate the beta values for elongated tokamak without triangularity but underestimate for crescent or bean shapings.

In order to clarify the high-beta properties of crescent shaping in comparison with dee-shaping in the first-second transition regime of stability, ballooning optimized beta values normalized by $4I_N$ or $4I_N^*$ are plotted in Fig.2, which clearly shows that the crescent shaping allows gradual but more rapid access to the second stability regime than the kidney-shaping.

3. TYPICAL MACHINE DESIGNS

Preliminary system studies are carried out to compare the crescent-shaped design and the normal dee-shaped design, using the TFCX/ISP design system code. As for typical designs, the design value of toroidal beta is assumed as a 75% of the presently expected maximum beta of Eq.(3) or Eq.(4) for avoiding disruptions, and the normalized plasma current I_N related to the surface q-value q_ψ is approximately estimated from

$$I_N \simeq \frac{5}{A}\,\frac{1+\kappa^2}{2}\,\frac{f}{q_\psi} \qquad (5)$$

$$f \simeq \frac{\sqrt{\kappa}}{1-1/A^2}\left(1.85-\frac{1}{1+\delta^*}\right) \qquad (5a)$$

where the central q value is fixed to unity. The plasma cross-sectional shapes defined by Eq.(1) are used here and the ellipticity κ is assumed 1.8 . The ignition margin

$$C_{ig} = \frac{P_\alpha+P_{in}}{P_{loss}} \qquad (6)$$

is assumed 2.2 for Mirnov H-mode-type confinement scaling

$$\tau_E(s) = 0.15\ I_p(MA)\ a^*(m)\ \sqrt{\kappa} \qquad (7)$$

with the plasma temperature of 10 keV.

The TF coil system with wedging structure against centripedal forces and the PF coil system inside the TF coils are considered in this design. Since the short burning time ($\tau_{burn} \sim 5\tau_E$; $\sim$ 5 s in this design) is considered, the coil design is mainly limited by the stress consideration, where ASME criteria are used in the simple system code. For TF system, simple ripple consideration (~ 1.0 % with iron shim and ~ 1.5 % without iron shim) are taken into account and the PF coil design is determined by the stress and the volt-second requirement. The flow diagram of this system code is shown in Fig.3. The plasma size is adjusted to get required ignition margin C_{ig}^{target} , and OH & TF coil sizes R_{OH} & R_{TF} are determined by the allowable stress levels σ_{OH} & σ_{TF} , the required flux swing $\Phi^{required}$ and the TF magneto-motive force related to RB_T .

After simple optimization of the device system, we can obtain typical examples for the C_{ig} = 2.2 (Mirnov) ignition device (Fig.4 and Table 2). In comparison with dee-shaped design, crescent shaped design becomes more compact. A little higher aspect-ratio was permitted by the beta increase due to triangularity-indentation effects, therefore, slightly higher toroidal field is permitted. Even if the higher surface safety factor (q_ψ=3.4) is assumed, the crescent-shaped device becomes more compact than the dee-shaping with q_ψ=2.2 when the new β-scaling law is adopted.

To confirm these engineering advantages of this crescent shaping as well as physics merits in beta value, more detailed analysis especially related to pushing coil design, TF coil analysis with bending moment and possible divertor scheme consideration are required. Some engineering considerations related to this configuration have already been carried out in Ref.9.

5. SUMMARY

The high-beta features of the crescent shaping is clarified in the transition region of the first stability to the second stability. This shaping makes the device more compact than the normal dee-shaping, and is supposed to be a reasonable and reliable extension from the dee-shaping as a next-generation ignition device, different from second-stability bean-shaped design.

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Table 1. Compact Ignition Configurations of Tokamak

	Configuration	Typical Designs	Stability Region
High-Field & ($B_T > 7T$) Medium-Beta ($\beta < 5\%$)	Modrate A & ($A > 3$) Normal Dee ($\delta < 0.5$)	ISP, LITE, Ignitor	First Regime
Medium-Field ($B_T < 7T$) & High-Beta ($\beta > 5\%$)	Low-A ($A < 2$)	ST (Spherical Tokamak)	First Regime
	High-κ ($\kappa > 4$)	ET (Elongated Tokamak)	
	Strong-i ($i > 0.2$)	BT (Bean-Shaped Tokamak)	Second Regime
	Small-i & ($i = 0.1$) High-δ ($\delta > 0.7$)	CT (Crescent-Shaped Tokamak)	First-Second Transition

Table 2. Typical design of Crescent-Shaped Tokamak Compared with Dee-Shaped Design

	Dee-Shape	Crescent-Shape	
Ellipticity κ	1.8	1.8	
Triangurality δ^*	0.4	0.95	
Indentation i	0.0	0.10	
Safety Factor q_ψ	2.6	2.6	
β - Model	Troyon or New	Troyon	New
Plasma Major Radius R(m)	1.69	1.62	1.51
Plasma Minor Radius a(m)	0.62	0.54	0.48
Troidal Field B_T (T)	6.6	6.9	7.4
Plasma Current I_P (MA)	10.6	10.3	9.1
Plasma Beta β (%)	7.8	9.1	10.3
Density $n(10^{20}m^{-3})$	3.8	4.9	6.4
Temperature T(Kev)	10.	10.	10.
Ignition Margin C_{ig}	2.2	2.2	2.2

FIGURE CAPTIONS

Fig.1(a) Definition of plasma shape parameters for a typical crescent-shaped configuration:

Aspect ratios; $A^*=R_0^*/a^*$, $A=R_0/a$,

Ellipticities; $\kappa^*=b/a^*$, $\kappa=b/a$,

Triangularities; $\delta^*=c^*/a^*$, $\delta=c/a$,

Indentation; $i=d/a$.

Fig.1(b) Several plasma shape configurations marginally stable against ballooning mode at A = 3.0, κ = 2.0, q_0 = 1.0 and q_s = 2.0 .

λ = 1 (sharp tip) case;

ellipse (δ^*=0.0), standard sharp dee (δ^*=0.5), crescent (δ^*=1.0).

λ = 2 (round tip) case;

race-track (δ^*=0.0), indented round dee (δ^*=0.5), kidney-bean (δ^*=1.0).

Fig. 2 Accessibility to the second stability region by increasing the triangularity-indentation. Calculated ballooning optimized beta value are normalized by I_N or I_N^*.

Fig. 3 Flow chart of system design code

Fig. 4 Typical design of CT (Crescent-Shaped Tokamak)

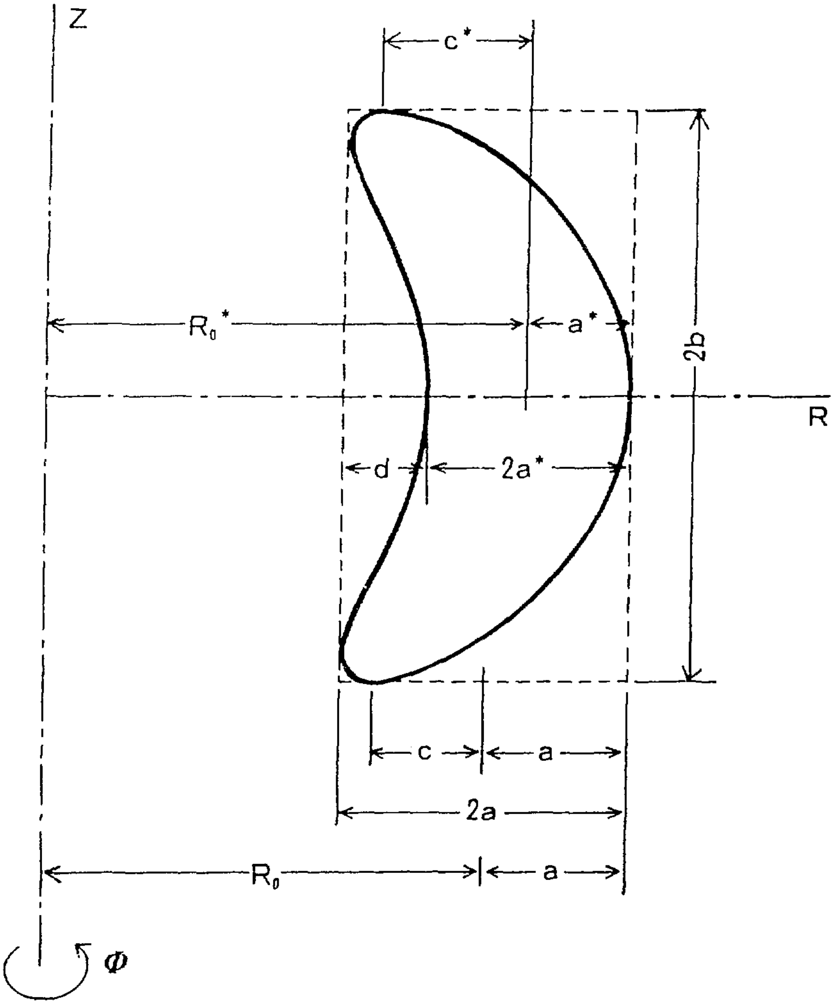
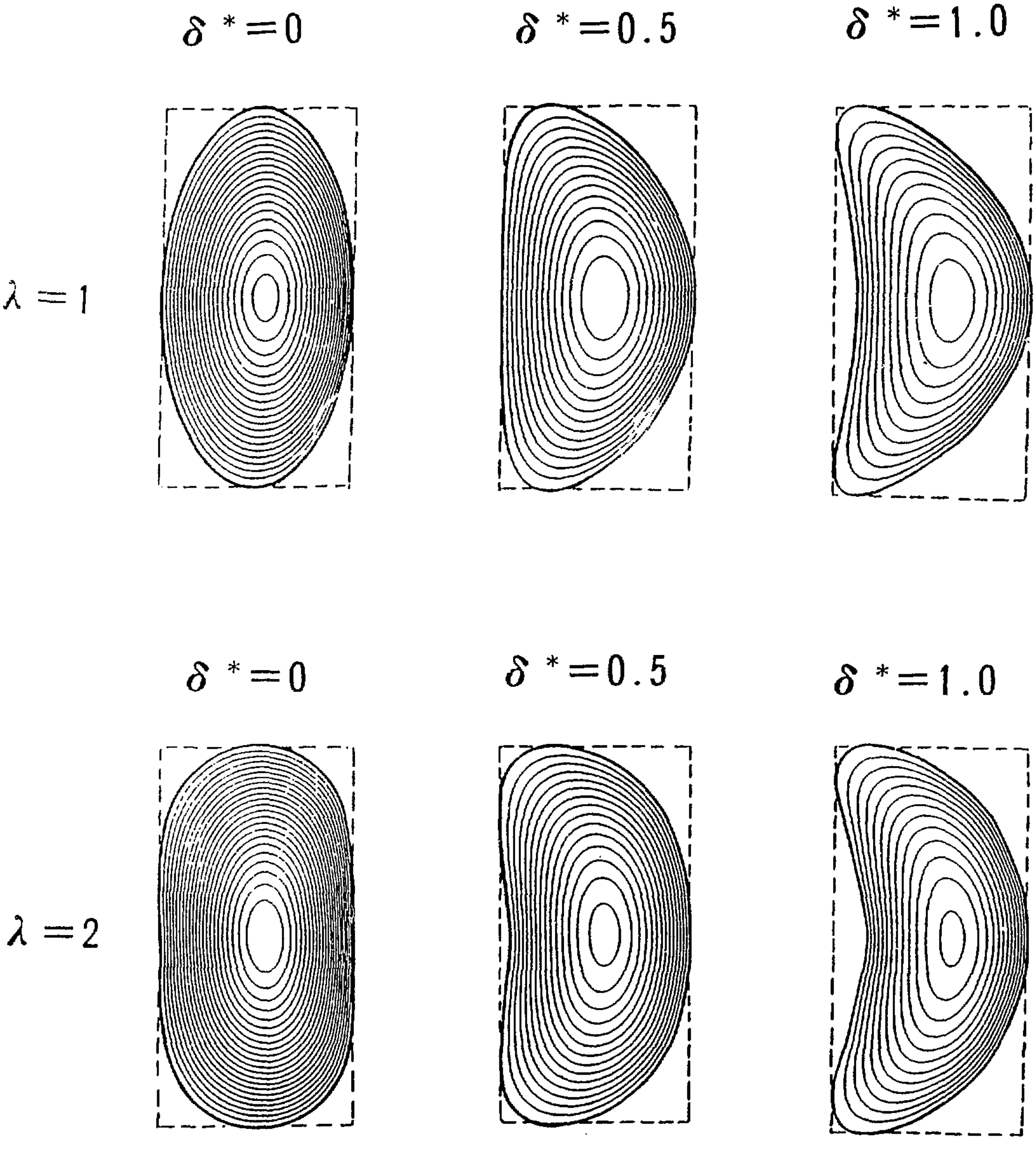


Fig. 1 (a)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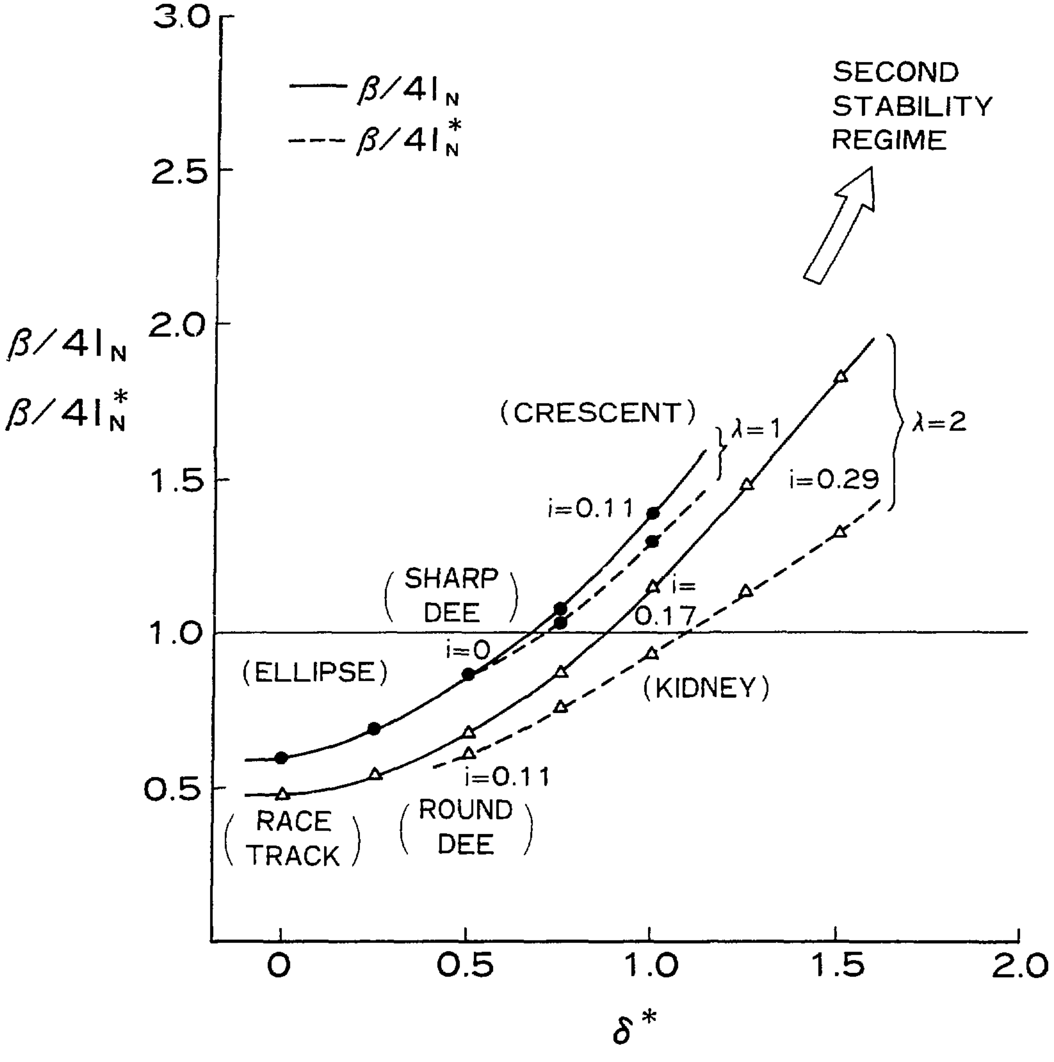
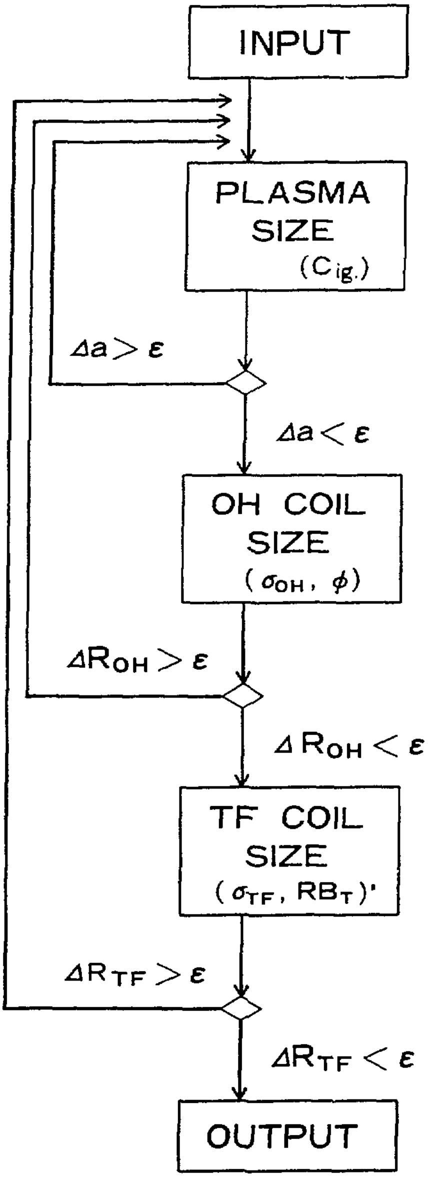
$\delta^*=0.5$
$\delta^*=1.0$
$\lambda=1$
$\delta^*=0$
$\delta^*=0.5$
$\delta^*=1.0$
$\lambda=2$

Fig. 1 (b)



—— $\beta/4I_N$
--- $\beta/4I_N^*$
SECOND STABILITY REGIME
$\beta/4I_N$
$\beta/4I_N^*$
3.0
2.5
2.0
1.5
1.0
0.5
0
0.5
1.0
1.5
2.0
δ^*
(CRESCENT)
$\lambda=1$
$\lambda=2$
i=0.11
i=0.29
(SHARP DEE)
i=0.17
i=0
(ELLIPSE)
(KIDNEY)
i=0.11
(RACE TRACK)
(ROUND DEE)

Fig. 2

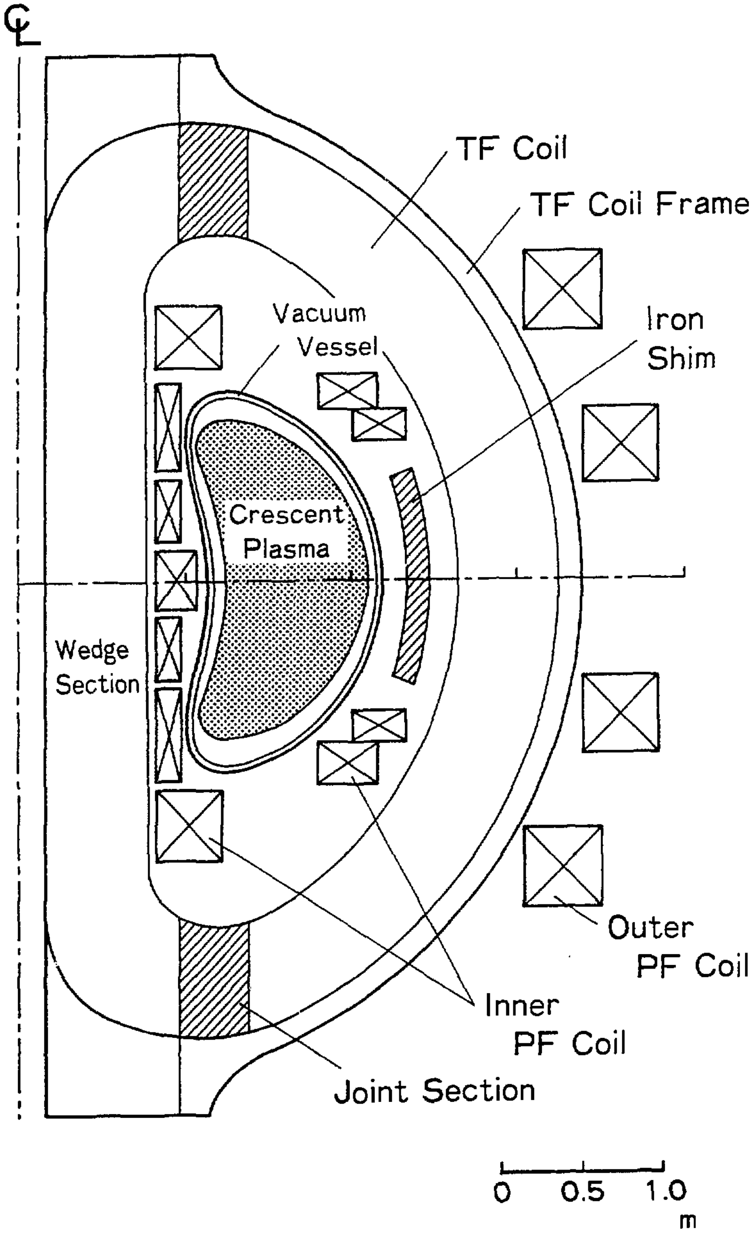


$$\left[\begin{array}{l} \varDelta a \propto \left(\dfrac{C_{ig}^{target}}{C_{ig}} - 1 \right) \\ a \rightarrow a \pm \varDelta a \\ R \rightarrow R \pm \varDelta a \end{array}\right.$$

$$\left[\begin{array}{l} \phi = \phi_{EF} + \phi_{OH}(\sigma_{OH}) \\ \varDelta R_O \propto f(\phi^{reqired} / \phi) \\ R_{OH} \rightarrow R_{OH} \pm \varDelta R_{OH} \end{array}\right.$$

$$\left[\begin{array}{l} \varDelta R_{TF} \propto f(\sigma_{TF}{}^{max} / \sigma_{TF}) \\ R_{TF} \rightarrow R_{TF} \pm \varDelta R_{TF} \\ B_T \rightarrow B_T / (1 \pm \varDelta R_{TF} / R_{TF}) \end{array}\right.$$

Fig. 3



CL
TF Coil
TF Coil Frame
Vacuum Vessel
Iron Shim
Crescent Plasma
Wedge Section
Outer PF Coil
Inner PF Coil
Joint Section
0 0.5 1.0
m

Fig. 4