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A MINIMUM-SIZE TOKAMAK CONCEPT FOR CONDITIONS NEAR IGNITION

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ABSTRACT

Based on a combination of Alcator scaling and a recent theory on the Murakami density limit, a minimum-size tokamak concept ("Minitor") is proposed. Even if this concept does not aim at alpha particle containment, it has the important goal of reaching plasma core temperatures and Lawson parameter values required for ignition, by ohmic heating alone and under macroscopically stable conditions. The minimized size, and the associated enhancement of the plasma current density, are found to favour high plasma temperatures, average densities, and beta values. The goal of this concept appears to be realizable by relatively modest technical means.

1. Introduction

According to an earlier proposal by Coppi[1], ignition should be attainable by ohmic heating alone in relatively high density tokamak plasmas under macroscopically stable conditions. The main goal of the proposal is to investigate the effects of alpha particle containment and heating. With this goal, and because of the low beta value, the required magnetic field strengths are in the multi-100-kG range, so that superconducting toroidal field coils cannot be used[2]. Nevertheless there remains considerable interest in attempting such a purely scientific "Ignitor" experiment along Alcator ohmic-heating lines.

This paper proposes a somewhat different tokamak concept being less ambitious than that of Coppi[1], by abandoning the condition of alpha particle containment and thereby leading to a smaller and less expensive design. Also the present proposal is based on pure ohmic heating, and has the following main features:

(a) The plasma parameter ranges are assumed to be determined by a combination of Alcator scaling[3], a recent theory[4] on the Murakami limit[2,5], and a required value of the Lawson parameter $\bar{n}\tau_E$ where $\bar{n}$ is the average plasma density and τ_E the energy containment time. According to this theory the highest plasma core temperatures T_o, being close to the ignition value, are reached in minimum-size tokamak geometry[4], also when taking magnetic surface splitting into account.

(b) Even if alpha particle containment cannot be realized in the presently proposed minimum-size ("Minitor") geometry, this concept has the important goal of demonstrating a macroscopically stable plasma at the values of $\bar{n}\tau_E$ and T_o being required for ignition. This appears to be possible at much lower costs and technical efforts than those of planned and started large tokamak ignition experiments[2].

(c) The present concept can be used as a pulsed neutron source and a material testing station.

2. Plasma Physical Background

In a recent theory[4] on the density limit of tokamaks, it has been shown that the plasma pressure gradient in the outer layers of the plasma body becomes mainly determined by the plasma-neutral gas balance, in a quasi-steady state. Ballooning instabilities are driven by the pressure gradient when the average plasma density $\bar{n}$ exceeds the critical value[4]

$$n_c = C_n \bar{j}_t \sqrt{R} \; ; \quad C_n = \left[3\mu_o \theta_n \exp(1)/4c_b^3\right]^{1/2} / (Am_p \xi \xi_n k T_b)^{1/4} \tag{1}$$

Here $\bar{j}_t = J_t/\pi \bar{a}^2$ is the average toroidal plasma current density given by the total toroidal current J_t and the average minor radius $\bar{a}$, R is the major radius, A the mass number, m_p the proton mass, $\xi = \langle\sigma'_{en} w_e\rangle$ the ionization rate due to the ionization cross section σ'_{en} for electron-neutral impacts at the electron velocity w_e, $\xi_n = \xi + \xi_{in}$, $\xi_{in} = \langle\sigma_{in} w_{in}\rangle$ is the rate of ion-neutral impacts due to the ion-neutral collision cross section σ_{in} and the relative ion-neutral velocity w_{in}, T_b is the average plasma temperature in the outer layers, and θ_n, c_b are dimensionless plasma profile factors being close to unity. That the toroidal field strength B_t does not appear explicitly in Eq. (1) is a result of the magnetic field-dependent plasma-neutral gas balance[4]. As will be seen later in this paper, account will also be taken of the Kruskal-Shafranov limit and the corresponding safety factor q. For relevant tokamak data, i.e. $T_b \cong 10^6$ K, $\xi \cong 3 \times 10^{-14}$ m^3/s, $\xi_{in} \cong 4 \times 10^{-14} m^3/s$, $c_b \cong 1.3$ and $\theta \cong 0.7$, we have $A^{1/4} C_n \cong 3.4 \times 10^{14}$ $amp^{-1} m^{-3/2}$ in SI-units. This value is consistent with so far performed tokamak experiments[4]. It is independent of anomalous transport. The density limit given by condition (1) is associated with an equivalent beta limit[4].

With the stability criterion (1) as a constraint, we investigate the parameter ranges of tokamaks satisfying the Lawson condition

$$\bar{n}\tau_E = c_L \equiv \theta_L c_{Lc} \; ; \quad \theta_L \geqslant 1 \tag{2}$$

where $c_{Lc} \approx 10^{20}$ s/m^3 represents the marginal value of the plasma energy balance for the DT-reaction. For this purpose the aspect ratio $A_r = R/\bar{a}$ and the q-value at the limiter $q_a = 2B_t/\mu_0 R\bar{j}_t$ are introduced. Further, Alcator-scaling of the energy confinement time is adopted[3], i.e.

$$\tau_E = c_A \bar{n}\bar{a}^2 \qquad (3)$$

with $c_A \approx 3.6 \times 10^{-21}$ m · s.

To obtain an expression for the energy containment time of a plasma sustained by ohmic heating alone, a model is now adopted in a first approximation where the plasma density and temperature distributions are given by $n/n_o = 1-(r/\bar{a})^2$ and $T/T_o = \exp[-4(r/\bar{a})^2]$, with n_o, T_o denoting values at the magnetic axis $r = 0$. These profiles are similar to those observed[6] in ALCATOR-C. With this model the heat content W of the plasma column per unit length and the ohmic heating power P_η per unit length combine to

$$\tau_E = W/P_\eta \approx 3k\bar{n}T_o^{5/2}/16\theta_\eta k_{\eta c}\bar{j}_t^2 \qquad (4)$$

Here $\eta = k_\eta/T^{3/2}$, $k_\eta = \theta_\eta k_{\eta c}$, $k_{\eta c} \approx 65.3$ ($\ell n\Lambda$) for the classical Spitzer resistivity along a strong magnetic field, and the factor $\theta_\eta > 1$ simulates anomalous resistivity effects of ohmic heating. In this model we assume θ_η to be constant and exclude the effects of its possible variation in the scaling laws. At the same time it should be observed that the density limit of Eq. (1) is independent of anomalous resistivity and cross-field diffusion effects[4].

Combination of Eqs. (1)-(4) finally yields the following expressions for the relevant plasma parameters and the safety factor q_a, in terms of the core temperature T_o:

$$\bar{a} = 16\, k_{\eta c} c_L \theta_\eta / 3kC_n^2 A_r T_o^{5/2} \qquad (5)$$

$$\bar{n} = 3kC_n^2 A_r T_o^{5/2}/16k_{\eta c}(c_L c_A)^{1/2}\theta_\eta \qquad (6)$$

$$\bar{j}_t = (3k/16k_{\eta c})^{3/2} C_n^2 A_r T_o^{15/4}/c_L c_A^{1/2}\theta_\eta^{3/2} \qquad (7)$$

$$B_t = (3k/k_{\eta c} c_A)^{1/2} \mu_o q_a A_r T_o^{5/4} / 8\theta_\eta^{1/2} \qquad (8)$$

$$J_t = \pi \bar{a}^2 \bar{j}_t = 4\pi k_{\eta c}^{1/2} c_L \theta_\eta^{1/2} / (3kc_A)^{1/2} C_n^2 A_r T_o^{5/4} \qquad (9)$$

$$\phi_t = 2\pi A_r \bar{a} E_t = 3\pi (3kk_{\eta c})^{1/2} A_r \theta_\eta^{1/2} / c_A^{1/2} T_o^{1/4} \qquad (10)$$

$$\phi_t J_t = 12\pi^2 k_{\eta c} c_L \theta_\eta / c_A C_n^2 T_o^{3/2} \qquad (11)$$

where ϕ_t is the loop voltage due to the induced toroidal electric field E_t in a quasi-steady state. From expression (5) is seen that the highest temperatures T_o are reached when choosing a minimum-size concept.

We now introduce the average beta value

$$\bar{\beta} = 4\mu_o \bar{n} k c_T T_o / B_t^2 \qquad \bar{T} = c_T T_o \qquad (12)$$

where $\bar{T}$ is the average plasma temperature and c_T is a profile factor. Combination of expressions (1), (6) and (8) yields

$$\bar{\beta}/\beta_c = (\bar{n}/n_c)^2 \qquad (13)$$

where

$$\beta_c = 16 k c_T C_n^2 c_A^{1/2} T_o / \mu_o A_r c_L^{1/2} q_a^2 \qquad (14)$$

Finally, the magnetic surface splitting limit[7,4] imposes the condition

$$s \equiv a\beta_p/R = \bar{\beta} A_r q_a^2 = 16 k c_T C_n^2 c_A^{1/2} T_o / \mu_o c_L^{1/2} \le 1 \qquad (15)$$

for $\bar{\beta} = \beta_c$.

Thus the stability condition $\bar{n} < n_c$ given by the critical density of Eq. (1) becomes equivalent to the condition $\bar{\beta} < \beta_c$ determined by the beta limit of Eq. (14). This implies that, when considering the recently treated ballooning mode in the outer plasma layers[4], the presently deduced density limit[4] and the beta limit are just two sides of the same instability phenomenon. The limit given by Eq. (1) appears to be consistent with so far performed tokamak experiments[4]. The corresponding limits given by Eqs. (14) and (15) are illustrated in Figs. 1 and 2 for $A_r = 2$, $c_T = 0.5$ and the cases $\theta_L = 1$ and 5, as functions of the q-value at the limiter. Four points should be made in this connection:

(i) The beta limit of expressions (13) and (14) applies only to systems for which the pressure gradient in the outer plasma layers becomes determined by the plasma-neutral gas balance. This is the case when $n_c/\bar{n}$ does not exceed unity by orders of magnitude[4].

(ii) For the tokamak experiments listed in a recent review[8] and being performed near the observed density limit, such as those with FT, TBR, JFT-2, TORIUT-4, ALCATOR-C and ISX-B, insertion into Eq. (14) of the observed values of T_o, A_r, $c_L = \bar{n}\tau_E$ and q_a yields beta limits of a few percent. This also seems to be consistent with experiments.

(iii) At given values of c_L, A_r and q_a it is seen from Eqs. (5), (7), (14) and Figs. 1 and 2 that increasing beta values are available when the linear dimensions are decreased and the current density $\bar{J}_t$ becomes enhanced. Also this speaks in favour of a minimum-size concept.

(iv) Magnetic surface splitting imposes an additional constraint on systems of small size.

3. Plasma Parameter Choice of a Minimum-Size Concept

As a first aim of the present concept, a core temperature close to the ignition value of the DT reaction has to be reached. Consequently, we choose $T_o = 4 \times 10^7$ K. To make the system as compact as possible, an aspect ratio $A_r = 2$ is further adopted. In order not to overestimate the efficiency of ohmic heating, we put $k_{\eta c} = 650$ and $\theta_\eta = 1$. Finally, a safety factor $q_a = 2$ is being assumed. With these data and $A = 1$, the parameters given by Eqs. (5)-(11) vary with the Lawson parameter $c_L = \bar{n}\tau_E$ as shown in Fig.3. The figure demonstrates that the radius $\bar{a}$

can be increased by increasing c_L above the marginal value $c_{Lc} = 10^{20} s/m^3$, at the expense of an increased total toroidal current J_t. That the critical beta value of Eq. (14) decreases with increasing c_L at a given temperature T_o is due to a simultaneous increase in the size $\bar{a}$ which impairs the stability. Magnetic surface splitting finally puts a lower limit on c_L.

When abonding the possibilities of auxiliary heating, alpha particle containment and a reactor blanket, the smallest possible values of $\bar{a}$ appear to be in the range of a few centimeters. As a first illustration of a minimum-size ("Minitor") concept we choose $\bar{a} = 0.05$ m which just satisfies condition (15) of the magnetic surface splitting and which leads to $\theta_L = c_L/c_{Lc} = 5$. Then $R = 0.1$ m, $\bar{n} = 6.8 \times 10^{21} m^{-3}$, $\bar{\beta} = \beta_c = 13\%$, and $B_t = 8.4$ tesla, $\bar{j}_t = 62 \times 10^6 A/m^2$, $J_t = 0.56 \times 10^6$ A, $\bar{\phi}_t J_t = 0.37 \times 10^6$ W and $\phi_t = 0.65$ V. The wall load becomes $\Pi_w = 1.9 \times 10^6 W/m^2$. The obtained data are listed in Table I.

In this connection it should finally be observed that ignition by ohmic heating in a tokamak has also been discussed by Sestero[9] who suggests a low-shear-stress magnet for high toroidal magnetic field strengths.

4. Plasma Current Induction System

The small size of the present system does not make it possible to use an iron-core transformer alone for breakdown, build-up and maintenance of the plasma and its toroidal current. Two possible ways of designing the plasma current induction system will be outlined here.

The first way implies that a layer of toroidal air windings is placed near the plasma boundary as outlined in Fig.4. The current distribution within this layer should be chosen such as to generate a negligible poloidal magnetic field inside the plasma volume. For a circular cross section of the layer, with a minor radius ρ_t as given in Fig.4, this condition is fulfilled by the distribution $j_{t1} \propto (R + \rho_t \cos\alpha)^{-1}$ where the angle α is defined in the figure and the details of the corresponding deduction are given in the Appendix. The induced current $J_t = 0.56$ MA of Table I should become realizable by ordinary technical means. At the dimensions given in the table, the self-inductances and the mutual inductance of the equivalent single-turn current circuits defined by j_{t1} and j_t are thus of the order of 10^{-7} henrys. With a coefficient of coupling of about 0.4 between these circuits, a condenser bank of capacity 10^{-2} farads loaded to 5 kV would be able to deliver a current pulse of the order of 0.5 MA during about 10^{-4}s, with a primary total current of about 1.3 MA. Further, the temperature increase for normally conducting copper coils then becomes about 1 K/ms within the parts of the windings where the current density has its maximum. This estimate is based on a coil thickness $\delta_t a \cong 10^{-2}$m in Fig. 4, and with the fraction $f_c = 0.8$ of the coil area being occupied by metal windings. Finally, the mechanical stresses on the same coil structure are then of the order of 10^8 N/m^2 which is somewhat below the tensile strength limit of copper.

The second way is based on a compromise between an air-core and iron-core system. Thus, breakdown and start-up are assumed to be provided by a simple arrangement of loop-shaped toroidal air coils which do not satisfy the condition of generating a negligible poloidal magnetic field strength within the plasma, but leave more space and flexibility to the construction than a coil system based on the deduction in the Appendix. The field errors may not result in optimal tokamak discharge conditions, but the system may still be used for start-up and pre-heating of the plasma. The main discharge period of a hot plasma at nearly constant toroidal current J_t is thereafter sustained by an iron-core transformer. This becomes possible for a core of cross section πa^2 which is magnetized to saturation, thereby providing a flux swing of about 10^{-2} Vs. The latter at least becomes sufficient for sustaining a loop voltage $\phi_t \cong 1$V during a ten-millisecond pulse, thereby exceeding the required value of ϕ_t given in Table I.

5. Toroidal Magnetic Field System

For generation of the toroidal field $\underline{B}_t$ a conventional coil system can be placed around the torus. In the case where the poloidal field from the current induction system has to be eliminated, the toroidal-field coils should be placed outside those used for current induction, as outlined in Fig. 4.

If instead the simpler current induction system is used in combination with an iron core, the toroidal-field coils could be placed more closely to the plasma boundary.

With a coil thickness $\delta_p a \cong 1.25 \times 10^{-2}$ m in Fig.4, and the fraction $f_p = 0.8$ of the coil area being occupied by metal windings, the field $B_t = 8.4$ tesla leads to a maximum current density $j_{plm} \cong 1.3 \times 10^9$ A/m^2 at $\alpha = \pi$. For copper coils this results in a temperature increase of about 10 K/ms. Finally, with these data the mechanical stresses on the coil windings are of the order of 2×10^7 N/m^2, being well below the tensile strength limit of copper.

6. Conclusions

The present data are based on an analysis which is consistent with so far performed experiments and which takes the density, beta, Kruskal-Shafranov and surface splitting limits into account. If this analysis can be extrapolated to the large current densities $\bar{j}_t$ considered here, new possibilities would open up for tokamak experiments under conditions near ignition. These conditions appear to be realizable in minimum-size geometry by ordinary and relatively modest technical means, at least for pulsed discharges on the millisecond time scale, and without the requirement of alpha particle containment. Longer time scales are likely to become available by modifying the present choice of parameters and using cryogenic or superconducting coils.

As far as plasma physics is concerned, these statements hold true, provided that there are no other phenomena than those considered here in terms of n_c, β_c, and q_a and S which put additional restrictions to the regime of stable tokamak operation. Also the influence of impurities released through plasma-wall interaction may affect the plasma balance. Further analysis is as well required on the magnetic field errors due to a poloidal component, and on the corresponding closure of the field lines which is expected to affect the plasma balance and stability.

Concerning the technology of the present proposal, only a simplified first discussion of some major questions has been undertaken within the frame of this paper. Further detailed analysis is necessary on the coil systems, including the thermal and mechanical stresses, their placement with respect to accessibility, repair, diagnostics and vacuum ports, the possible use of cryogenic or superconducting windings, and the application of an iron core as auxiliary means for toroidal current induction.

Stockholm, January 5, 198[illegible]

7. Acknowledgements

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Stockholm, January 30, 1983

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Table I. Data of proposed "Minitor" device.

Minor radius	$\bar{a} = 0.05$ m
Major radius	$R = 0.1$ m
Toroidal magnetic field strength	$B_t = 8.4$ tesla
Toroidal plasma current	$J_t = 0.56 \times 10^6$ A
Toroidal plasma current density	$\bar{j}_t = 62 \times 10^6 A/m^2$
Loop voltage	$\phi_t = 0.65$ V
Ohmic heating power	$\phi_t J_t = 0.37 \times 10^6$ W
Wall load	$\Pi_w = 1.9 \times 10^6$ W/m^2
Safety factor at limiter	$q_a = 2$
Average plasma density	$\bar{n} = n_c = 6.8 \times 10^{21} m^{-3}$
Average beta value	$\bar{\beta} = \beta_c = 13\%$
Core plasma temperature	$T_o = 4 \times 10^7$ K
Lawson parameter	$\bar{n}\tau_E = 5 \times 10^{20} s/m^2$

APPENDIX. Current Distribution in the Transformer Coil

The current distribution in the coil used for generation of the induced plasma current has to be chosen in a way not to produce a poloidal magnetic field within the plasma volume of Fig.4. Here we introduce the coordinates $r = R + \rho\cos\alpha$ and $z = \rho\sin\alpha$. The poloidal field $\underline{B}_{pl} = \text{curl } \underline{A}_{tl}$ is generated by the current system $\underline{j}_{pl}$ in Fig.4, where $\psi = rA_{tl}$ is the corresponding flux function. Thus the components of $\underline{B}_{pl} \equiv (B_r, 0, B_z)$ can be written as

$$B_r = -\left(\frac{\partial\psi}{\partial\rho}\sin\alpha + \frac{\partial\psi}{\partial\alpha}\cdot\frac{1}{\rho}\cos\alpha\right)/(R + \rho\cos\alpha) \tag{A 1}$$

$$B_z = \left(\frac{\partial\psi}{\partial\rho}\cos\alpha - \frac{\partial\psi}{\partial\alpha}\cdot\frac{1}{\rho}\sin\alpha\right)/(R + \rho\cos\alpha) \tag{A 2}$$

A surface current $j_{tl}(\alpha)$ is now introduced in a thin layer of radius $\rho = \rho_t$, to approximate the current distribution in the coil which forms the primary circuit of the induced plasma current. Immediately outside of the surface $\rho = \rho_t$ the lines of the field $\underline{B}_{pl}$ are required to run parallel with the same surface. This implies that $B_r/B_z = -\operatorname{tg}\alpha$ for $\rho = \rho_t$, which only becomes possible when $\partial\psi/\partial\alpha = 0$ at $\rho = \rho_t$. Finally, introducing the field strength

$$B(\rho_t,\alpha) = (d\psi/d\rho)_{\rho=\rho_t}/(R + \rho_t\cos\alpha) \tag{A 3}$$

immediately outside of the surface $\rho = \rho_t$, and the surface current

$$j_{tl}(\alpha) = B(\rho_t,\alpha)/\mu_o \tag{A 4}$$

the field inside the surface $\rho = \rho_t$ is made to vanish. Since $\partial\psi/\partial\alpha = 0$ at $\rho = \rho_t$, it is thus seen that $j_{tl}(\alpha) \propto 1/(R + \rho_t\cos\alpha)$ is the required current distribution.

Figure Captions

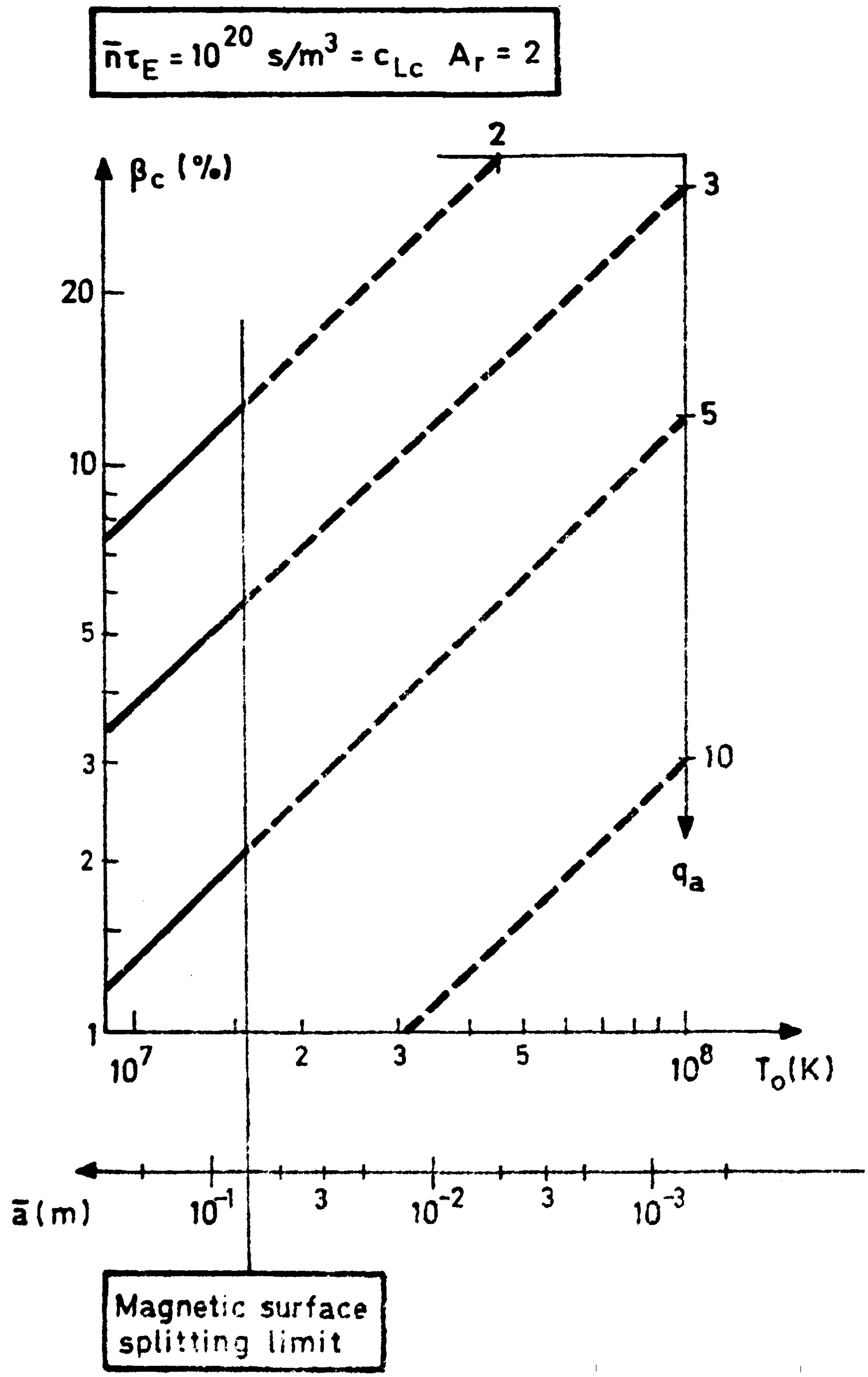
Fig.1. The critical average beta value β_c as a function of the minor radius $\bar{a}$ (or the core temperature T_o), at an aspect ratio $A_r = 2$, $c_T = 0.5$, at the marginal value c_{Lc} of the Lawson parameter($\theta_L = 1$), and for various values of the safety factor q_a. The figure applies to ohmically heated systems being near the density limit n_c and where the plasma pressure gradient in the outer layers is mainly determined by the plasma-neutral gas balance. The broken parts parts of the lines correspond to values $S > 1$ exceeding the magnetic surface splitting limit.

Fig.2. Same as Fig. 1, but with $\theta_L = 5$.

Fig.3. Minor radius $\bar{a}$, average plasma density $\bar{n}$, total toroidal plasma current J_t, and average current density $\bar{j}_t$ as functions of the Lawson parameter $c_L = \bar{n}\tau_E$, at a plasma core temperature $T_o = 4 \times 10^7$ K of the present tokamak system. The broken parts of the lines correspond to $S > 1$.

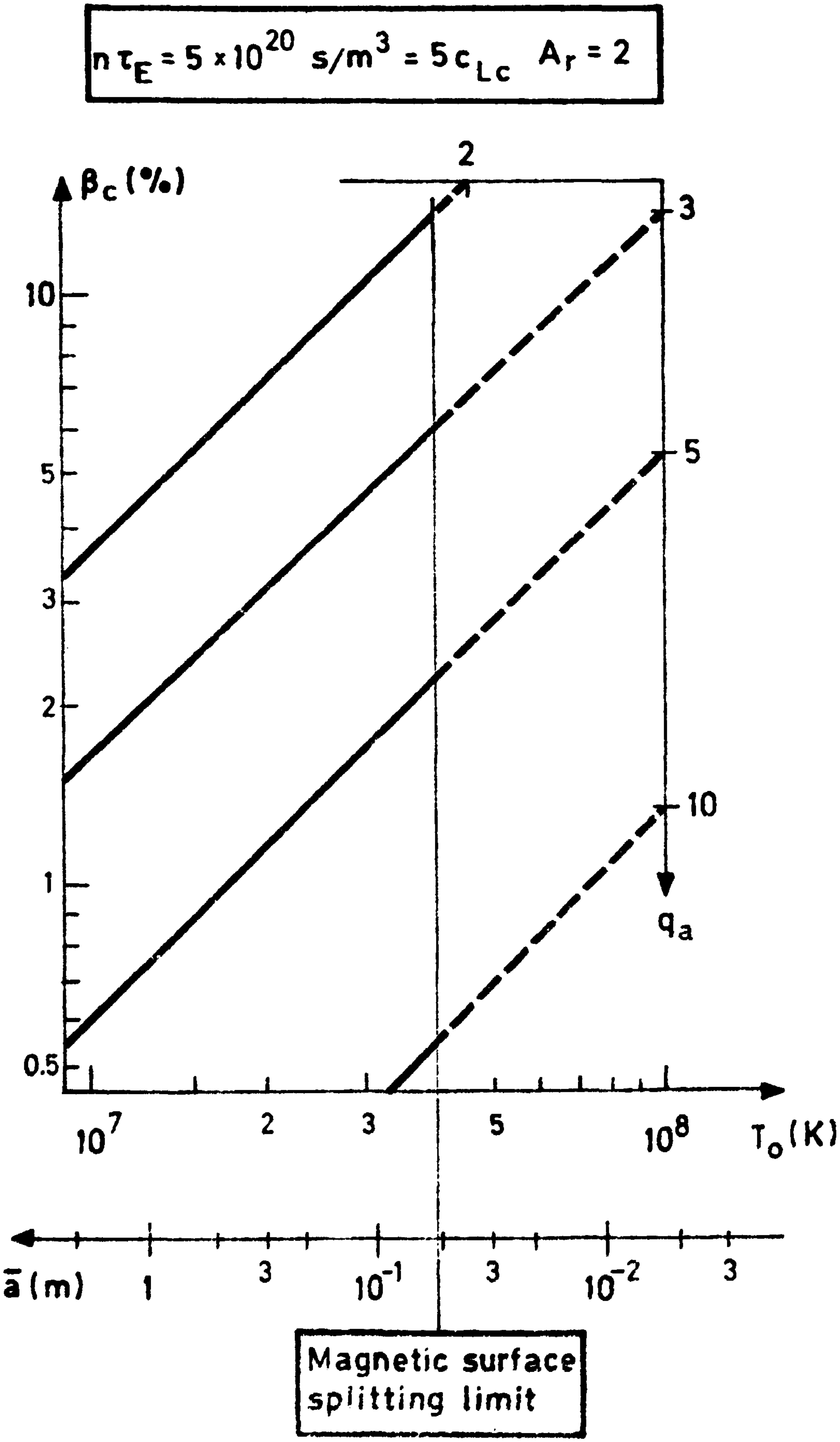
Fig.4. Outline of a "Minitor" device with an air-core transformer coil arrangement which produces a negligible poloidal magnetic field within the plasma volume.

Fig. 1



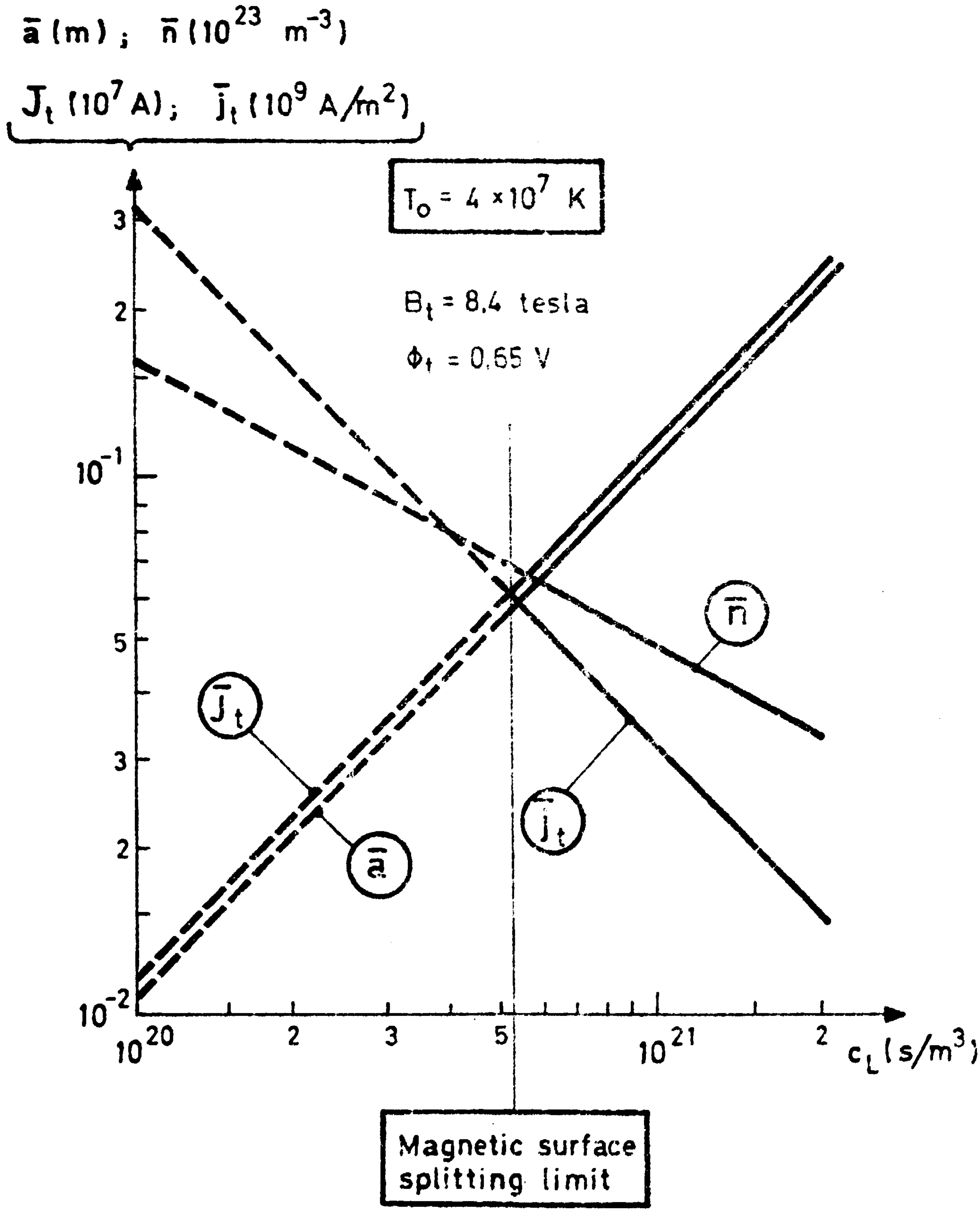
$\bar{n}\tau_E = 10^{20}$ s/m³ = c_{Lc} A_r = 2
β_c (%)
20
10
5
3
2
1
2
3
5
10
q_a
10^7
2
3
5
10^8
T_o(K)
$\bar{a}$(m)
10^{-1}
3
10^{-2}
3
10^{-3}
Magnetic surface splitting limit

Fig. 2



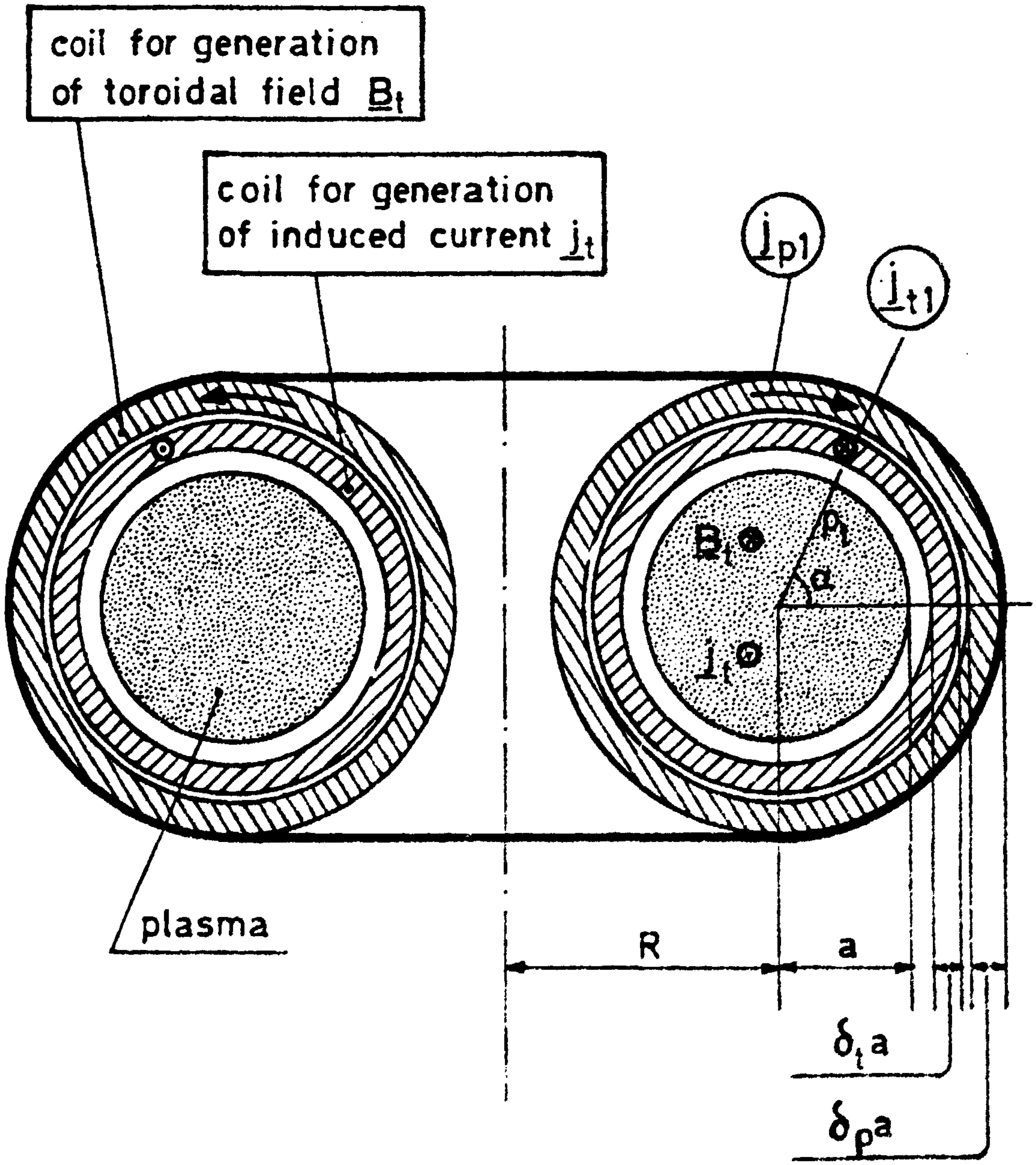
nτ_E = 5 × 10^20 s/m^3 = 5 c_Lc A_r = 2
β_c (%)
10
5
3
2
1
0.5
2
3
5
10
q_a
10^7
2
3
5
10^8
T_o (K)
ā (m)
1
3
10^-1
3
10^-2
3
Magnetic surface
splitting limit

Fig. 3



ā (m) ; n̄ (10^23 m^-3)
J_t (10^7 A) ; j̄_t (10^9 A/m^2)
T_o = 4 × 10^7 K
B_t = 8.4 tesla
Φ_t = 0.65 V
3
2
10^-1
5
3
2
10^-2
10^20
2
3
5
10^21
2
c_L (s/m^3)
n̄
J̄_t
j̄_t
ā
Magnetic surface splitting limit

Fig. 4



coil for generation of toroidal field $\underline{B}_t$
coil for generation of induced current $\underline{j}_t$
$\underline{j}_{p1}$
$\underline{j}_{t1}$
$\underline{B}_t$
ρ_1
α
$\underline{j}_t$
plasma
R
a
$\delta_t a$
$\delta_p a$

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Key words: Tokamaks, density and beta limit, ignition, minimum-size experiment.