163
11-1-77

LA-6815-MS

Informal Report

MASTER

Lh. 1544

UC-20d

Issued: October 1977

Preliminary Engineering Calculations for a Toroidal Reverse-Field Pinch Reactor

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UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

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PRELIMINARY ENGINEERING CALCULATIONS FOR A TOROIDAL REVERSE-FIELD PINCH REACTOR

by

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ABSTRACT

The energy balance for a model reverse-field pinch reactor is determined by assuring specific values for the plasma beta, temperature, compression ratio, and circulating power. A parameter range of the toroidal current and the minor bore of the machine is then calculated, with additional limitations imposed by the neutron flux to the first wall and electrical engineering considerations. This work is intended to serve as a guide for advancing the reverse-field pinch reactor design.

I. INTRODUCTION

This report will present some of the general parameters required of a reverse-field pinch reactor (RFPR) based on engineering considerations. To simplify the presentation, specific requirements are imposed on the plasma beta, temperature, compression ratio, and circulating power in the generating system. Additional restrictions are imposed by electrical engineering requirements and by limiting the total integrated neutron flux to the first wall. No attempt is made to optimize the design, rather it is the intent to determine if the reactor requirements with a nonoptimized model are at all "reasonable." This calculation is then just a first attempt at a reactor design that must follow. Until this additional work is accomplished, it is intended that this work will serve as a guide in understanding some of the aspects of a RFPR so that appropriate experiments can be designed to supply the data base required to refine the reactor design.

II. MODEL

The conceptual design of the RFPR shown in Fig. 1 is used for the energy balance calculations and incorporates some of the intrinsic requirements

of the reactor.¹ Although these calculations do not consider the setting-up phase, the design uses a segmented blanket to allow penetration of the magnetic field on a rapid time scale. A copper coil at the outside of the shield supplies the initial toroidal magnetic field (bias field). A second copper field programming coil, located inside the shield, is used to establish the reverse toroidal field required for stability. It and the copper primary, which drives the toroidal current, operate at 300°C; the ohmic losses are included in this calculation. The ohmic loss could be reduced if the field programming coil supplied the initial bias magnetic field on a pulsed basis. Programming would drive the current to zero at the time of the implosion and would then remain at zero while the reverse field is maintained by the external coil. Some trimming of the reverse field by current in the field programming coil would be required, but the ohmic losses would be drastically reduced.

The thin sheath model is used to develop a set of equations relating the plasma parameters to the reactor requirements. Figure 2 presents the radial profiles of the magnetic field, plasma temperature, and density used for the calculations, along with the idealized time history of the toroidal and poloidal current.

The neutron flux to the first wall is limited to an average of 10^{18} #/m²-s per cycle with a duty of cycle of 0.1, and the requirement that the first wall last for two years.¹

A magnetic core is included in this calculation to couple the toroidal primary current to the plasma current. The volt-second limitation imposed by a saturation magnetic field of 1.8 T is assumed.

III. ENERGY BALANCE

The energy equations are obtained from the model shown in Fig. 3. No direct conversion of energy is assumed, and all the energy input to the reactor is recovered with a thermal efficiency. An equation defining the energy gain of the reactor is

$$M = \frac{\eta_T W_T}{\eta_C W_C}, \quad (1)$$

W_T and W_c are defined as

$$W_T = (W_n + W_e + W_e + W_b + W_p + W_{br}) ,$$

and

$$W_c = (W_p + W_e + W_b + W_{br} / \eta_c) ,$$

where

η_T is the thermodynamic efficiency with which the heat energy is converted to electrical energy,

W_n is the energy from nuclear fusion reactions,

W_e is the resistive loss in the conductors that establish and maintain the appropriate fields,

W_b is the total magnetic field energy,

W_p is the plasma energy,

W_{br} is the energy lost by the plasma due to bremsstrahlung radiation,

M is the power gain of the reactor including the thermodynamic cycle, and

η_c is efficiency of plasma heating, power supplies, etc.

A glossary of symbols used in this paper is given on page 15.

From these equations and definitions, the following performance values are defined.

<u>Symbol</u>	<u>Definition</u>	<u>Equation</u>
Q	energy multiplication factor	$Q = \frac{W_T}{W_c} = \frac{M\eta_c}{\eta_T}$
ϵ	recirculating power fraction	$\epsilon = \frac{W_c}{\eta_T W_T} = \frac{1}{M\eta_c}$

These quantities are then expressed (in MKS units) in terms of the following variables: The total toroidal current I as deduced from the generalized Bennett relation, the poloidal beta β_θ , the time of burn τ_B , the radius of the

conducting wall r_w , the compression ratio K , i.e., the radius of the wall/radius of the plasma and δ_p and δ_f , which are the thicknesses of the primary and field programming windings (Fig. 1). Also, an ion temperature of 15 keV has been assumed, and the extra energy due to the lithium reaction in the blanket has been included. The equations for the energies considered in the system are:

$$W_n = 7.7 \times 10^{-21} \frac{\beta_\theta^2 I^4 K^2}{r_w^2} \tau_B ,$$

$$W_e = \frac{3.4 \times 10^{-8} I^2}{2 \pi r_w} \left[\frac{r_w}{(r_w + \delta_b) \delta_p} + \frac{(r_w + \delta_b) 4(1 - \beta_\theta)}{\delta_f r_w K^2} \right] \tau_B ,$$

$$W_b = \frac{10^{-7} I^2}{2} \left[2 \ln K \left(1 + \frac{0.4}{r_w} \right) + (1 - \beta_\theta) \left(1 + \frac{R_s^2}{r_w^2 K^2} - \frac{1}{K^4} \right) \right] ,$$

$$W_p = 7.5 \times 10^{-8} \beta_\theta I^2 , \text{ and}$$

$$W_{br} = 7.1 \times 10^{-23} \frac{\beta_\theta I^4 K^2 \tau_B}{r_w^2} .$$

For additional details see the Appendix.

The energy equation then gives a relation between I and r_w , for given values of τ_B , K , β_θ , δ_p , δ_f , η_T , M , and η_c . (See Sec. VI, Appendix.) The result is shown in Fig. 4 for two values of the burn time: 1 and 10 s. The following values for the adjustable parameters were assumed $\beta_\theta = 0.5$, $K = 2.5$, $M = 10$, $\eta_T = 0.4$, $\delta_p = \delta_f = 0.2$ m, and $\eta_c = 0.5$. These values of β_θ and K are consistent with the requirements of plasma stability. The value of $\eta_T = 0.4$ represents a typical thermal efficiency and the chosen values of M , η_T , and η_c yield a circulating-power fraction $\epsilon = 0.2$, and a Q of 12.5. Also plotted on this graph is the current upper limit curve labeled $A = 10$, where A is the aspect ratio of the torus R_m/r_w . This limit is a result of the requirement that the area inside the torus is sufficient to provide the volt-seconds necessary to drive the toroidal current. It is assumed that the flux is supplied by a magnetic core, with a saturation magnetic field of 1.8 T, and a packing fraction of 0.85. The fraction of the area available for the core is assumed to be 0.75.

Fig. 1.

Idealized Model chosen for the RFPR incorporating a segmented blanket to allow for penetration of the magnetic field.

Fig. 2.

Idealized models for the magnetic field, density and temperature profiles and current time history. Only the burn time τ_B is considered in this calculation.

Fig. 3.

Model chosen for calculation of the power balance of the reactor.

Fig. 4.

Results of the calculation showing the current and density required for a 1- and 10-s burn if the recirculating power fraction is 0.2. Also shown are the maximum current allowed if the neutron flux to the wall is limited to prevent wall damage, and the maximum current allowed for an aspect ratio of 10.

The upper limit of I due to the neutron flux at the first wall is also plotted in Fig. 4. The neutron flux is limited to $10^{18}/\text{m}^2\text{-s}$ with a duty cycle of 0.1 for the reactor, and the requirement that the first wall last for two years.

These simple considerations indicate that a crucial constraint on the maximum current and hence on the minimum burning time of a RFPR, with a given first wall diameter, is imposed by the limited lifetime of the first wall as a result of neutron damage. A reactor having a wall with a minor radius of $\sim 1\text{ m}$ would have a minimum burning time of 10 s, an aspect ratio of ~ 10 , a current of 10 MA and a particle density $\approx 3 \times 10^{20}\text{ m}^{-3}$. Since a large range of reactor sizes is permitted by the above analysis, it is evident that the actual size of a working reactor depends primarily upon the physics and scaling of confinement time and field diffusion.

APPENDIX

SUPPLEMENTARY CALCULATIONS

I. ENERGY FROM NUCLEAR FUSION REACTIONS

The reaction rate is given by

$$R = n_D n_T \langle \sigma v \rangle .$$

A 50% mixture of deuterium and tritium is assumed so the total number of particles is then,

$$n = n_e + n_i = 2n_i = 4n_D = 4n_T .$$

The neutron rate is then expressed, in terms of the total number density of particles, as

$$R = \frac{n^2}{16} \langle \sigma v \rangle .$$

To calculate the total energy, it is assumed that the plasma density is uniform out to the radius of the plasma. The energy deposited in the blanket per neutron is 22.4 MeV, and $\langle \sigma v \rangle$ is $2.5 \times 10^{-22}\text{ m}^3/\text{s}$. Substituting these values gives the following expression for the thermonuclear energy,

$$W_n = 1.78 \times 10^{-35} \frac{N^2 K^2 \tau_B}{r_w^2} \text{ J/m} ,$$

where

N is the total line density,

K is the plasma compression (r_w/r_p) , and

τ_B is the burn time.

Using the Bennett equation expressed below as

$$\beta_\theta I^2 = 2 \times 10^7 N k T ,$$

and assuming an average temperature of 15 keV, the following expression for the thermonuclear energy is derived,

$$W_n = 7.7 \times 10^{-21} \frac{\beta_\theta^2 I^4 \tau_B K^2}{r_w^2} , \text{ J/m} ,$$

where I is in amperes.

II. OHMIC HEATING OF CONDUCTORS

A. Toroidal Current Circuit

The ohmic heating of the copper primary is,

$$W_{ep} = \frac{\rho_o I^2 \tau_B}{2\pi r_1 \delta_p} \text{ J/m} .$$

B. Poloidal Current Circuit

1. Field Programming Coil. The ohmic heating of the copper field programming coil can be expressed as

$$W_{\theta 1} = \frac{\rho_1 2\pi r_c}{\delta_f (2\pi R_m)^2} I_{\theta 1}^2 \tau_B , \text{ J/m} .$$

The current $I_{\theta 1}$ is given by the total change of toroidal magnetic field across the field programming coil,

$$I_{\theta 1} = \frac{2\pi R_m}{\mu_o} (B_{zo} + B_{zR})$$

Substituting the above equation in the expression for $W_{\theta 1}$ then gives

$$W_{\theta 1} = \frac{2\pi \tau_B r_c \rho_1}{\mu_o^2 \delta_f} (B_{zo} + B_{zR})^2$$

To further reduce the equation, the bias and reverse magnetic fields are defined in terms of the poloidal magnetic field by the parameter θ as follows:

$$\theta_1 = B_{\theta}(r_w)/B_{zo} \quad \text{and}$$

$$\theta_2 = B_{\theta}(r_w)/B_{zR}$$

Substituting in the above equations for $W_{\theta 1}$ gives

$$W_{\theta 1} = \frac{2\pi \tau_B r_c \rho_1}{\mu_o^2 \delta_f} B_{\theta}(r_w)^2 \left(\frac{1}{\theta_2} + \frac{1}{\theta_1} \right)^2$$

$$\text{Since } B_{\theta}(r_w) = \frac{\mu_o I}{2\pi r_w}$$

$W_{\theta 1}$ can be expressed as,

$$W_{\theta 1} = \frac{\tau_B r_c \rho_1 I^2}{2\pi \delta_f r_w^2} \left(\frac{1}{\theta_2} + \frac{1}{\theta_1} \right)^2$$

2. Bias-Field Coil. The ohmic heating of the copper bias-field coil can be expressed as

$$W_{\theta 2} = \frac{\rho_2}{\delta_c} \frac{2\pi R_s}{(2\pi R_m)^2} I_{\theta 2}^2 \tau_B, \quad \text{J/m}.$$

The current $I_{\theta 2}$ is calculated from the amplitude of the initial bias magnetic field. Using the definition of θ_1 given in Sec. II, B-1, results in the following equation for $W_{\theta 2}$,

$$W_{\theta 2} = \frac{\tau_B \rho_2 I^2}{2\pi r_w} \left(\frac{R_s}{r_w \theta_1^2 \delta_c} \right), \quad \text{J/m}.$$

Using the pressure balance equation

$$\frac{K^2}{\theta_1^2} = 1 - \beta_\theta, \quad ,$$

gives

$$W_{\theta 2} = \frac{\tau_B \rho_2 I^2}{2\pi r_w} \left[\frac{R_s (1 - \beta_\theta)}{r_w \delta_c K^2} \right], \quad \text{J/m}.$$

Taking the ratio of $W_{\theta 2}$ to $W_{\theta 1}$ results in the following equation:

$$\frac{W_{\theta 2}}{W_{\theta 1}} = \frac{\rho_2}{\rho_1} \left[\frac{R_s \delta_f}{4 \delta_c (r_w + \delta_b)} \right].$$

Taking R_s equal to $r_w + 0.94$ and $\delta_b \approx 0.4$ from the RTPR study,¹ page 23, results in

$$\frac{W_{\theta 2}}{W_{\theta 1}} = \frac{1}{4} \frac{\rho_2}{\rho_1} \left[\left(\frac{r_w + 0.94}{r_w + 0.4} \right) \frac{\delta_f}{\delta_c} \right].$$

Since this coil is outside the shield, it can be run at room temperature, which gives a value for $\rho_2/\rho_1 = 0.5$. The ratio can be reduced further by making the thickness of the bias field coil greater than that of the field programming coil. The result is to reduce the ohmic heating loss in the outer coil to less than 10% of that of the field programming coil, which, for the purpose of these calculations, allows the energy loss in the outer coil to be neglected.

3. Total Ohmic Losses. Assuming that $\rho_o = \rho_1$ and that δ_p and δ_w are small with respect to r_c , the equation for the total ohmic heating loss in the copper primary and the copper field programming coil is,

$$W_e = \frac{\rho_1 I^2 \tau_B}{2\pi r_w} \left[\frac{r_w}{(r_w + \delta_b) \delta_p} + \frac{r_w + \delta_b}{\delta_f r_w} \left(\frac{1}{\theta_2} + \frac{1}{\theta_1} \right)^2 \right]$$

Stability² considerations can be used to define θ_1 as being approximately equal to θ_2 , while pressure balance requires that

$$\frac{K^2}{\theta_1^2} = 1 - \beta_\theta ,$$

where K is the compression ratio.

Substituting into the above equation gives

$$W_e = \frac{\rho_1 I^2 \tau_B}{2\pi r_w} \left[\frac{r_w}{(r_w + \delta_b) \delta_p} + \frac{(r_w + \delta_b)}{\delta_f r_w} \frac{4(1 - \beta_\theta)}{K^2} \right] , \quad J/m$$

Referring to the RTPR,¹ the blanket thickness (δ_b) is taken to be equal to 0.4m, and the resistivity is that of 300° C copper, 3.4×10^{-8} ohm-m.

III. ENERGY IN THE MAGNETIC FIELD

A. Energy in the Poloidal Magnetic Field

The energy in the poloidal magnetic field is given by,

$$W_{b\theta} = 10^{-7} I^2 \ln \frac{r_1}{r_p} = 10^7 I^2 \ln K \left(1 + \frac{0.4}{r_w} \right) , \quad J/m$$

where it has been assumed that the blanket is 0.4-m thick.

B. Energy in the Toroidal Magnetic Field

$$W_{bz} = \frac{1}{2\mu_0} B_z^2(o) \pi r_p^2 + \frac{1}{2\mu_0} B_{zR}^2 \pi (r_c^2 - r_p^2) + \frac{B_{zo}^2}{2\mu_0} \pi (R_s^2 - r_c^2), \quad J/m$$

The field in the metal conductors is neglected in the above equation. Conservation of toroidal magnetic flux within the first wall, expressed as

$$B_z(o) = B_{zo} \frac{r_w^2}{r_p^2},$$

allows the equation to be reduced further. Multiplying by $B_\theta(r_w)/B_\theta(r_w)$, using the definitions for θ_1 and θ_2 given in Sec. II, and relating $B_\theta(r_w)$ to the plasma current results in the following equation,

$$W_{bz} = \frac{\mu_0 I_z^2}{8\pi} \left[\frac{k^2}{\theta_1^2} + \frac{r_1^2 - r_p^2}{\theta_2^2 r_w^2} + \frac{R_s^2 - r_c^2}{\theta_1^2 r_w^2} \right]$$

Again, using the equation for pressure balance

$$\frac{k^2}{\theta_1^2} = 1 - \beta_\theta,$$

and the stability requirement that $\theta_1 \simeq \theta_2$ results in the following equation,

$$W_{bz} = \frac{10^{-7}}{2} I^2 (1 - \beta_\theta) \left(1 + \frac{R_s^2}{r_w^2 k^2} - \frac{1}{k^4} \right), \quad J/m$$

The expression for the total energy in the magnetic field is then

$$W_b = \frac{10^{-7}}{2} I^2 \left[\ln K \left(1 + \frac{0.4}{r_w} \right) (1 - \beta_\theta) \left(1 + \frac{R_s^2}{r_w^2 k^2} - \frac{1}{k^4} \right) \right], \quad J/m$$

IV. PLASMA ENERGY

$$W_p = \frac{3}{2} NkT$$

Using the Bennett equation and substituting for kT gives

$$W_p = 7.5 \times 10^{-8} \beta_\theta I^2, \text{ J/m}$$

V. BREMSSTRAHLUNG

The energy loss due to bremsstrahlung is given by Rose and Clark³ as

$$W_{Br} = 5.3 \times 10^{-37} n_i n_e T_e^{1/2} \tau_B, \text{ J/m}^3,$$

where T_e is in keV and n is in $\#/m^3$.

Assuming T_e is equal to 15 keV and using the Bennett relation gives

$$W_{br} = 7.1 \times 10^{23} \frac{\beta_\theta^2 I^4 K^2}{r_w^2} \tau_B, \text{ J/m}$$

VI. SOLUTION TO THE ENERGY EQUATION

Substituting the expression obtained for the energies into Eq. (1) results in the following relation for I/r_w .

$$\frac{I^2}{r_w^2} = \frac{9.74 \times 10^{12}}{\beta_\theta^2 K^2 \tau_B} \left[\frac{(M - \eta_T)/n_T}{1 - 9.2 \times 10^{-3} (M - \eta_T)/n_T} \right] \left[\beta_\theta + \frac{0.072 \tau_B}{r_w} \left[\frac{r_w}{(r_w + \delta_b) \delta_p} + \frac{4(1 - \beta_\theta)}{K^2} \left(\frac{r_w + \delta_b}{\delta_f r_w} \right) \right] + 0.657 \left[2 \ln \left(K + \frac{\delta_b}{r_w} \right) + (1 + \beta_\theta) \left(1 + \frac{R_s^2}{r_w^2 K^2} - \frac{1}{K^4} \right) \right] \right]$$

Solutions of this equation with the parameters specified on page 5 are shown in Fig. 4. R_s is taken equal to $r_w + 0.94$ from the RTPR study,² page 23.

VII. LIMIT TO THE ASPECT RATIO

The allowable range of flux in the magnetic core is given by

$$\phi_c \leq \pi (R_m - R_s)^2 f_1 f_2 B_s, \quad \text{Wb},$$

where

f_1 = packing fraction of the magnetic core (0.85),

f_2 = fraction of area inside torus available for core (0.75), and

B_s = saturation magnetic field (1.8 T).

The possibility of back-biasing the magnetic core is not included in this calculation.

The magnetic flux associated with the poloidal field is given by

$$\phi_p = L_p I = 2 \times 10^{-7} \times 2\pi R_m \ln K \left(1 + \frac{0.4}{r_w}\right) I, \quad \text{Wb}.$$

Neglecting the ohmic drop, the flux in the magnetic core and the plasma can be equated giving,

$$I \leq \frac{f_1 f_2 B_s}{4 \times 10^{-7} R_m \ln K \left(1 + \frac{0.4}{r_w}\right)} \frac{(R_m - R_s)^2}{}, \quad \text{A}.$$

Again, utilizing the RTPR study

$$R_s = r_w + 0.94.$$

With the above relation for the outer radius, the following equation is obtained

$$I \leq \frac{2.87 \times 10^6 r_w}{\ln K \left(1 + \frac{0.4}{r_w}\right)} \left[(A-2) - \frac{1.88}{r_w} + \frac{1}{A} \left[1 + \frac{1.88}{r_w} + \frac{0.88}{r_w^2} \right] \right], \quad \text{A}.$$

The upper limit to this equation is plotted in Fig. 4 as a dashed line.

VIII. NEUTRON FLUX TO FIRST WALL

The production rate of neutrons is

$$R = \frac{n^2}{16} \langle \sigma v \rangle \cdot \frac{\#}{m^3-s} .$$

The total number of neutrons generated within the plasma volume per unit time is then

$$R_T = \frac{n^2}{16} \langle \sigma v \rangle \times \pi r_p^2 \times 2 \pi R_m , \# / s ,$$

which then results in the following expression for the neutron flux to the first wall

$$F = \frac{n^2 \langle \sigma v \rangle r_p^2}{32 r_w} , \# / s - m^2 .$$

Expressed in terms of the compression ratio K, we obtain

$$F = \frac{n^2 \langle \sigma v \rangle r_w}{32 K^2} , \# / s - m^2 .$$

Using the Bennett relation,

$$\beta_\theta I^2 = 2 \times 10^7 N k T ,$$

to relate the current to the plasma density results in the following equation

$$I = \frac{232 F^{1/4} r_w^{3/4}}{(\beta_\theta K)^{1/2}} ,$$

where $\langle \sigma v \rangle = 2.5 \times 10^{-22} m^3/s$ and $T = 15$ keV.

Limiting the neutron flux to the wall to $10^{18}/m^2-s$ per pulse and assuming a 10% duty cycle, $\beta_\theta = 0.5$ and $K = 2.5$ gives

$$I = 1.17 \times 10^7 r_w^{3/4} ,$$

as the maximum current, which is plotted in Fig. 4.

GLOSSARY OF SYMBOLS

Symbol

A	aspect ratio of torus R_m/r_w
B_s	saturation magnetic field of magnetic core
$B_\theta(r_w)$	poloidal magnetic field at first wall
B_{z0}	initial magnetic field on axis
B_{zR}	reverse magnetic field
F	flux of neutrons to the first wall
f_1	packing fraction of the magnetic core
f_2	fraction of area available for core
I	toroidal current
$I_{\theta 1}$	current in field programming coil
$I_{\theta 2}$	current in toroidal bias field coil
K	compression ratio r_w/r_p
M	power gain of the reactor, including the thermodynamic cycle
N	total plasma line density $(N_e + N_i)$
n	total plasma density $(n_e + n_i)$
n_e	electron density
n_i	ion density
Q	energy multiplication factor
r_1	radius of primary
r_c	radius of field programming coil
R_m	major radius of torus
r_p	radius of plasma
R_s	radius of toroidal bias
r_w	radius of first wall
$\bar{T}$	average plasma temperature

GLOSSARY OF SYMBOLS (Cont)

Symbol

T_e	electron temperature
W_b	total magnetic field energy
W_c	recirculating energy
W_{br}	energy lost by the plasma due to bremsstrahlung radiation
W_e	resistive loss in the conductors
W_E	electrical output of plant
W_T	total thermal output of reactor
W_n	energy of nuclear fusion reactions
W_p	plasma energy
$W_{\theta 1}$	resistive loss in field programming coil
$W_{\theta 2}$	resistive loss in toroidal bias field coil
β_θ	poloidal plasma beta
δ_c	thickness of bias field coil
δ_b	thickness of blanket
δ_f	thickness of field programming coil
δ_p	thickness of primary
δ_w	thickness of first wall
δ_s	thickness of shield
ϵ	recirculating power fraction
η_c	efficiency of plasma heating, power supplies, etc.
η_T	thermodynamic efficiency
θ_1	ratio of poloidal magnetic field at the wall to the initial longitudinal magnetic field
θ_2	ratio of poloidal magnetic field at the wall to the reversed longitudinal magnetic field

GLOSSARY OF SYMBOLS (Cont)

Symbol

ρ_0	resistivity of copper primary
ρ_1	resistivity of the copper field programming coil
ρ_2	resistivity of toroidal bias coil
τ_B	plasma burn time
ϕ_c	magnetic flux of core
ϕ_p	magnetic flux of poloidal field

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