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EFFECTS OF BOUNDARY CONDITIONS ON TEMPERATURE AND DENSITY IN AN EXTRAP Z-PINCH

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ABSTRACT

Using the fluid equations, we examine transport in an Extrap configuration by carrying out calculations incorporating model profiles for the density and temperature. The goal of this analysis is to examine the scaling of the pinch equilibrium plasma density, temperature and radius with parameters that are characteristic for Extrap Z-pinches. These parameters include the discharge current, the neutral hydrogen filling density, an oxygen impurity fractional concentration and the conditions at the pinch boundary. An Extrap Z-pinch is a pinch discharge where the current channel has a characteristic non-circular cross-section achieved by bounding the discharge by a magnetic separatrix produced when a vacuum octupole magnetic field, generated by currents in external conductors, combines with the self-magnetic field produced by the discharge current. The pinch boundary is changed from a plasma-vacuum boundary to an interface between a high-beta pinch plasma and a low-beta plasma contained in the vacuum magnetic field. The energy that is lost from the pinch region sustains this boundary layer. The introduction of a separatrix boundary around the pinch with four X-point nulls deteriorates the containment of the pinch somewhat. However the presence of the warm,low-beta plasma scrape-off layer, which provides a boundary condition on the pinch, tends to counteract the negative effects of the poorer confinement. Thus the equilibrium parameters that characterize the pinch may not be severely deteriorated by the introduction of the separatrix when the entire configuration, including the scrape-off layer, is considered.

1. INTRODUCTION

An Extrap Z-pinch is a pinch discharge where the current channel has a characteristic non-circular cross-section.[1-3] The cross-section deformation is achieved by bounding the discharge by a magnetic separatrix produced when a vacuum,octupole magnetic field, generated by currents in external conductors, combines with the self-magnetic field produced by the discharge current. The separatrix acts as a magnetic limiter which both deforms the cross-section and alters the equilibrium pressure profile in a manner which improves the stability of the configuration.[4-6] In a linear configuration, schematically represented in Fig.1, the octupole field is produced by currents in four parallel rod conductors and has a magnetic null on the Z-axis. The axis of the plasma discharges coincides with the Z-axis and the plasma current is antiparallel to the rod currents. The discharge current together with the rod currents produce a magnetic field with a separatrix with four X-point nulls. There is also an O-point null on the axis. The high-beta,Z-pinch discharge is contained in the rod-free region inside the four X-points. This separatrix boundary affects the pinch equilibrium in a manner which has a significant stabilizing influence. In linear Extrap experiments it has been shown that pinch equilibria exhibiting Bennett scaling can be sustained for up to 100 Alfvén times.[2,3]

In this paper, we examine transport in the Extrap configuration by carrying out fluid equation calculations incorporating model profiles for the density and temperature. In this analysis, we examine the scaling of the pinch equilibrium plasma density, temperature and radius with parameters that are characteristic for Extrap Z-pinches. These parameters include the discharge current, the neutral hydrogen filling density and an oxygen impurity fractional concentration. In addition, the characteristic gradient scale lengths and boundary values used for the model profiles are selected to simulate the modifications in the transport brought about by the presence of the octupole field. The magnetic nulls at the four X-points on the boundary of the pinch introduce strong transport effects in both the particle and energy balances. The most notable effect is that the pinch boundary is changed from a plasma-vacuum boundary to an interface between a high-beta pinch plasma and a low-beta plasma contained in a vacuum magnetic field region which can have average minimum-B stability. This low-beta region is similar to the scrape-off layer outside a magnetic separatrix.[4] The plasma transport in this low-beta layer establishes the boundary conditions for the pinch discharge. These conditions are significantly different from what is normally considered for a sharp-boundary pinch where a plasma-vacuum interface is assumed. The most significant effect observed in the transport calculations is a strong pinch temperature and density dependence on pinch boundary temperature. Both the temperature and density increase somewhat faster than linearly with increasing values of the temperature at the separatrix boundary.

2. DESCRIPTION OF THE DIFFERENT TRANSPORT REGIONS

The high beta pinch discharge is bounded by a low beta scrape-off region where the vacuum magnetic field produced by the currents in the rod conductors is predominant. In Fig.2 we show a schematic diagram of one quadrant of the cross-section of an Extrap discharge where qualitative features of the plasma flow are indicated by arrows. As discussed by Tendler,[5] the character of the transport is different in the different regions of the discharge. In our discussion we consider four different regions which are summarized as follows:

I) O-point region; Near the Z-axis, the magnetic field is weak, and the pressure profile is essentially constant.

II) Magnetized plasma; Outside the O-point region, there is a layer which is a few ion gyroradii thick where the plasma is magnetized. The plasma diffusion flux, $\underline{\Gamma}$, is predominantly perpendicular to the magnetic field in this region, and the contribution to the magnetic field from the vacuum octupole field is small, and the field lines are nearly circular.

III) X-point region; The outer magnetic flux surfaces of the discharge region bounded by the separatrix on the outside, are dominated by the X-points, and the pressure profile is again essentially flat. Near the separatrix, but still in the discharge region, the deformation caused by the vacuum field becomes significant, and the field strength is modulated as a function of poloidal position along the field lines. The cross-field transport becomes dependent on poloidal position, and for most diffusion models the transport would be expected to be largest in the weak field regions near the X-points. Parallel transport along the field lines is necessary to compensate for the poloidal dependence of the cross-field transport. The associated parallel gradients are however small so the pressure along field lines can still be considered constant.

IV) Scrape-off layer; The separatrix field line and the field lines outside the separatrix are open in the sense that they pass into a region where they can intersect supports. The plasma that leaves the pinch discharge region through parallel flow along the separatrix enters the low-beta plasma region where the plasma is contained by the vacuum field. Here there are particle losses due to mass flow to the supports which act as neutralizing surfaces, as well as the associated convective losses of energy due to this mass flow. In addition there are thermal conductive losses to the supports,as well as radiation losses from the volume.

It is apparent that a complete analysis of transport in an Extrap configuration must include all of these regions with their different transport mechanisms. In Fig.3, we show a schematic diagram of the plasma pressure profile where these four regions are indicated. The transport balance in the low-beta,scrape-off region must be considered in a self-consistent fashion with the pinch region itself in order to completely describe the transport in Extrap Z-pinch discharges. The balance in the scrape-off layer includes the plasma parameters at the separatrix boundary which is the interface between the pinch region and the scrape-off layer. These parameters then constitute the boundary conditions for transport in the pinch region. In a first attempt to study the transport in Extrap, we examine the regions inside the scrape-off layer and we specify boundary values for the plasma density and temperature at the separatrix boundary. We select appropriate values for the plasma parameters at this boundary by looking at simple global particle and energy balances in the low-beta, scrape-off layer.

3. EQUILIBRIUM CALCULATIONS IN THE PINCH

In order to obtain equilibrium values for the plasma parameters, the volume-integrated, stationary,particle, momentum and energy fluid balance equations are solved self consistently. The solutions give the equilibrium parameters, n_0 (density), T_0 (temperature),and a_p (pinch radius). We do not solve the spatially dependent problem. Model profiles for the density and the temperature are assumed and these profiles are used to calculate the volume-averaged terms in the set of balance equations. Neutral hydrogen effects are included,and in addition a fractional concentration of oxygen can be included to simulate the effects of impurities. The spatial dependence of the neutral hydrogen penetration is calculated for the model profiles. This means that the associated particle and energy source and sink terms, when spatially integrated and incorporated in the balance equations, are dependent on the conditions at the pinch boundary. It is important to include a dependence on the boundary parameters in this way when studying the equilibrium parameters for these pinches which are impermeable to neutral penetration. The significance of treating the boundary in this fashion is apparent from the observed strong dependence of the core parameters on the boundary parameters. The model profiles are incorporated so that the various scale lengths and profile shape factors, particularly those involving neutrals, that are used in the set of zero-dimensional balance equations can be readily evaluated in a self-consistent fashion including a density, temperature, and pinch radius dependence.

A cylindrical coordinate system is used and the model profiles are dependent only on the radius r. The model profiles have the following form:

$$n(r) = \begin{cases} n_o & r < r_p \\ n_o(1 - r/a_p)/\rho & r > r_p \end{cases} \qquad (1)$$

$$T(r) = \begin{cases} T_o & r < r_p \\ T_a + (T_o - T_a)(1 - r/a_p)/\rho & r > r_p \end{cases} \qquad (2)$$

where a_p is the dependently varying equilibrium pinch radius and the input parameter ρ is the normalized thickness of the magnetized plasma layer (Region II) given by

$$\rho = (a_p - r_p)/a_p. \qquad (3)$$

The radius r_p is the characteristic radius of the central core region, which is Region I in Fig.3. This is the O-point-dominated, weak-field region where the pressure profile is flat. In the magnetized layer, $r_p < r < a_p$, the gradients dn/dr and dT/dr are constant but dependent on a_p. The code solves for a_p while self-consistently maintaining the transport calculations dependent on a_p.

In this model, the poloidal dependence of the magnetic field strength due to the contribution from the vacuum octupole field is not explicitly included. We have made this simplification for a number of reasons. First, the field lines in the magnetized layer are nearly circular. The strongest deformation appears in Region III where transport is dominated by the X-points and here the pressure gradient is again weak. For purposes of evaluating the transport, in our approach, Region III becomes the interface between the high-beta pinch and the low-beta, scrape-off layer.

A second reason can be seen if the model profiles are substituted into the equilibrium relation,

$$\nabla p = \underline{J} \times \underline{B}. \tag{4}$$

where $p = 2\ nkT$ is the plasma pressure, $\underline{J}$ is the current density and $\underline{B}$ is the total magnetic field including the octupole field contribution. Substitution gives

$$JB = -2k[n_0 T + (T_0 - T_a) n]/(a_p \rho) \tag{5}$$

In the code, the total plasma current is specified in addition to the n and T profiles which are specified by ρ. From Eqs. (4) and (5), we see that an increase in ρ, the normalized thicknesses of the magnetized layer, is equivalent to a decrease in pressure gradient and a corresponding increase in equilibrium pinch radius. In this representation, this decrease in pressure gradient models the deterioration of the confinement associated with the X-points produced by the octupole field.

We now turn to a discussion of the terms included in the equilibrium calculation.

3.1. Particle Balance

Integration of the equilibrium continuity equation gives the particle balance which has the form

$$[S_i] = [S_r] + 2\Gamma_a/a_p, \tag{6}$$

where S_i and S_r correspond to ionization and recombination terms and Γ_a represents the diffusion losses. The brackets indicate that the terms are volume-averaged values defined by

$$[f] = \int_0^{a_p} (2r/a_p^2) f \, dr. \tag{7}$$

The value Γ_a is defined by

$$\Gamma_a = [r\Gamma/a_p]. \tag{8}$$

The expressions for these terms that were used in the calculations are given in Table I. Here Γ has the classical form for diffusion perpendicular to the magnetic field. We point out that the value for Γ_a used in the particle balance is not the diffusive flux that would be arrived at by evaluating Γ at $r = a_p$ using the model profiles since the model profiles are not solutions to the spatially dependent equations. The value for Γ_a is a characteristic value for the magnetized layer arrived at by taking a volume average as given by Eq. (8).

3.2. Momentum Balance

The momentum transfer equation together with Ampère's law give the Bennett relation when integrated over the pinch cross-section. This relation has the form

$$I_p^2 = (32\ {}^2/\mu_0)\int_0^{a_p} r\ n\ kT\ dr, \tag{9}$$

where I_p is the total pinch current. Inserting the model profiles gives the following relation

$$I_p^2 = (\ ,T_a,T_0)n_0T_0a_p^2 \tag{10}$$

where is a known factor which depends on the parameters determining the pressure profile shape. By using the model profile technique for evaluating such shape factors, self-consistency is maintained.

3.3. Energy Balance

Integration of the energy transfer equation gives the power balance equation which has the form

$$[P_0] = [P_X] + [P_I] + 2Q_i/a_p + 2Q_e/a_p + 2Q_v/a_p. \tag{11}$$

The power input, P_0, is due to Ohmic heating. The volume power loss terms are respectively hydrogen radiation and impurity radiation. The terms at the boundary (the Q-terms) correspond respectively to ion thermal conduction, electron thermal conduction, and convective enthalpy loss across the boundary due to the plasma mass flow. These terms are defined by expressions of the form

$$Q = [r\ q/a_p], \tag{12}$$

where q represents a heat flux. In Table II we present the expressions that were used in the equilibrium calculations. Note that the forms that were used for the electron and ion thermal conduction terms include the dependence on the ratio between the collision frequency and the gyrofrequency as derived by Braginski.[8] Therefore both electron and ion conduction terms are considered. The form for Z-effective used in the equilibrium calculations includes a temperature dependence.

In order to include the effects of impurity radiation, we assume that oxygen is present in a concentration equal to a fraction of the electron density. The spatially dependent radiation energy loss is first calculated for the given density and temperature profiles and then integrated to give the volume-averaged terms used in the balance equation. Since the radiation is strongly dependent on temperature, it is important to proceed in this fashion in order to properly include the low temperature boundary region when estimating the radiation energy losses.

The synchrotron and bremsstrahlung radiation losses were also included in the calculation but their contribution to the energy balance was negligible and the terms are not included in this discussion.

3.4. Neutral Penetration

To properly calculate the particle and energy balance terms that involve the neutral density (n_H), the neutral pressure profiles must be calculated. In the density and temperature range of the extrap experiments, the plasma is impermeable to neutral penetration.[9] The neutral pressure profile is calculated from the relationship

$$dp_H/dr = m_i \xi_{iH}(n_H + n)\Gamma \tag{13}$$

where p_H is the neutral pressure, m_i is the proton mass and ξ_{iH} is the ion-hydrogen reaction rate which is dominated by resonant charge exchange collisions in this parameter range. For the model profiles used in the equilibrium calculations, Eq. (13) can be solved to give the neutral pressure profile in terms of the neutral-H filling density and the model profile parameters.[10] Because the charge exchange reaction rate is large, the

the neutral temperature is taken as equal to the plasma temperature.

3.5. Structure of the Code

A code has been developed to solve the three balance equations self-consistently for the equilibrium parameters n_o, T_o and a_p. The necessary input parameters are as follows:

I_p ;	total plasma current.
n_H ;	neutral-H filling density.
f_z ;	Oxygen impurity fractional concentration.
T_a ;	temperature at the boundary.
ρ ;	relative thickness of region where $dp/dr \neq 0$

The details of the code are discussed in Reference 11.

4. MODEL IN THE LOW-BETA SCRAPE-OFF PLASMA REGION

The high-beta pinch is bounded by the separatrix which functions somewhat like a magnetic limiter. The plasma that leaves the pinch discharge region through parallel flow along the separatrix enters the low-beta, scrape-off layer plasma region where the plasma is contained by the vacuum field. In this layer, there are particle losses due to mass flow to the supports which act as neutralizing surfaces. In addition there is energy transport from the pinch region into this low-beta layer both through thermal conduction and through energy transport associated with the convective mass flow. In turn there is energy transport from the low-beta layer through thermal conduction to the supports, convection to the supports,and radiation from the volume.

The scrape-off layer is important because the particle and energy balances in this layer determine the boundary conditions for the pinch discharge. A complete solution of the transport problem in the Extrap configuration would require a three-dimensional analysis of the scrape-off layer region as well as the analysis of the pinch region. The transport parameters would then be matched at the separatrix boundary to the pinch region. We do not attempt such a solution here. Our purpose is to determine how the pinch equilibrium parameters are affected by changes in the boundary conditions of a type that would be expected for the Extrap configuration. We therefore simplify the analysis of transport in the scrape-off layer in order to arrive at relevant boundary values to be used in the model profiles presented in Sec. 3.

We shall see that the pinch boundary temperature is the parameter which has the largest influence on the equilibrium pinch parameters. In order to estimate an appropriate range of values for T_a that can be used in our calculations, we adopt a simple model for the energy balance in the scrape-off layer. The total power input into the scrape-off layer is assumed equal to the Ohmic power; this implies that radiation losses from the pinch region are not the dominant losses. This power input can then be equated with power losses in the scrape-off layer due to electron thermal conduction to the supports, convection to the supports,and radiation. These calculations depend on the geometry of the configuration and mechanical features of the supports so only rough estimates can be made; we have used mechanical parameters corresponding to the linear experiments described in Reference 2 in our calculations. The calculations indicate that boundary temperatures in the range 0.5 eV to 2 eV are appropriate for the equilibrium calculations.

5. RESULTS OF EQUILIBRIUM CALCULATIONS

Our goal is to determine the scaling of the plasma pinch parameters n_o, T_o and a_p with the various input parameters. These input parameters are of two types. First we have the externally determined experimental parameters; n_H, I_p, and f_z. Second, we have the parameters associated with the boundary conditions which appear in the expressions for the density and temperature profiles; ρ and T_a. The scaling dependence on the experimental parameters is examined first; for these studies the boundary parameters are held constant. We then proceed to examine the scaling dependence on the boundary parameters with fixed experimental parameters. In Table III, a summary of the parameters used in the various studies is presented.

For the studies of scaling dependence on the experimental parameters, the boundary parameters are fixed. We have selected a boundary temperature of $T_a = 2$ eV and normalized magnetized layer thickness of $\rho = 0.7$. We first show the dependence of n_o, T_o and a_p on the total plasma current in Fig.4. We see that T_o is essentially constant while n_o and a_p both increase with increasing values of I_p. The fact that the temperature is essentially constant can be explained when the distribution of the energy losses between the various loss channels is examined. The dominant energy loss channel is ion thermal conduction. A balance between Ohmic heating input and ion thermal conduction losses gives no scaling dependence between T_o and I_p when the Bennett relation is incorporated. The temperature is essentially determined by the coefficients for the various processes and is therefore constant if the dominant loss mechanism is not changed. We point out that the Bennett relation given in Eq. (9) is of course satisfied for the equilibria values shown in Fig.4.

We now turn to the dependence of the plasma parameters on the filling pressure. The dependence of n_o, T_o and a_p on n_H is shown in Fig.5. The temperature is weakly dependent on the variable parameter, but the density shows a stronger dependence. Lehnert has discussed the scaling laws for an impermeable, fully-ionized plasma surrounded by a partially ionized cold-gas mantle.[8,15] This scaling has the form

$$n_o \propto n_H^{1/3} B^{2/3} \qquad (14)$$

and follows directly from the balance between the radially-outward,diffusive plasma flux and the radially-inward flux of neutral particles. If the Benenett relation and Maxwell's Equations are incorporated to eliminate B from Eq. (14), one obtains

$$n_o \propto n_H^{1/2} T^{3/4} . \tag{15}$$

The observed scaling for density with temperature and filling density shown in Fig.5 is consistent with these scaling laws for impermeable plasmas.

The dependence of n_o, T_o and a_p on the fractional concentration of an oxygen impurity is shown in Fig.6. An increase of f_z above 0.005 leads to sharp decreases in n_o and T_o while a_p increases. The distribution of energy losses between the various channels is shown in Fig.7 and from this figure it is clear that the decrease in T_o is due to an increase in the energy losses through oxygen radiation. For the parameters discussed here, the oxygen impurity level must be held below about 1% in order to assure low oxygen radiation losses.

We now turn to a discussion of the dependence of the plasma parameters on the boundary parameters. For these studies, we hold the experimental parameters fixed at the standard values; $n_H = 5 \times 10^{21}\ m^{-3}$, $I_p = 50$ kA, and $f_z = 0.005$. The dependence of n_o, T_o and a_p on the profile parameter ρ is shown in Fig.8, and the corresponding contribution of energy losses between the various loss channels is shown in Fig.9. Larger values of ρ correspond to weaker profile gradients in the magnetized plasma layer. These weaker gradients simulate, in the model profiles, an effective deterioration in the confinement due to the octupole field contribution. In Fig.8, we see that the temperature decreases with increasing values of ρ while the density remains nearly constant and the radius increases.

Finally, we present the equilibrium values for n_o, T_o and a_p versus the boundary temperature T_a in Fig 10 and the distribution of energy losses in Fig. 11. Here we see a strong dependence for the equilibrium parameters. Higher edge temperatures lead to significantly higher plasma pressures and, in keeping with the Bennett relation requirement, smaller pinch radii. Furthermore, the relative importance of impurity radiation decreases with increasing values of edge temperature.

6. DISCUSSION

Equilibrium values for the pinch density, temperature, and radius have been calculated self-consistently using the fluid balance equations for the particles, momentum, and energy, together with Ampère's law. Model profiles for the density and temperature have been used to carry out the calculations, but these profiles were dependent on the dependently varying pinch radius. The spatial dependence of the neutral penetration at the boundary to the impermeable dense pinch region has been included in the calculations so that the particle and energy, source and sink terms that were dependent on the neutral density could be correctly estimated. The effects of impurities have been included by considering oxygen line radiation assuming a fractional concentration of oxygen. In the studies, we have examined the scaling of the equilibrium parameters versus experimental parameters as well as the dependence of the parameters on the model profile shape. In these latter studies, an attempt has been made to simulate the effects that the bounding separatrix introduce in the transport equations through the model profile shape parameters.

First, we have studied the scaling of equilibrium plasma parameters with the experimental parameters; discharge current, hydrogen filling density and oxygen concentration. We find that the temperature is quite independent of both the discharge current and the filling density in this range of parameters where the major energy transport process is ion thermal conduction; a balance between Ohmic heating input and conduction losses gives no scaling dependence between T_0 and I_p. The temperature is essentially determined by the coefficients for the various processes and is therefore constant if the dominant loss mechanism is not changed. However the density and pinch radius both increase with increasing values of discharge current and the Bennett relation in the form $I_p^2 \sim nTa_p^2$ is of course satisfied. When the discharge current is fixed, the density increases with increasing values of the filling density as expected in this parameter regime for an impermeable plasma surrounded by a cold gas mantle. The radius decreases again satisfying the requirements of the Bennett relation.

Second, we have studied the dependence of the plasma parameters on the model profile parameters, the thickness of the magnetized plasma region and the boundary temperature. Increasing the thickness of the magnetized layer is equivalent to a deterioration of the confinement which simulates the effects of the vacuum octupole field. Such an increase in thickness gives an increase in pinch radius and a decrease in the core pinch temperature. This trend is consistent with what would be expected for an Extrap configuration where the pinch is bounded by a separatrix with four X-point magnetic nulls. The gradient scale lengths are increased as the containment is made less effective. This implies that a price is paid for the stabilizing effects of bounding the pinch by a separatrix in the form of poorer confinement. However we see that the pinch temperature and density are also strong functions of the boundary temperature; both increase with increasing values of boundary temperature. This tends to counteract the negative effects of the separatrix boundary described above. Introduction of the separatrix leads to a low-beta scrape-off layer which serves as a warm plasma boundary for the pinch where the temperature is a few electron volts. The energy that is lost from the pinch region sustains this boundary layer. Thus the equilibrium parameters that characterize the pinch may not be severely deteriorated by the introduction of the separatrix when the entire configuration, including the scrape-off layer, is considered.

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Table I. Summary of Particle Balance.

Description	Scaling	Reference
S_i (ionization)	$n\, n_H \xi(T)$	ξ; Ref. 12
S_r (recombination)	$n^2 \alpha(n,T)$	α; Ref. 13
Γ (classical diffusion)	$n \eta(T)(dp/dr)B^{-2}$	η; Ref. 8

Table II. Summary of the Energy Balance

Description	Scaling	Reference
P_0 (Ohmic heating)	$J^2\eta(T,Z_{eff})$	η; Ref. 8 Z_{eff}; Ref. 13
P_x (H radiation)	$n\ n_H R(T)$	R; Ref. 14
P_I (impurity radiation)	$f_z n^2 R_z(T)$	R_z; Ref. 13 f_z; impurity fraction
q_i (ion conduction)	$\lambda_i(n,T,B)(dT/dr)$	λ_i; Ref. 8
q_e (electron conduction)	$\lambda_e(n,T,B)(dT/dr)$	λ_e; Ref. 8
q_v (convection)	$(2.5kT + \phi)\Gamma$	ϕ = ionization potential

Tabell III. Summary of parameters used in the scaling studies.

Parameters					Figure
I_p kA	n_H (m^{-3})	f_z (O fraction)	ρ (thickness)	T_a (eV)	
var.	5×10^{21}	0.005	0.7	2	4
50	var.	0.005	0.7	2	5
50	5×10^{21}	var.	0.7	2	6,7
50	5×10^{21}	0.005	var.	2	8,9
50	5×10^{21}	0.005	0.7	var.	10,11

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FIGURE CAPTIONS

Fig.1. A linear Extrap-Z pinch configuration is produced when a Z-pinch is generated along the axis of a vacuum octupole magnetic field produced by currents in four rod conductors. The self-field of the discharge together with the octupole field give a configuration where the pinch discharge region is surrounded by a separatrix field line defined by four X-point field nulls. The high-beta pinch is located inside the region defined by the nulls and a low-beta plasma, contained by the vacuum field, is located outside this region.

Fig.2. Schematic representation of a quadrant of the Extrap cross-section qualitatively showing the flow of the plasma from the pinch region to the low-beta,scrape-off layer. The dominant flow into the scrape-off layer is parallel to the magnetic field. Conductor supports in the low-beta layer act as neutralizing surfaces for diffusive mass flow.

Fig.3. The pressure profile has four characteristic regions: I) O-point dominated weak-field region where the pressure is constant. II) magnetized layer. III) X-point dominated region where the gradients are small. IV) low-beta,scrape-off layer where the transport is three dimensional due to the presence of discrete supports.

Fig.4. Scaling of the equilibrium,core plasma parameters versus the discharge current.

Fig.5. Scaling of the equilibrium,core plasma parameters versus the filling pressure.

Fig.6. Scaling of the equilibrium,core plasma parameters versus the fractional concentration of an oxygen impurity.

Fig.7. Distribution of the energy losses between the various channels versus the fractional concentration of an oxygen impurity. The energy loss channels that are considered are ion and electron conduction, convection, and hydrogen and oxygen radiation.

Fig.8. Scaling of the equilibrium,core plasma parameters versus the normalized thickness of the magnetized layer.

Fig.9. Distribution of the energy losses between the various channels versus the normalized thickness of the magnetized layer.

Fig.10. Scaling of the equilibrium,core plasma parameters versus the temperature at the edge of the pinch.

Fig.11. Distribution of the energy losses between the various channels versus the temperature at the edge of the pinch.

Fig. 1

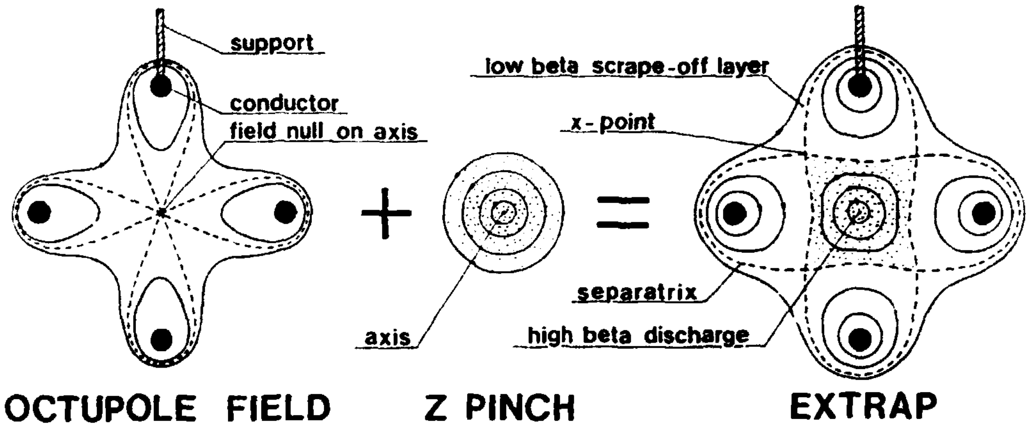

support
conductor
field null on axis
low beta scrape-off layer
x-point
axis
separatrix
high beta discharge
OCTUPOLE FIELD
Z PINCH
EXTRAP

Fig. 2

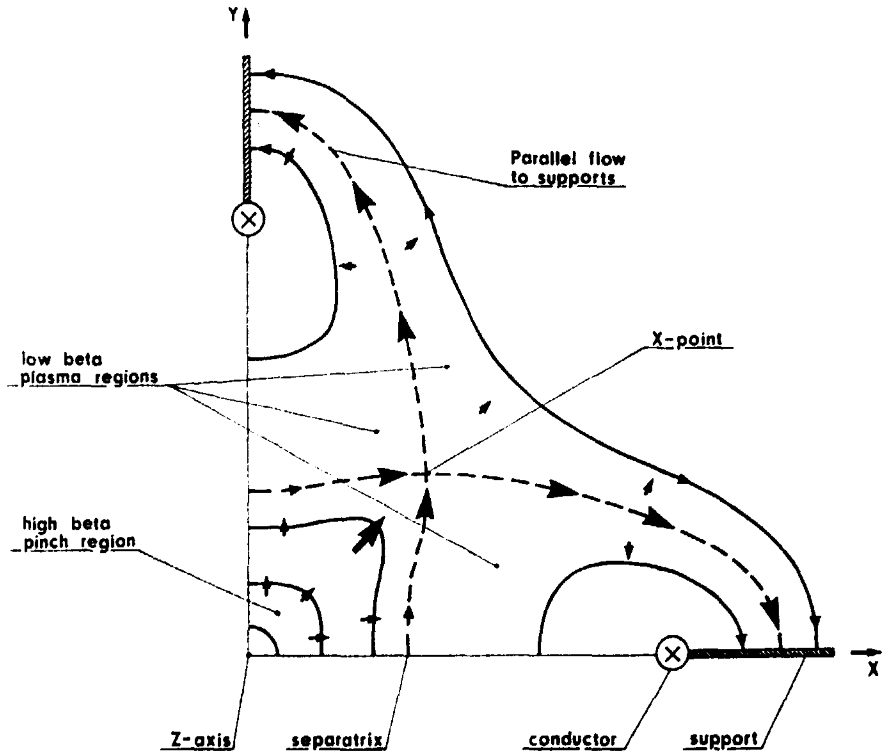

Y
X
Parallel flow to supports
X-point
low beta plasma regions
high beta pinch region
Z-axis
separatrix
conductor
support

Fig. 3

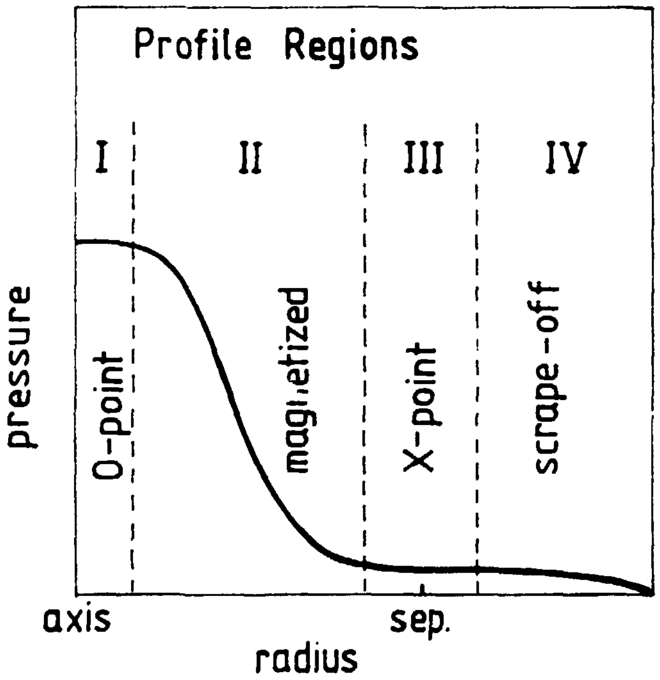

Profile Regions
I
II
III
IV
O-point
magnetized
X-point
scrape-off
pressure
axis
sep.
radius

Fig. 4

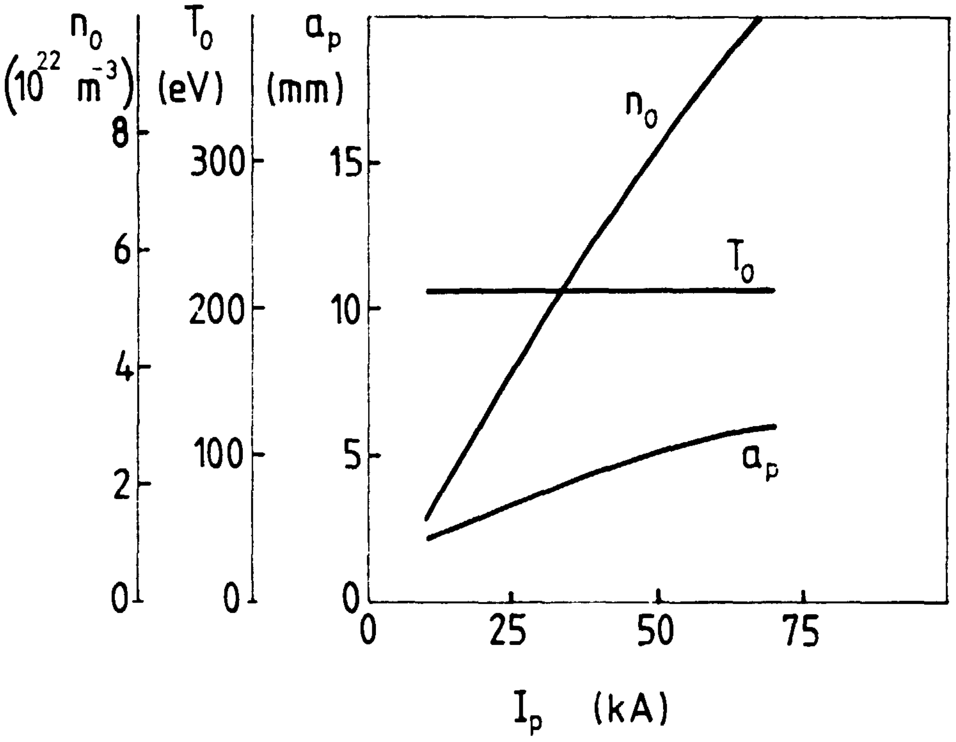
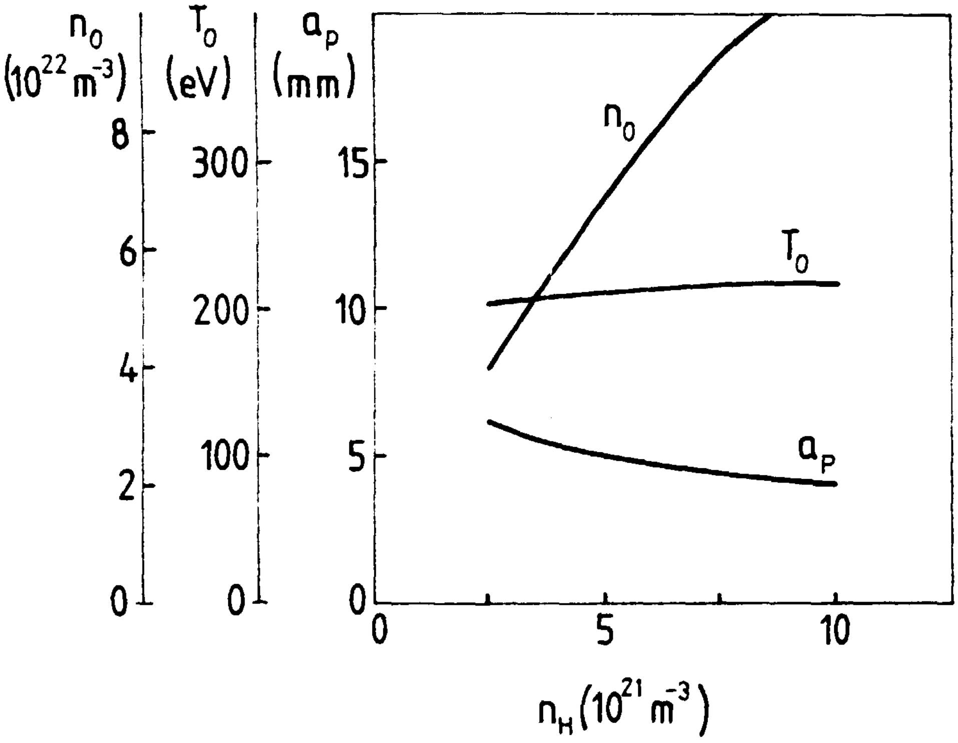
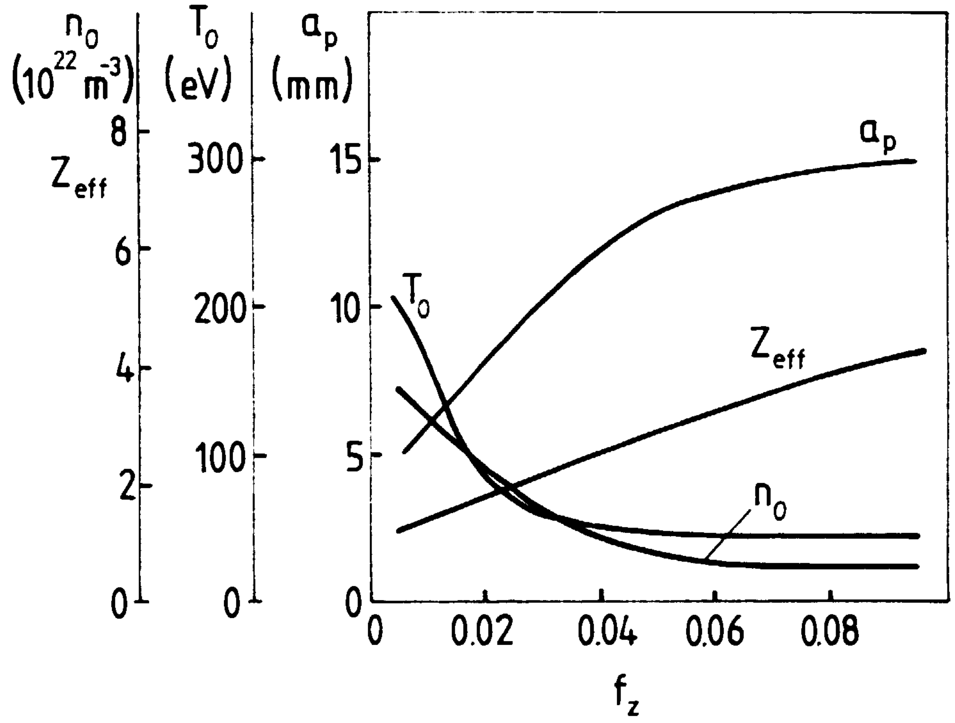

n_0
$(10^{22}$ $m^{-3})$
T_0
(eV)
a_p
(mm)
8
6
4
2
0
300
200
100
0
15
10
5
0
n_0
T_0
a_p
0
25
50
75
I_p (kA)

Fig. 5



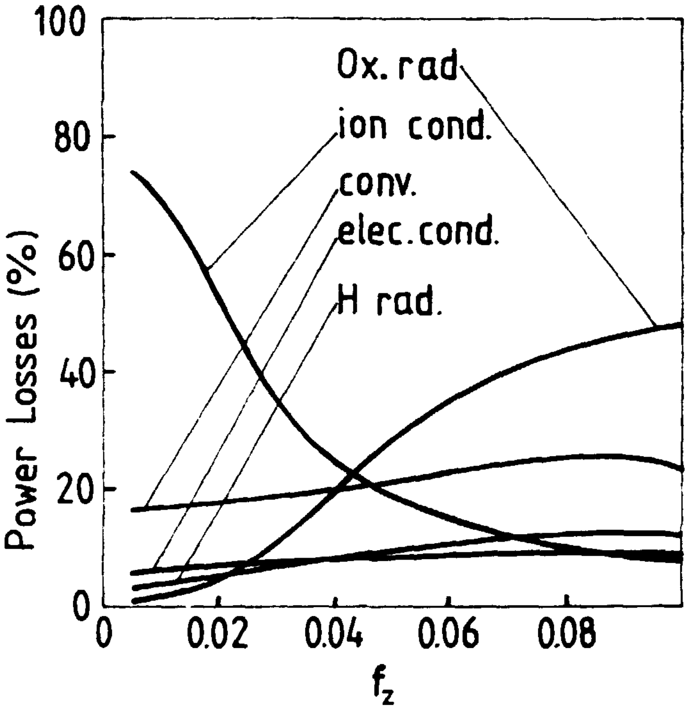
n_0
$(10^{22}\,m^{-3})$
T_0
(eV)
a_p
(mm)
8
6
4
2
0
300
200
100
0
15
10
5
0
n_0
T_0
a_p
0
5
10
$n_H\,(10^{21}\,m^{-3})$

Fig. 6



n_0
$(10^{22}\,m^{-3})$
Z_{eff}
T_0
(eV)
a_p
(mm)
0
2
4
6
8
0
100
200
300
0
5
10
15
0
0.02
0.04
0.06
0.08
f_z
a_p
T_0
Z_{eff}
n_0

Fig. 7


Power Losses (%)
100
80
60
40
20
0
0
0.02
0.04
0.06
0.08
f_z
Ox. rad
ion cond.
conv.
elec. cond.
H rad.

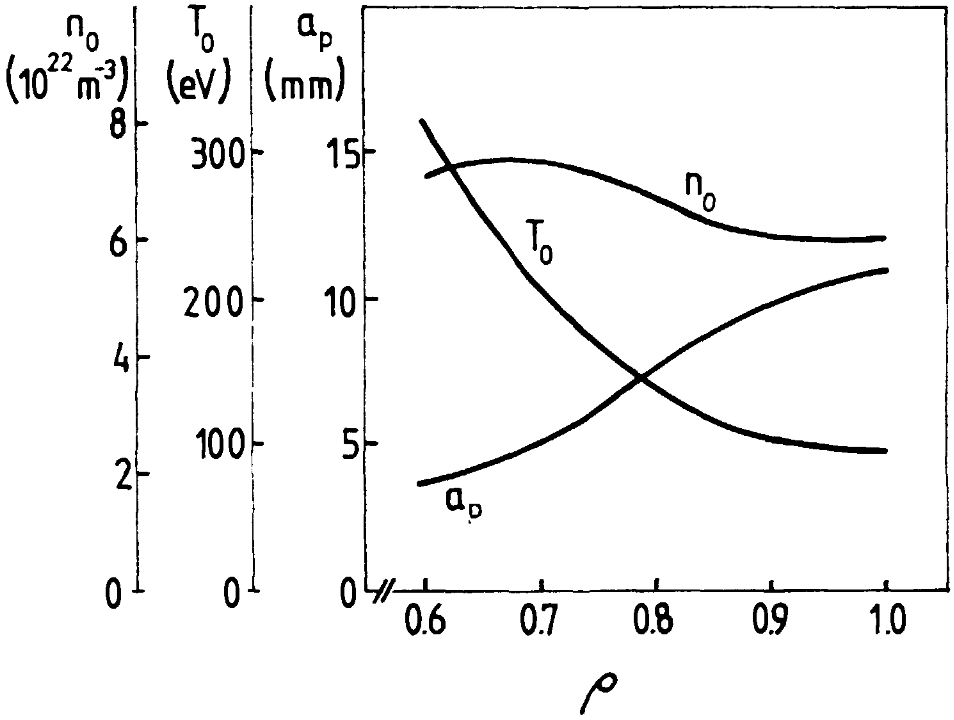
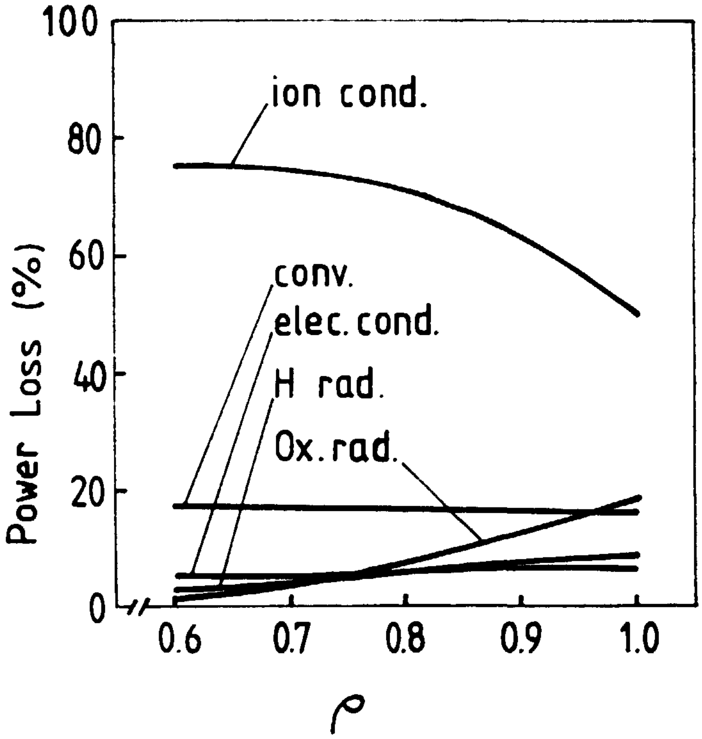
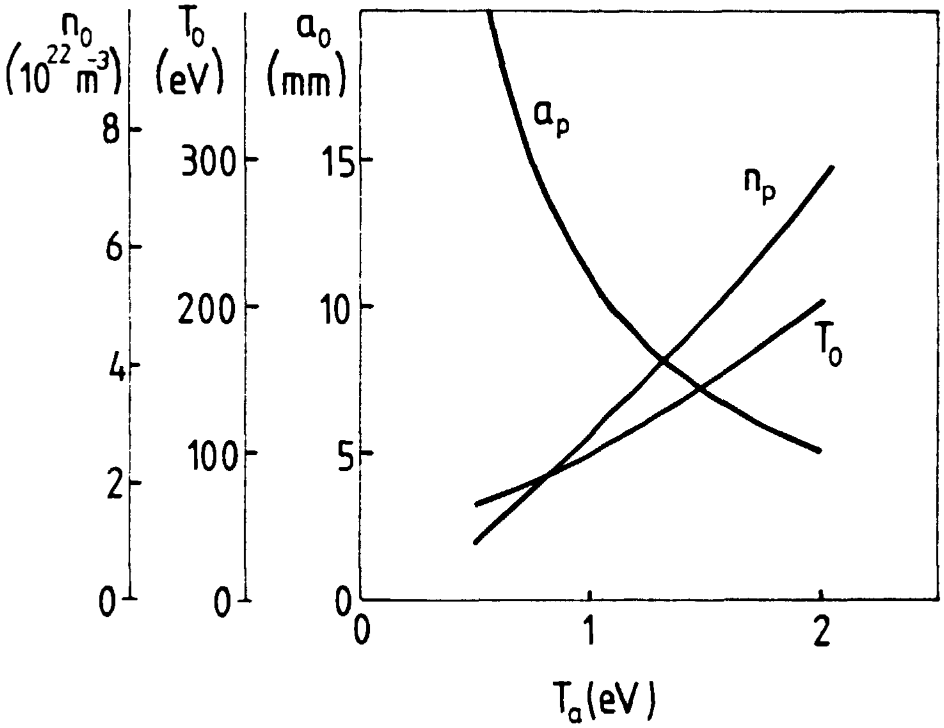

n_0 (10^{22} m^{-3})
T_0 (eV)
a_p (mm)
0
2
4
6
8
0
100
200
300
0
5
10
15
0.6
0.7
0.8
0.9
1.0
ρ
n_0
T_0
a_p

Fig. 9



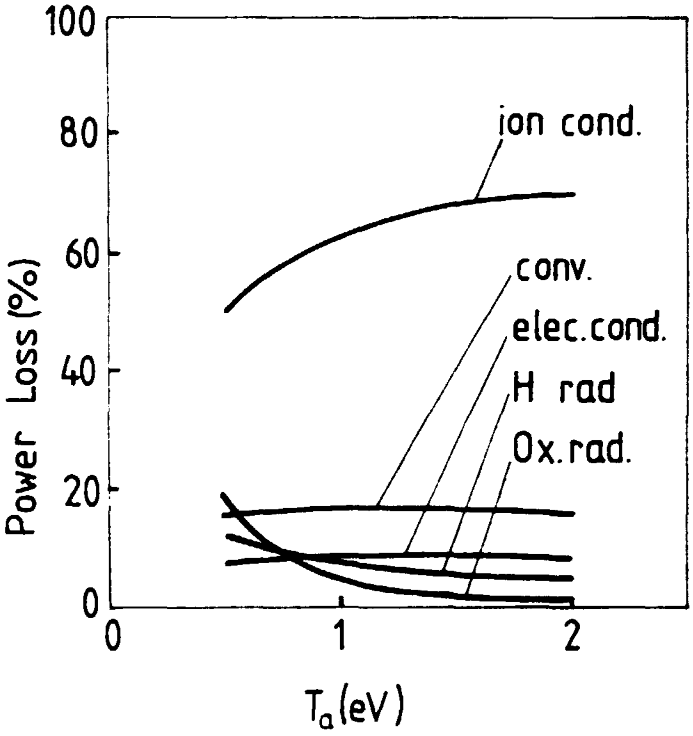
100
80
60
40
20
0
Power Loss (%)
ion cond.
conv.
elec. cond.
H rad.
Ox. rad.
0.6
0.7
0.8
0.9
1.0
ρ

Fig. 10



n_0 $(10^{22}\,m^{-3})$
0
2
4
6
8
T_0 (eV)
0
100
200
300
a_0 (mm)
0
5
10
15
a_p
n_p
T_0
0
1
2
T_a(eV)

Fig. 11



ion cond.
conv.
elec.cond.
H rad
Ox.rad.
Power Loss (%)
0
20
40
60
80
100
0
1
2
T_a(eV)

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EFFECTS OF BOUNDARY CONDITIONS ON TEMPERATURE AND DENSITY IN AN EXTRAP Z-PINCH

J.R. Drake and P. Karlsson, August 1985, 23 p. in English

Using the fluid equations, we examine transport in an Extrap configuration by carrying out calculations incorporating model profiles for the density and temperature. The goal of this analysis is to examine the scaling of the pinch equilibrium plasma density, temperature and radius with parameters that are characteristic for Extrap Z-pinches. These parameters include the discharge current, the neutral hydrogen filling density, an oxygen impurity fractional concentration and the conditions at the pinch boundary. An Extrap Z-pinch is a pinch discharge where the current channel has a characteristic non-circular cross-section achieved by bounding the discharge by a magnetic separatrix produced when a vacuum octupole magnetic field, generated by currents in external conductors, combines with the self-magnetic field produced by the discharge current. The pinch boundary is changed from a plasma-vacuum boundary to an interface between a high-beta pinch plasma and a low-beta plasma contained in the vacuum magnetic field. The energy that is lost from the pinch region sustains this boundary layer. The introduction of a separatrix boundary around the pinch with four X-point nulls deteriorates the containment of the pinch somewhat. However the presence of the warm low-beta plasma scrape-off layer, which provides a boundary condition on the pinch, tends to counteract the negative effects of the poorer confinement. Thus the equilibrium parameters that characterize the pinch may not be severely deterioted by the introduction of the separatrix when the entire configuration, including the scrape-off layer, is considered.

Key words: Z-pinch, fluid transport equations, scrape-off layer, Bennett relation, impermeable plasma, cold gas mantle, non-circular Z-pinch.