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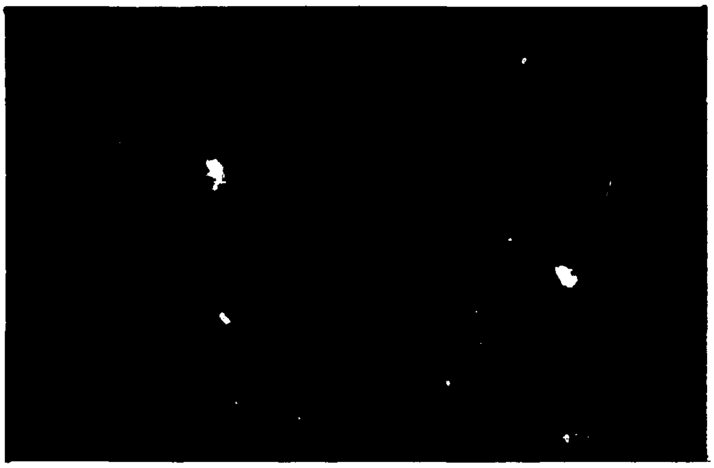

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A COMPARISON BETWEEN LINEAR AND TOROIDAL EXTRAP SYSTEMS

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ABSTRACT

The Extrap scheme consists of a Z-pinch immersed in an octupole field generated by currents in a set of external conductors. A comparison between linear and toroidal Extrap geometry is made in this paper.

As compared to toroidal systems, linear geometry has the advantages of relative simplicity and of a current drive by means of electrodes. Linear devices are convenient for basic studies of Extrap, at moderately high pinch currents and plasma temperatures.

Within the parameter ranges of experiments at high pinch currents and plasma temperatures, linear systems have on the other hand some substantial disadvantages, on account of the plasma interaction with the end regions. This results in a limitation of the energy confinement time, and leads in the case of an ohmically heated plasma to excessively high plasma densities and small pinch radii which also complicate the introduction of the external conductors.

1. Introduction

The Extrap plasma confinement scheme consists of a Z-pinch which is immersed in a multipole magnetic field, generated by currents in a set of external conductors [1]. An example of toroidal Extrap geometry with an imposed octupole field is given in Fig.1. In principle both linear and toroidal Extrap systems are imaginable as fusion devices [1,2].

Some theoretical considerations on the energy balance of linear Extrap systems have earlier been made with special emphasis on the end losses [1,2]. Experiments were also performed at an early stage on Extrap discharges of finite length, being bounded by end electrodes and having no magnetic field component along the pinch axis. These experiments were conducted both in linear [3] and toroidal-sector [4] geometry.

In this paper a comparison will be made of linear and toroidal Extrap geometry, in particular with respect to the available parameter ranges.

2. The End Losses in Linear Geometry

A linear Extrap configuration of finite axial length L is now considered which is bounded at its ends by electrodes. We introduce a frame (x,y,z) with z along the pinch axis, and restrict ourselves to a system where there is no magnetic field component in the z direction.

2.1. The Axial Heat Loss due to Particle Motion

When there is an electric current density j along z, but no axial fluid motion, the heat loss per unit volume of the pinch becomes [2]

$$\Pi_L = -(5kj/2e)\,\frac{\partial T}{\partial z} \qquad (1)$$

where $T = T(x,y,z)$ is the temperature distribution. Integrating the power (1) over the plasma volume, with the exception of the anode and cathode layers which require a special treatment [2], the corresponding power loss becomes

$$P_L = (5k/2e) f_L T_o J_p \qquad (2)$$

where f_L is a profile factor of order unity, T_o is the peak temperature within the plasma body, and J_p is the total pinch current. The result (2) has been obtained from the steady-state MHD fluid equations. It should be observed that this result includes the integrated effects of all guiding centre drifts produced by the magnetic and electric fields [2]. Thus the power loss P_L is due to the heat being carried away by the charged particles to the end electrodes.

In general there are a number of other loss channels in addition to that represented by P_L, such as

- heat conducton losses along z to the electrodes; these become enhanced when there is also a superimposed axial magnetic field component;

- heat conduction losses in the perpendicular direction of the pinch axis, to a cold-mantle which surrounds the hot plasma core;

- heat losses due to radiation.

In an integrated form the transverse pressure balance of the pinch is given by the Bennett relation

$$n_o T_o \bar{a}^2 = 5 f_p \mu_o J_p^2 / 24\pi^2 k \tag{3}$$

where n_o stands for the peak electron density within the plasma body, $\bar{a}$ is the average pinch radius of the non-circular cross section, and f_p is a profile factor of order unity. From the power loss (2), the energy confinement time due to axial particle losses becomes

$$\tau_{EL} = \mu_o e f_p L J_p / 4\pi f_L k T_o \tag{4}$$

With the expression [2]

$$\theta_i = \left[\mu_o e / (8\pi^2 m_i k)^{1/2}\right] f_i J_p / \sqrt{T_o} \tag{5}$$

for the number of ion Larmor radii being contained within the pinch radius, and the profile factor f_i, the confinement time (4) can also be expressed as

$$\tau_{EL} \simeq (f_p/f_L f_i)(m_i/2kT_o)^{1/2}\theta_i L \quad (6)$$

The time τ_{EL} is therefore about θ_i times longer than the time of flight of an ion along the pinch length L. The value given by eq. (6) is maximal in the sense that it represents the longest possible confinement time which can be reached in presence of end losses.

2.2. The Ohmically Heated Pinch

When there are no extra heat sources, the power loss P_L and all other losses have to be balanced by the ohmic heating power

$$P_\eta = f_\eta k_\eta J_p^2 L/\pi \bar{a}^2 T_o^{3/2} \quad (7)$$

where f_η is a profile factor of order unity and $k_\eta = 129(\ell n\Lambda) \simeq 1300\,[VmK^{3/2}/A]$. The heat balance can thus be represented by

$$P_\eta \geqslant P_L \quad (8)$$

where the equality sign represents the marginal case of dominating end losses due to the pinch current.

Combining relations (2), (7) and (8), we have

$$\bar{a} \leqslant \bar{a}_{max} = (2ef_\eta k_\eta LJ_p/5\pi f_L kT_o^{5/2})^{1/2} \quad (9)$$

Further, combination of relations (2), (7), (8) and (3) yields

$$n_o \geq n_{omin} = 25\mu_o f_p f_L T_o^{3/2} J_p / 48\pi e f_\eta k_\eta L \quad (10)$$

The marginal case $P_\eta = P_L$ thus represents a maximum value (9) of the pinch radius, and a minimum value (10) of the peak density. The physical reason for this is that the pinch radius has to be small enough for the current density to result in an ohmic heating power which becomes large enough at least to balance the end losses.

3. Examples

To illustrate the obtained results we choose a number of examples as shown in Table 1:

(i) In earlier performed experiments on finite pinch lengths L and without a magnetic field component along the pinch axis [3,4], the measured and estimated data lead to values of $\bar{a}/\bar{a}_{max}$ and n_{omin}/n_o being below unity by a substantial margin, as shown by the first two columns of Table 1. In these cases the power loss (2) due to end effects only becomes a small fraction of the total power loss.

(ii) In the planned next-step experiment Extrap-T2, a major radius $R = 0.9$ m has been assumed. In an equivalent linear experiment of the same length $L = 2\pi R = 5.6$ m, and with the same assumed data on $(T_o, J_p, n_o, \bar{a})$, the resulting values are shown in the third column of Table 1. This leads to a maximum available value $\tau_{EL} \simeq 390$ µs of the energy containment time, even this being too short to meet the goals of a planned experiment in which also slowly developing instabilities can be studied during pulse lengths of at least a few milliseconds. Further, and what becomes a more serious problem, the assumed and desired data on $(T_o, J_p, n_o, \bar{a})$ would get into conflict with the possible ranges of plasma density and pinch radius, as shown by the resulting inadequate values of $\bar{a}/\bar{a}_{max}$ and n_{omin}/n_o which by far exceed unity in an equivalent linear case.

(iii) For a linear reactor of a technically reasonable length $L \simeq 30$ m, and with values of $(T_o, J_p, n_o, \bar{a})$ in conventional ranges, the result becomes as indicated in the last column of Table 1. Here it is shown that the equivalent linear case yields far too short marginal (maximum) containment times τ_{EL} for a steady-state reactor operated within conventional parameter ranges. It leads to excessively small pinch radii and excessively high plasma densities (see also Ref. [2]). The range of small $\bar{a}$ and large n_o could on the other hand apply to the electrode-driven linear and dense Z-pinch [5]. However, the small linear dimensions of such a pinch system renders the introduction of external coils difficult, at least in the case of normally conducting windings.

4. Conclusions

The comparison between linear and toroidal Extrap systems can be summarized as follows:

- As compared to toroidal systems, linear geometry has the advantages of a relative simplicity and of a straight-forward current drive by means of an electrode system. Linear devices are convenient for basic studies of the Extrap concept at moderately high pinch currents and plasma temperatures for which the end losses become a minor fraction of the total power loss.

- Within the parameter ranges of larger experiments at higher pinch currents and plasma temperatures, and under reactor conditions, linear systems have on the other hand some substantial disadvantages as compared to toroidal systems, on account of the plasma interaction with the end regions and electrodes, and the resulting limitation of the energy confinement. For an ohmically heated plasma this leads to excessively high plasma densities and excessively small pinch radii which render the introduction of stabilizing external coils a difficult task. In addition, there arises a non-uniform temperature distribution along the pinch axis in linear geometry [2], and there is a strong plasma-electrode interacton which leads to impurity release. The electrode-driven current also yields a substantial contribution to the recirculating power in the case of a reactor.

- In cases where an axial magnetic field component has to be introduced in linear geometry, the axial heat losses will increase beyond those estimated from eq. (2), whereas such a component does not have a corresponding effect in closed toroidal geometry.

- Auxiliary heating, and other types of additional heat sources, could modify some of the present results, but a corresponding analysis is outside the frame of this paper.

Consequently, there are several arguments for toroidal geometry to be preferred to linear geometry, both in the case of a full-scale reactor and when performing experiments with hot plasmas at high pinch currents, such as in the planned next-step device Extrap-T2.

5. References

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Table 1. Examples on the experiments with devices Extrap-LO and Extrap-TO, on a linear configuration being equivalent to the planned toroidal device Extrap-T2, and on an Extrap reactor based on linear geometry. In all these examples there is no axial magnetic field component. In Extrap-LO and Extrap-TO the values of T_o, J_p, n_o and L have been measured or estimated. All profile factors f_L, f_p, f_i and f_η have been put equal to unity. Figures within brackets represent assumed "conventional" data in toroidal models, leading to inadequate parameter values in the equivalent linear cases.

Parameters	Extrap-LO	Extrap-TO	Extrap-T2 (eq.linear case)	Extrap Reactor (eq.linear case)
T_o(K)	10^5	$7x10^4$	$5x10^6$	$3x10^8$
J_p(kA)	9	9	300	7300
n_o(m^{-3})	$2x10^{22}$	$2x10^{22}$	(10^{21})	($1.5x10^{20}$)
L (m)	0.20	0.42	5.6	30
θ_i	4.2	5.0	20	40
τ_{EL}(μs)	21	62	390	539
$\bar{a}$ (m)	$8.8x10^{-3}$	$11x10^{-3}$	(0.185)	(1.5)
$\bar{a}_{max}$ (m)	$3.9x10^{-2}$	$8.8x10^{-2}$	$8.9x10^{-3}$	$6.1x10^{-4}$
$\bar{a}/\bar{a}_{max}$	0.23	0.125	(21)	($4.45x10^3$)
n_{omin}(m^{-3})	$1.4x10^{21}$	$4.0x10^{20}$	$6.0x10^{23}$	$1.3x10^{27}$
n_{omin}/n_o	0.07	0.02	(600)	($8.7x10^6$)

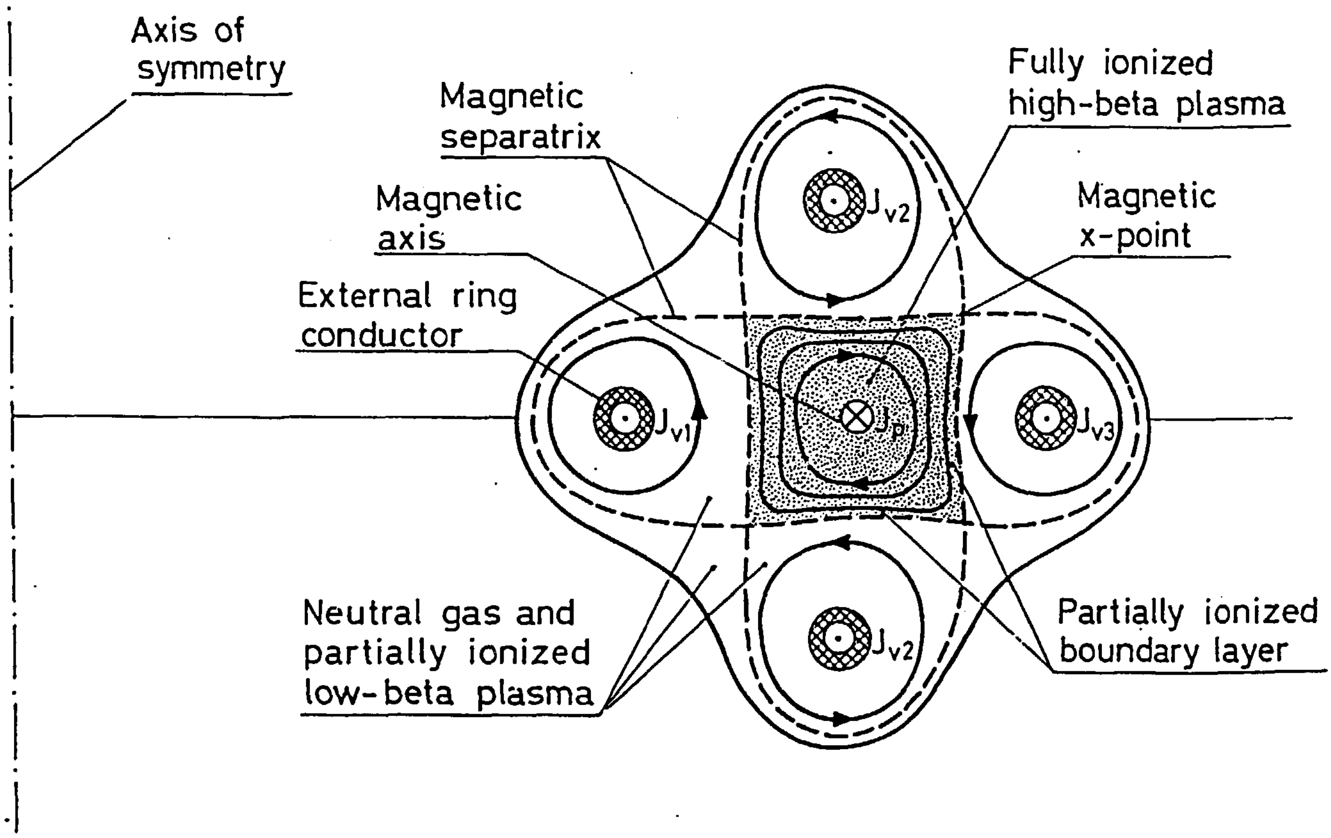

Fig.1. Outline of a toroidal Extrap (External Ring Trap) configuration showing an earlier proposed special case of four external ring conductors. The latter carry currents which are antiparallel to the pinch current which flows in the fully ionized high-beta plasma. There are four magnetic x-points at a common separatrix. The shape of the non-circular plasma cross section depends on the current profile. The figure shows a fully ionized plasma bounded by a thin partially ionized boundary layer which extends from the magnetic separatrix towards the plasma interior. In the volume outside of this layer there is neutral gas and a partially ionized low-beta plasma. The geometry represented by the figure gives one example of a class of possible Extrap configrations. Geometries with other numbers, positions and current directions in the ring conductors also belong to this class. A weak toroidal magnetic field can be superimposed along the pinch axis.

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Key words: Plasma confinement, linear and toroidal geometry.