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# POWER LOSS PROBLEMS IN EXTRAP COIL SYSTEMS

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ABSTRACT

The Ohmic power loss in the coils of external ring traps is minimized with respect to the thermonuclear power production. In the case of the DT-reaction this leads to dimensions and power densities being relevant to full-scale reactors. Not only superconducting or refrigerated coil windings can thus be used, but also hot-coil systems which are operated at several hundred degrees centrigrade and form part of a steam cycle and power extraction system. For hot coils the problems of void formation and tritium regeneration have to be further examined. The high beta value leads to moderately large coil stresses. Finally, replacement and repair become simplified by the present coil geometry.

## 1. Introduction

Recently a new scheme, EXTRAP (External Ring Traps), for magnetic high-beta confinement has been proposed, in which a toroidal plasma pinch is immersed in a strongly inhomogeneous poloidal vacuum field [1,2]. The latter is generated by an arrangement of external ring-shaped coils, all carrying current in the direction being opposite to that of the plasma current. From the reactor technological point of view this scheme has some advantages in common with internal conductor devices, such as those concerning the Ohmic power loss in the main magnetic coil system [3]. On the other hand, the absence of internal rings and their magnetically shielded supports simplifies the technology of EXTRAP systems, also with respect to the cooling of the coil structure, the mechanical stresses, and to repair and replacement.

This report is restricted to a simple analysis of the power balance in EXTRAP coil geometry under full-scale conditions.

## 2. Basic Concepts

The EXTRAP concept includes a class of magnetic bottles having some flexibility in the choice of radial and axial dimensions, aspect ratios, and numbers of coils [1,2]. To illustrate the power balance problems of the coil system, we shall in this paper adopt the geometry of Fig.1, as a working hypothesis. Here a toroidal pinch of non-circular cross-section and average minor and major radii $a_o$ and $r_o$ is carrying the current $J_o$, and is situated in the magnetic field generated by the external coil currents $J_1$ and $J_2$. The "inner" coil pair being closest to the axis has the average major radius $r_1$, the average distance $h_1$ from the mid-plane, and an equivalent square cross section of thickness $2a_1$. For the "outer" pair with the larger axial distance the corresponding data are $r_2$, $h_2$, and $2a_2$. The resistivity of the coil windings is denoted by $\eta$.

We normalize the dimensions and currents with respect to $a_o$ and $J_o$, in writing

$$r_\nu = c_{r\nu} a_o \; ; \qquad h_\nu = c_{h\nu} a_o \; ; \qquad a_\nu = c_{a\nu} a_o \tag{1}$$

$$J_\nu = c_{J\nu} J_o \tag{2}$$

where subscripts $\nu = 0,1,2$ stand for the plasma and the inner and outer coil pairs.

The plasma is assumed to be sustained in a stable state, by steady bootstrap operation, or by quasi-steady induction methods. We further assume the temperatures to be equal for ions and electrons, and introduce $n$ and $T$ as characteristic average values of ion density and temperature. The spatial variations of the parameters across the plasma body will be included in corresponding geometric factors throughout this paper. SI-units are used.

## 3. Relative Magnitude of the Resistive Power Loss

With the starting points of Section 2, we now compare the Ohmic power loss in the coils with the thermonuclear power production.

### 3.1. Plasma Physical Conditions

Following an earlier theoretical analysis [1,2], the plasma current is first connected with the rest of the plasma parameters by the equilibrium pressure balance condition

$$J_o^2 = 32\pi^2 kTna_o^2/\mu_o\beta \tag{3}$$

where $\beta$ is of order unity and includes the geometrical factors due to the spatial distributions of current density, T, and n.

Further, the total thermonuclear power becomes

$$P = 2\pi^2 g_R r_o a_o^2 Rn^2 = 2\pi^2 g_R c_{ro} R(na_o^2)^2/a_o \tag{4}$$

where $g_R$ is a geometrical factor representing the effective fraction of the plasma volume within which thermonuclear reactions take place, and

$$R = (1-f)\left[\frac{1}{2}(1-f)R_{DD}Q_{DD} + fR_{DT}Q_{DT}\right] \tag{5}$$

is the total reaction density in a mixture of fn tritons and (1-f)n deuterons, $0 \leqslant f \leqslant 1$, the reaction rates of the individual DD- and DT- reactions are $R_{DD}$ and $R_{DT}$, and $Q_{DD} = 6 \times 10^{-13}$, $Q_{DT} \approx 28.2 \times 10^{-13}$ are the corresponding released energies in joules per reaction. In a real thermonuclear plasma f should always differ from zero, since there is tritium formed even when the primary fuel consists of pure deuterium.

Finally, stabilization of kink modes and other disturbances requires the distance between the plasma and each external coil to be as small as possible, and the total coil current $2(J_1 + J_2)$ to be of the order of $J_o$ [1,2,4]. In the present notation this implies that $c_{J\nu}$ in Eq. (2) should be of order unity, and that the ratio

$$\delta_\nu = \left[ c_{h\nu}^2 + (c_{ro} - c_{r\nu})^2 \right] / (1 + c_{a\nu}\sqrt{2})^2 \tag{6}$$

should be chosen as close to unity as possible. This choice depends on the subsidiary condition of having a sufficiently large thickness of the chamber wall, as well as of the shields which possibly are inserted between the plasma and the coils.

## 3.2. Ohmic Power Losses in the Coils

When the current density and resistivity distributions are nearly homogeneous, the Ohmic power loss in the coils becomes

$$\Lambda = \pi\eta \sum_{\nu=1,2} (r_\nu J_\nu^2/\delta a_\nu^2) = \pi\eta(J_o^2/a_o)\Sigma; \quad \Sigma = \sum_{\nu=1,2} c_{r\nu}(c_{J\nu}/c_{a\nu})^2/\delta \tag{7}$$

where $\delta$ is the fraction of the coil cross-section consisting of metal with the resistivity $\eta$. The relative magnitude of the coil losses thus becomes (compare Ref. [3])

$$F = \Lambda/P = (C\tau/Pa_o)^{1/2} \tag{8}$$

where

$$C = (32\pi^2 k\eta_o/\mu_o)^2 \cdot (\Sigma^2/2g_R c_{ro})(h/\beta)^2 \tag{9}$$

$$\tau = T^2/R \tag{10}$$

$h = \eta/\eta_o$ with $\eta_o \approx 1.7 \times 10^{-8}$ Vm/A being the resistivity of copper at $0^oC$, and use has been made of the relations (3) and (4) between $na_o^2$, $J_o$, and $Pa_o$.

In Eq. (8) the factor $C$ depends on $\eta$, $\beta$, and the geometry, whereas the plasma temperature dependence appears in $\tau$, and the power and linear dimensions in $1/Pa_o$ only. The relative magnitude $F$ of the Ohmic losses is thus minimized by choosing the smallest values of each of these factors, within the ranges of practical applicability. Concerning the temperature dependence we put $\tau$ equal to the smallest values (compare Ref. [3])

$$\tau_{min} \approx 6.2\times10^{49} K^2/Wm^3 \quad at \quad T = 8\times10^7 \ K \quad for \quad f = 0.5 \tag{11}$$

$$\tau_{min} \approx 5\times10^{52} \ K^2/Wm^3 \quad at \quad T = 10^9 K \quad for \quad f = 0 \tag{12}$$

At these values the plasma temperature exceeds the ignition temperature, such as to make the ratio between $P$ and the bremsstrahling loss equal to about 16 and 7 in the cases of the DT- and DD-reactions, respectively. Consequently,

$$Pa_o F^2 = C\tau = G(h/\beta)^2(\Sigma^2/g_R c_{ro}) \tag{13}$$

where $G(f=1) \approx 1.0 \times 10^5$ and $G(f=0) \approx 8.4 \times 10^7$ Wm for the DT- and DD-reactions.

### 3.3. Numerical Illustrations

The present results are now illustrated by some numerical examples. For this purpose we choose the plasma parameters $\beta = 1$, $c_{J1} \approx c_{J2} = 0.5$, $g_R = 0.7$, and $c_{ro} = 4$, as well as aluminium coils kept at an average temperature of 400 $^oC$ resulting in $h = 4.6$, and having the normalized dimensions $c_{r1} = 2$, $c_{r2} = 4.8$, $c_{a1} = 0.8$, $c_{a2} = 1.2$, and $\delta = 0.8$.

The relation between the total power $P$, the plasma radius $a_o$, and the Ohmic power ratio $F$ for a DT-mixture then becomes as demonstrated by Fig.2. The latter shows that the Ohmic losses can be kept at an acceptably low level within the parameter ranges of interest to full-scale reactors. In particular, when putting $F = 0.1$, we obtain $P = 1.5 \times 10^9$W, $n = 5.8 \times 10^{20}$ $m^{-3}$, and $J_o = 13 \times 10^6$ A at a plasma radius $a_o = 1$ m.

In the case of the DD-reaction the corresponding basic data yield $C\tau \approx 1.3 \times 10^{10}$ Wm, being a too large value for $F$ to become small at realistic values of $Pa_o$. This case therefore requires coil systems having a much smaller resistivity than that of the previous example on the DT-reaction. Thus, $h$ has to be decreased to 0.16 for the power balance to lead to a result identical with that demonstrated by Fig.2. Such values are not only availavle by means of superconductors, but can also be reached in refrigerated coil systems.

## 4. Possible Types of Coil Systems

According to the present results there are several alternatives which can be chosen for EXTRAP coil systems.

### 4.1. Hot Coil Systems

In the case of the DT-reaction it should become possible to operate the coils at temperatures of several hundred degrees centrigrade, thereby cooling the windings by water at high pressure, or by other and similar means. The coils could then act as neutron shields, to be included in the steam cycle and power extraction system. In this case the spacing between the plasma and the coil windings should be chosen as small as possible, and the coil shapes and walls be matched to the non-circular plasma cross section.

In this connection there are also some important reactor technological problems which have to be further investigated before the hot-coil alternative can be fully judged, namely those of void formation in the coils, and the questions of tritium regeneration.

### 4.2. Refrigerated Coil Systems

By refrigeration of the coil windings the Ohmic losses can be further minimized, and/or the coil cross-sectional areas be reduced, such as to allow for the use of extra walls and shields, to absorb at least the major part of the outgoing heat and neutron flux. This possibility does not only apply to the DT-reaction. It should also be of interest to the DD-reaction, at least when having two or three times larger dimensions and powers than those represented by the example with $Pa_o = 1.5 \times 10^9$ W m discussed in Section 3,3.

## 4.3. Superconducting Coil Systems

When using superconducting windings, the coil cross sections can be decreased considerably, to allow for blankets and neutron shields to be inserted between the coils and the plasma. It is thus likely that such systems can be operated both with the DT- and DD-reactions, at plasma radii $a_o$ of the order of one or two meters.

## 5. Conclusions

Provided that the present premises regarding plasma equilibrium and stability in EXTRAP systems [1,2] hold true, such systems should have many reactor technological advantages, namely;

(i) In the case of the DT-reaction, and at relevant data of full-scale reactprs, hot coil systems can be used which form part of a steam cycle and power extraction system. However, the problems of void formation and tritium regerenation require further examination.

(ii) It may even become possible to make use of the DD-reaction, in the case of refrigerated or superconducting coils.

(iii) High power densities should become available in systems of moderately large size.

(iv) Due to the high beta value, the coil stresses can be kept at a tolerable level.

(v) Replacement and repair are expected to become simplified in the present geometry, where the external coils can be removed in the axial direction.

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## 6. References

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## Figure Captions

Fig.1. Crude outline of an EXTRAP system consisting of two external coil pairs carrying the parallel currents $J_1$ and $J_2$ in each coil. A plasma of non-circular cross-section is confined within the shaded area, and traversed by the total antiparallel current $J_o$.

Fig.2. Total thermonuclear power $P$ and plasma radius $a_o$ as functions of the ratio $F = \Lambda/P$ between the Ohmic coil loss $\Lambda$ and $P$, in the case of DT-mixture with $f = 0.5$. The plasma parameters are $\beta = 1$, $c_{J1} = c_{J2} = 0.5$, $c_{ro} = 3.2$, $g_R = 0.7$, and the coil parameters $h = 4.6$, $\delta = 0.8$, $c_{r1} = 2$, $c_{r2} = 4.8$, $c_{a1} = 0.8$, $c_{a2} = 1.2$. With the same basic data, this figure also applies to the DD-reaction with $f = 0$, when the coil resistivity is reduced to a value given by $h = 0.16$.

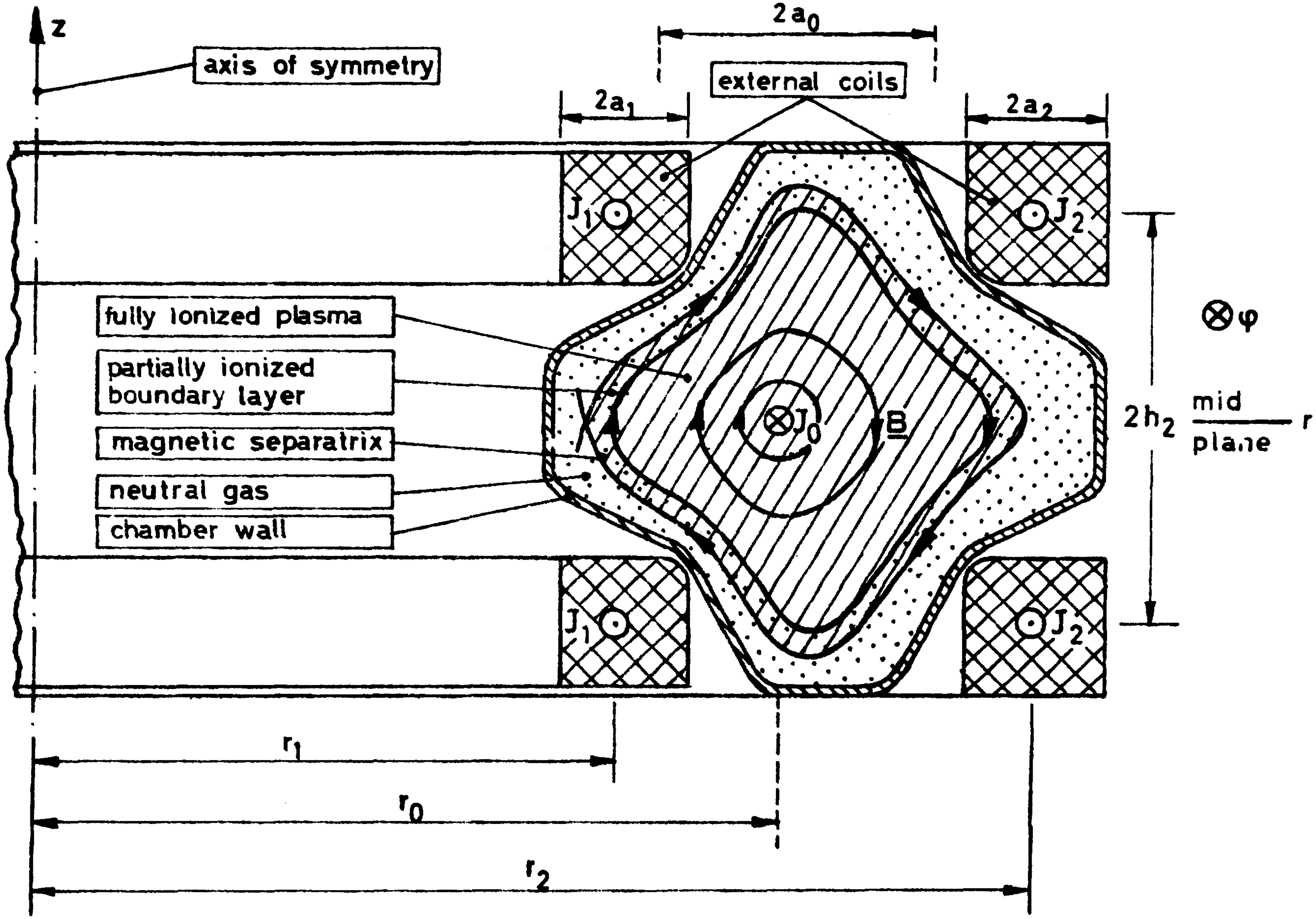
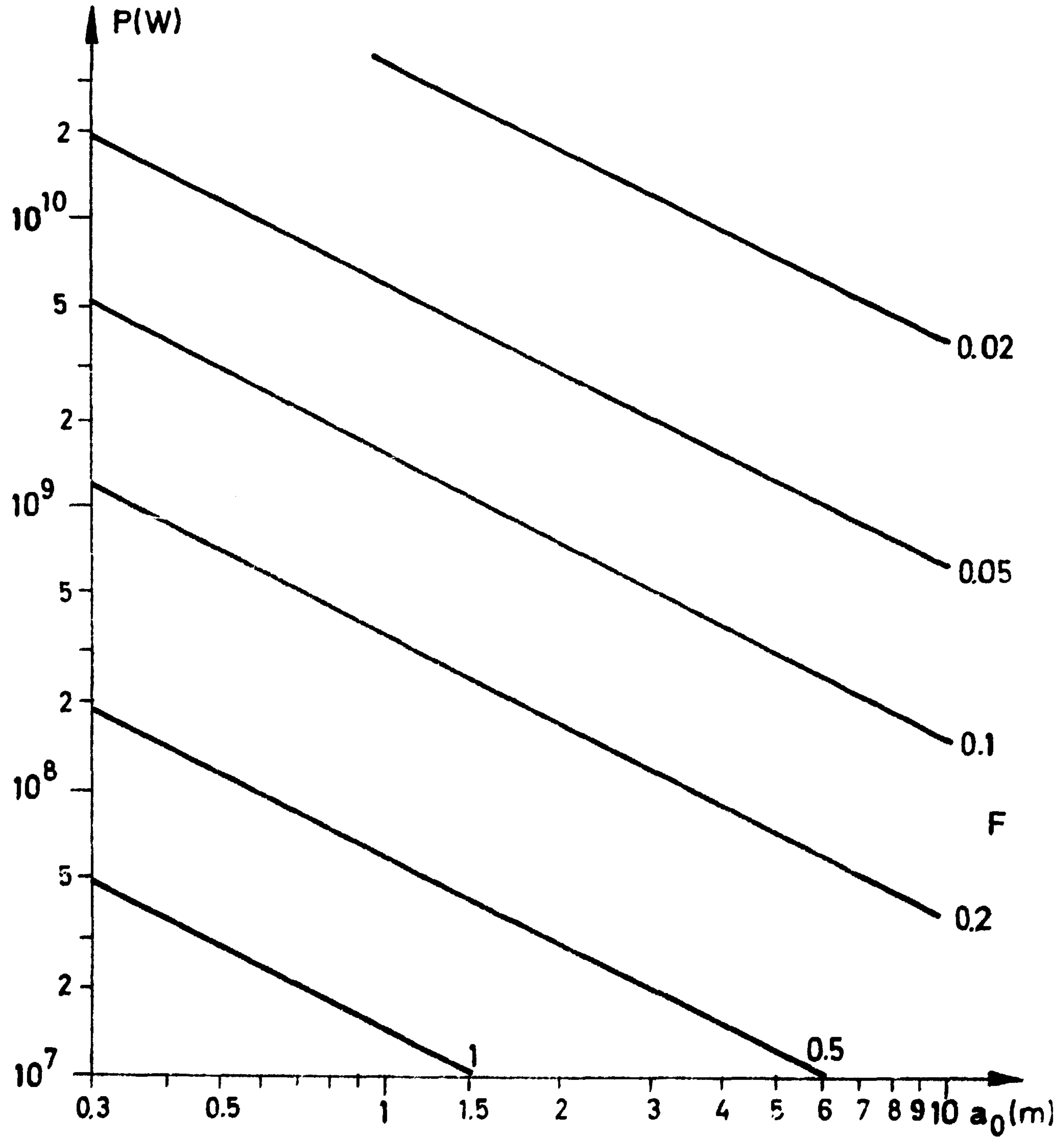

z
axis of symmetry
2a0
external coils
2a1
2a2
J1
J2
fully ionized plasma
partially ionized
boundary layer
magnetic separatrix
neutral gas
chamber wall
J0
B
φ
2h2
mid
plane
r
r1
r0
r2

Fig.1

Fig.2



P(W)
2
10^10
5
2
10^9
5
2
10^8
5
2
10^7
0.02
0.05
0.1
F
0.2
0.5
1
0.3
0.5
1
1.5
2
3
4
5
6
7
8
9
10
a0(m)

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Key words Magnetic bottles, coil power loss, fusion reactor technology.