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EXTRAP WITH IRON-CORED COILS

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ABSTRACT

In Extrap configurations there is a high average beta value with respect to the plasma confinement volume. The externally imposed magnetic field which is required for stabilization therefore comes out to have a rather moderate strength, even under expected reactor conditions. As a consequence, this field can be generated not only by conventional external conductor arrangements, but also by iron-cored coils being operated below the saturation limit. A proposal for such iron-cored coil systems is presented in this paper. As compared to conventional conductors, this has the advantage of localizing the magnetic energy of the externally imposed magnetic field mainly to the discharge vessel and the plasma volume, thereby increasing the engineering beta value substantially. Also the problems of the coil stresses and of irradiation of the coils appear to become simplified, as well as replacement of the coil system.

A main limitation of this proposal is due to combination of iron core saturation with the required stabilization effect from an ion Larmor radius of sufficient relative magnitude. This limitation requires further investigation, especially in the full-scale reactor case. Also the modifications of the field geometry by iron core shaping needs further analysis.

1. Introduction

In Z-pinch systems with a purely transverse (poloidal) magnetic field, such as Extrap [1,2], the average beta value, defined as an average taken over the plasma confinement volume (the plasma beta value), is close to unity. This implies that confinement at a given plasma pressure can be provided by a magnetic field which has the smallest possible strength within the plasma. In linear Extrap pinches [1-3] stable confinement has been achieved in a magnetic field $\underline{B} = \underline{B}_p + \underline{B}_v$ consisting of two parts, $\underline{B}_p$ and $\underline{B}_v$, the average strengths of which are roughly of the same order of magnitude at the plasma boundary. The first part is due to the pinch current density $\underline{j} = \mathrm{curl}\ \underline{B}_p/\mu_0$ and the second part $\underline{B}_v$ is generated by external sources.

As compared to tokamaks and a number of other schemes with rather low plasma beta values, the strength of the externally imposed field $\underline{B}_v$ thus becomes modest in the case of Extrap. This seems to open up the possibility of using iron-cored (non-saturated) external coils for creation of the external field in Extrap, thus providing an alternative to a conventional arrangement of external conductors. This paper outlines such an option, with its possible advantages and drawbacks.

2. The Field Configuration

The analysis is here limited to linear geometry with a straight pinch axis, but analogous considerations can readily be made in toroidal geometry. Various numbers and arrangements of the earlier proposed conductor systems are imaginable [1], but only the case of an octupole field will here be taken as an illustration. In the external conductor case such a field can be generated by four conductor rods placed outside of the plasma boundary and carrying currents which are all antiparallel to the pinch current density $\underline{j}$ [1]. In the corresponding case of iron-cored coils, a similar pattern of the external field $\underline{B}_v$ can be generated inside the plasma volume by means of four iron-cored coils placed around the plasma chamber is outlined in Fig.1. There is some possibility of varying the field geometry near the plasma boundary, by proper shaping of the iron cores.

The parameters are now assumed to be chosen such as to place the plasma boundary close to the magnetic separatrix which results from the superposition of the fields $\underline{B}_p$ and $\underline{B}_v$ [1-3]. Then the magnetic zero lines defined by

$\underline{B} = \underline{B}_p + \underline{B}_v = 0$ become localized near the "edges" of the plasma cross section, as shown in Fig.1. Placing the first wall in the vicinity of the plasma boundary further implies that the zero lines will be placed rather close to the iron-cores, in the mid-plane of an air gap between the pole-pieces. Thus the geometry outlined in Fig.1, and the condition div $\underline{B}_v = 0$, yield

$$B_{va} = \mu_0 J\, f_{va}/2\pi\bar{a} \tag{1}$$

where B_{va} is the average strength of the field $\underline{B}_v$ in an air gap for those field lines of $\underline{B}_v$ which pass through a zero line of the total field $\underline{B}$, the total pinch current is denoted by J, the average pinch radius by $\bar{a}$, and f_{va} is a dimensionless factor of order unity.

3. The Iron Core Circuit

We now introduce the length L_a of a field line of $\underline{B}_v$ which passes through a zero point of $\underline{B}$. The iron cores are assumed not to be saturated and should have a high magnetic permeability $\mu \cong 10^5 \gg 1$. According to magnet theory the average magnetic field strength B_{vi} within an iron core and the average field strength B_{va} in an air gap are then given by

$$B_{va} = \mu_0 J_v/c_L\bar{a} = c_B B_{vi} \tag{2}$$

Here J_v is the number of ampère-turns in an air-cored coil, and c_B and $c_L = L_a/\bar{a}$ stand for dimensionless factors of order unity.

For the iron cores to link the current J_v in the coil windings with the desired field $\underline{B}_v$ within the plasma, and for the air gaps of the cores to be the main "consumer" of the ampère-turns, the strength B_{vi} has to be chosen below its saturation value, with a sufficiently large margin. In the first-order estimates made in this paper we therefore put

$$B_{vi} \lesssim B_{vim} = 1 \text{ tesla} \tag{3}$$

4. Plasma Equilibrium and Stability

Introducing the plasma density n_o and temperature T_o at the pinch axis, the Bennett relation takes the form [4]

$$n_oT_o \cong C_pJ^2/\bar{a}^2 \qquad C_p = \mu_oF/8\pi^2k \tag{4}$$

where F is a profile factor and $C_p = 2 \times 10^{15}$ K/mA^2 in SI-units for a parabolic current density profile. Relation (4) simply expresses the pressure balance in the direction perpendicular to the magnetic surfaces. It corresponds to an average plasma beta value being close to unity. Auxiliary plasma heating is included whenever this becomes necessary.

We now choose B_{vi} at its maximum value B_{vim}. Combination of relations (1)-(4) then yields, with subscript $(_m)$ denoting maximum values,

$$(n_oT_o)_m = C_p(2\pi c_BB_{vim}/\mu_of_{va})^2 \tag{5}$$

$$J/\bar{a} = 2\pi c_BB_{vim}/\mu_of_{va} \tag{6}$$

$$J_v/\bar{a} = c_Bc_LB_{vim}/\mu_o \tag{7}$$

The stability of Extrap systems depends on a combination of MHD and kinetic effects. The former are partly related to the influence of the magnetic separatrix [5,6]. Further, on account of the comparatively large ion Larmor radius within substantial parts of the plasma volume, including zero-field O- and x-points, a stabilizing influence is expected to be due to both MHD-like FLR effects [1,3] and to "transverse" [3,7,8] as well as "longitudinal" [9] kinetic phase mixing effects. Both these latter effects have a stabilizing influence which becomes related to the number [10]

$$N_i = \bar{a}/a_i = JF_B/C_i(F_pT_o)^{1/2} \equiv G_iF_B/C_iF_p^{1/2} \tag{8}$$

of Larmor radii within the pinch radius $\bar{a}$, where F_B and F_p are profile factors of the magnetic field and pressure distributions in the pinch [7]. To be more specific, there is a spectrum of possible disturbance wave lengths $\lambda \lesssim \bar{a}$, for which kinetic effects will have increasing importance at decreasing values of λ [7-9]. In any case, so far performed experiments indicate that stability can at least be achieved for values of $G_i \approx 30$ A/K$^{1/2}$. Possibly much larger values of G_i can lead to stability, but this is an open question which requires further theoretical and experimental investigation.

In the case of a deuterium-tritium plasma we further introduce the total thermonuclear power

$$P_{DT} = 2\pi^2 c_R \bar{a}^3 \; Q_{DT} \rho_{DT} n_o^2 f_v \tag{9}$$

where $R = c_R \bar{a}$ is the major radius of a toroidal configuration (or the axial length of a linear one), $Q_{DT} = 7.05 \times 10^{-13}$ joules is the released reaction energy, ρ_{DT} is the reaction rate, and f_v is a profile factor due to the distribution of temperature and density acrosss the plasma body.

Finally, combination of expressions (5)-(9) and putting $B_{vi} = B_{vim}$ yields

$$n_o = (C_p/T_o)(2\pi c_B B_{vim}/\mu_o f_{va})^2 \tag{10}$$

$$\bar{a} = \mu_o f_{va} G_i \sqrt{T_o}/2\pi c_B B_{vim} \tag{11}$$

$$P_{DT} = 4\pi^2 c_R f_v Q_{DT} \rho_{DT} C_p^2 c_B B_{vim} G_i^3/\mu_o f_{va} \sqrt{T_o} \tag{12}$$

The present results can be illustrated by the numerical examples of Table 1 where a parabolic current density profile is assumed, and $c_B = 0.5$, $c_L = 1.5$, $f_{va} = 0.5$, $f_v = 0.25$, $c_R = 0.25$, $B_{vim} = 1$ tesla:

(i) In a laboratory experiment on intermediate scale we put $\bar{a} = 0.06$ m and $T_0 = 10^7$ K. Assuming a rather "conservative" value of $G_i = 30$, corresponding to the ratio $J/\sqrt{T_0}$ in earlier performed small-scale experiments [2,3], a pinch current $J = 300$ kA should be reached by having about 72 kA in each of the iron core windings.

(ii) In a reactorlike experiment of moderate size being without blanket we put $\bar{a} = 0.4$ m, thereby assuming that $G_i = 200$ still secures stability. Then the currents $J = 2$MA and $J_v = 0.48$ MA in the pinch and in the coil windings would result in a total thermonuclear power of 64 MW.

(iii) A full-size reactor with blanket thickness $d=0.6$ m and a total power of 10^3 MW would require a value of the Larmor radius parameter being as high as $G_i = 500$. Then $\bar{a} = 1$ m, $J = 5$ MA and $J_v = 1.2$ MA. Since the Pease limit [11] is exceeded, auxiliary heating becomes necessary in this case.

5. Conclusions and Discussion

Non-saturated iron-cored coils appear to provide a possible alternative to the earlier proposed external coil arrangements in Extrap devices. Among the advantages of this alternative, the following should be mentioned:

- The magnetic energy of the externally imposed magnetic field is localized mainly to the discharge vessel and the plasma volume, i.e. the "engineering beta value" is increased substantially as compared to a system with external conductors of conventional type.

- The current-carrying windings of the iron-cored coils can be localized at some distance from the discharge vessel, i.e. where ample space is available. This simplifies the problems of mechanical coil stresses and irradiation in the case of a reactor. Only the iron cores will end upon regions which are close to a blanket and a first wall. Possibly the geometry outlined in Fig.1 can be modified by letting the pole pieces of the iron cores end directly upon the first wall, and by making the blanket consist of sectors which are localized within the gaps between the pole pieces only.

- The iron-cored coils can be divided into replaceable modules of convenient size.

- At least in some cases permanent magnets with zero power consumption may be used.

Among the problems of this alternative which have to be further analysed, there are the following questions:

- The relative magnitude of the ion Larmor radius, as represented by the quantity G_i in eq. (8), is a crucial parameter with respect to stability. The possible maximum of G_i for stability provides an open question which requires further investigation, especially in terms of kinetic theory.

- The maximum of G_i combines with iron core saturation to a limitation of the present alternative for external field generation. This limitation is not expected to become crucial for intermediate-size experiments with hot plasmas. On the other hand the use of iron-cored coils in reactor systems with a blanket depends critically on the available maximum values of G_i and B_{vi}. This latter question requires further investigation.

- It is necessary to continue a study of the plasma breakdown process in the case where the external field $\underline{B}_v$ has lines ending on a wall surface.

- The possibilities of modifying the field geometry by iron core shaping needs further analysis.

- The irradiation problems of the iron cores and the placement of the blanket should be discussed more in detail.

- With the iron cores chosen as outlined in Fig.1, the plasma current J generates a magnetic field in a direction being opposite to the field produced by the currents J_v in the cylindrical parts of the core windings. This simplifies the saturation problem of the cores.

- The iron core effects on plasma stability [12] also have to be investigated.

6. Acknowledgement

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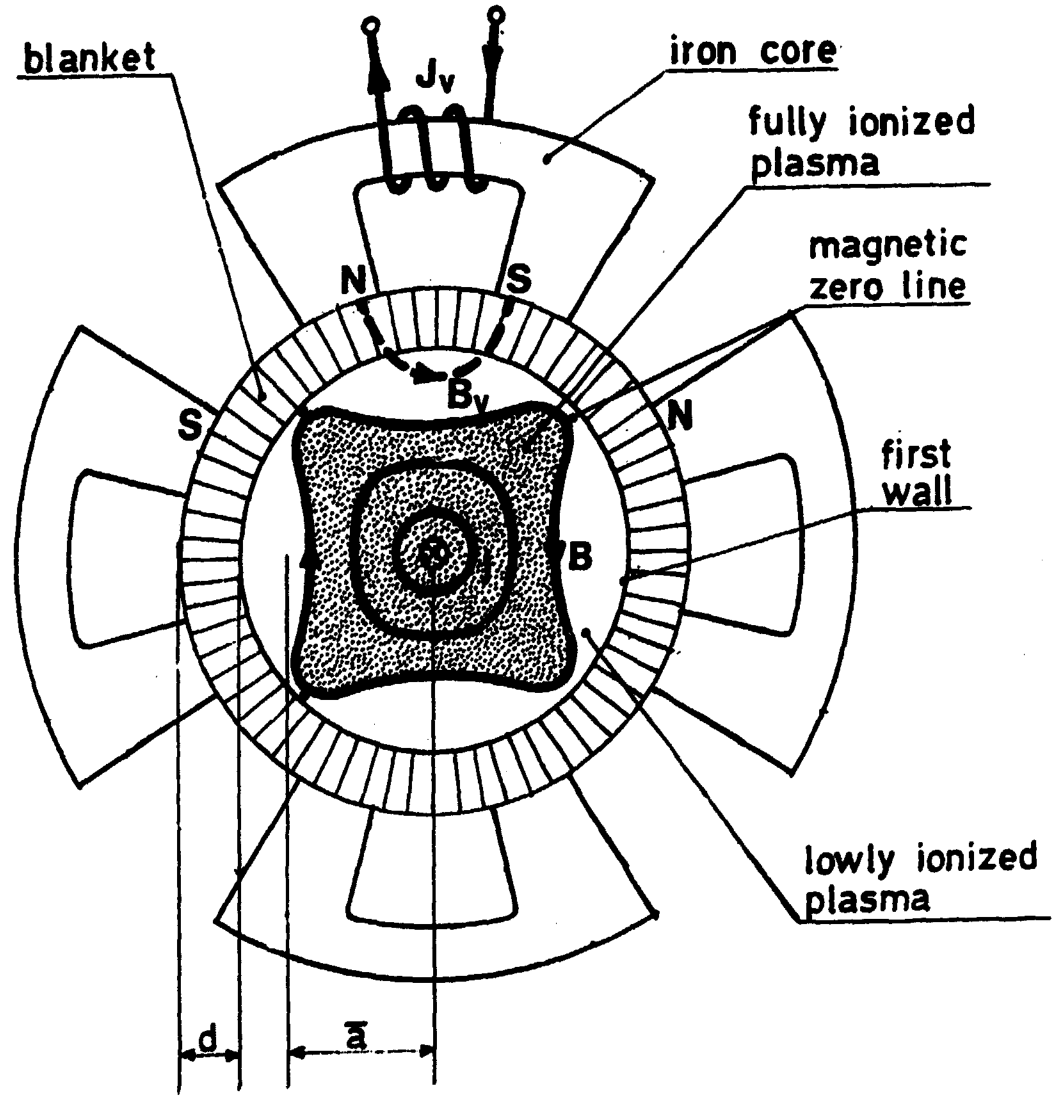
Table 1. Some numerical examples on Extrap systems with iron-cored coils at B_{vi} = 1 tesla.

Parameter	Experiment on intermediate scale	Reactorlike experiment without blanket	Reactor with blanket
T_o (K)	10^7	10^8	10^8
n_o (m^{-3})	5×10^{21}	5×10^{20}	5×10^{20}
G_i	30	200	500
$\bar{a}$ (m)	6×10^{-2}	0.4	1.0
J (A)	$0{,}3 \times 10^6$	2×10^6	5×10^6
J_v (A)	72×10^3	0.48×10^6	1.2×10^6
P_{DT} (W)	0	64×10^6	1.04×10^9
d (m)	no blanket	no blanket	0.6

Fig.1. Crude outline of a linear reactor-type Extrap device with iron-cored non-saturated external coils and a blanket. It is at this stage not clear whether or not the plasma boundary has to include parts with negative curvature, such as being shown in this figure.

Fig. 1


blanket
J_v
iron core
fully ionized plasma
magnetic zero line
N
S
S
N
B_v
first wall
B
lowly ionized plasma
d
$\bar{a}$

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Key words: External coils, iron-cored coils, magnetic confinement,
plasma, Extrap.