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Abstract

The creation of a thermal barrier between the central-cell and plug of a tandem mirror has been shown to produce a considerable improvement in tandem mirror performance. In this work we suggest a passive means of creating this barrier, by creating a mirror cell that lacks drift equilibrium and thereby cannot confine trapped ions. This approach is also shown to selectively remove high-Z ions, such as alphas, from the tandem mirror central-cell.

I. Introduction

Recent work by D. E. Baldwin and B. G. Logan[1] has indicated that a marked increase in tandem mirror performance can be obtained by creating a negative dip in the plasma potential in the region between the central-cell and the plug. This dip serves to thermally insulate the central cell and plug electrons, thereby allowing electrons that are locally trapped in the plugs to be heated to a temperature of 2 to 5 times that of the central-cell electron temperature. The high electron temperature in the plug then translates into a high central cell ion confinement potential barrier for much lower plug pressure than required by the earlier tandem mirror concepts[2,3]. In this paper we will describe a new method for creation of this thermal barrier.

We will refer to the region where the negative insulating potential barrier is created as the B-cell. Following Ref. 1, we see that the barrier density (n_b) is related to the central-cell (n_c) and plug (n_p) densities through the relations

$$n_b/n_c = \exp(-\phi_b/T_{ec}) \tag{1}$$

$$n_b/n_p = \exp(-(\phi_b+\phi_c)/T_{ep}) \tag{2}$$

with ϕ the potential and the subscripts b, c, p refer to barrier, central-cell and plug respectively. (Fig. 1 indicates expected magnetic field, density and potential profiles.) Eq. 1 indicates that $n_b < n_c$ is required for the creation of the barrier potential. From flux conservation and assuming

$\phi_b > T_c$ we find[1] for a species of charge Z

$$n_b = \frac{n_c}{R_b}\left(\frac{T_{ic}}{\pi Z\phi_b}\right)^{1/2} + n_b^* = n_{bs}^Z + n_b^* \qquad (3)$$

where the first term on the right side is the untrapped density of ions of charge Z streaming through the barrier region (n_{bs}^Z) and n_b^* represents the component of this species trapped in the B-cell. We define g_b as the ratio of the total B-cell density to the untrapped streaming density ($g_b \equiv n_b/n_{bs}$) for the dominant (hydrogenic) species. The equation for the barrier potential dip (ϕ_b) may be written as

$$\left(\frac{T_{ic}}{\phi_b}\right)^{1/2} \exp(\phi_b/T_{ec}) = \frac{R_b\sqrt{\pi}}{g_b} \qquad (4)$$

Fig. 2 shows (ϕ_b/T_c) vs. R_b/g_b for $T_{ic} = T_{ec} = T_c$.

It is evident that a high potential barrier is obtained by a large "B-cell" mirror ratio (R_b) and a small g_b ($g_b \sim 1$). Clearly $g_b \approx 1$ is desirable, and this implies a method be found which will pump out ions that try to accumulate in the B-cell. A further discussion of Eq. 1-4 may be found in Ref. 1.

II. Non-confining B-cell

Ref. 1 suggests that B-cell fill-up could be prevented by use of ion parallel heating. In this paper we present a passive method of accomplishing this same result; by a B-cell that is designed so that there is no drift equilibrium for trapped particles. In this situation ions that scatter into the confinement region of the B-cell will drift out of the device.

Two such magnetic field designs are indicated in Fig. 3. In Fig. 3a the elliptic flux tube (ellipticity ~ 25) is allowed to form a mirror constituting the B-cell while maintaining its elliptic cross-section. (Recircularization is done when the flux tube enters the central-cell, outside of the B-cell.) Fig. 4 indicates the coil topology, schematically drawn in the $Z-\theta$ plane, that could be used to create this magnetic field. Particles that trap in this region will tend to drift in a circle at a velocity

$$V_{\nabla B} = \frac{2\varepsilon}{m\omega_c\rho}\left(1-\sin^2\psi/2R_b\right) \tag{5}$$

for ε the ion energy, ω_c the cyclotron frequency, ρ the field line radius of curvature, R_b the B-cell mirror ratio and ψ the ion pitch angle. These trapped particles will drift away from the flux tube and can either be collected on a "limiter" or be magnetically diverted out of the tandem mirror. Ions and electrons both drift across the field at the same speed. Because the electrons are more collisional than the ions this region will develop a negative potential.

An estimate of the equilibrium trapped density (n_b^*) can be obtained by equating the ion trapping rate of the streaming plasma of density n_{bs} to the cross-field loss rate.

$$\frac{n_{bs}^2}{n\tau_s} = n_b^* \frac{V_{\nabla B}}{X} \tag{6}$$

for X an appropriate cross-field loss distance and $n\tau_s$ the Spitzer pitch-angle scattering time[4]. Using typical reactor parameters ($T_{ec} = T_{ic} = 30$ keV, $n_c = 6 \times 10^{13}$ cm^{-3}, $n_{bs} = 10^{13}$ cm^{-3}, $T_{ep} = 3\ T_{ec}$, $X = 50$ cm) yields the result $n_b^* \sim 10^9$ cm^{-3}. This serves to indicate that we may expect $g_b \sim 1$ in this scheme.

Although this proposed pumping scheme eliminates the need for RF pumping in the B-cell, it introduces an additional central cell particle loss. If we compare the loss rate from the B-cell to the central-cell loss rate noting that species Z scatters from the dominant (hydrogenic) species, we find

$$\eta \equiv \frac{\text{Loss through B-cell}}{\text{Loss from C-cell}} = \frac{n\tau_c}{(n\tau_s/R_b)} \frac{n_b n_{bs}^{Z}}{n_c^2} \frac{2V_b}{V_c} \tag{7}$$

$$= \frac{2}{\pi} \frac{g_b}{R_b} \frac{T_c}{\sqrt{Z}\phi_b} \frac{V_b}{V_c} G(R_c) \exp(Z\phi_c/kT_c) \tag{8}$$

$$\text{with } G(R_c) = \sqrt{\pi}\ (2R_c+1)\ \ln(4R_c+2)/4R_c$$

for $V_{c(b)}$ the volume of the central-cell (B-cell). We have used Pastukhov's formula[5] for central-cell confinement and Eq. 3. Typical reactor parameters ($V_c/V_b = 100$, $\phi_c/T_c \approx 3$, $\phi_b/T_c \approx 2$, $R_b = 5$, $R_c = 10$, $g_b = 1.1$) give $\eta = .05$, an acceptable decrease in confinement for hydrogen.

For alpha particles however, $\eta_\alpha = 0.7$ and higher Z impurities are even more strongly purged by the B-cell. For $R_b = 2$, η_α increases to 2.7 but ϕ_b/T_c drops to 1.3. This dependence is shown on Fig. 2 and it is clear that at low R_b a strong decrease in alpha confinement results.

A potential difficulty in the application of this approach is that whereas the grad-B drift tends to drift ions away from the elliptic flux tube, the E x B drift (V_E) is along the ellipse, and can be a dominant effect. For the grad-B drift to effectively drift ions away from the ellipse requires approximately

$$\frac{V_{\nabla B}}{V_E} \gtrsim \frac{1}{A} \tag{9}$$

for A the ellipse aspect ratio. This velocity ratio may be estimated from Eq. 3 to be

$$\frac{V_{\nabla B}}{V_E} = \frac{3T_c}{e\delta\phi} \left(\frac{L}{\rho}\right) \left(1-\sin^2\psi/2R_b\right) \tag{10}$$

for L the cross-field potential characteristic length ($E \sim e\delta\phi/L$).

If the radial electric field is small the grad-B drift is dominant. For a large anomalous cross-field electron transport in the central-cell we would expect a Boltzmann potential profile, that is

$$n(r) = n(r=0) \exp(-e\delta\phi/kT_c). \tag{11}$$

When the density falls to below about 10% of its peak value the ambipolar confining barrier (ϕ_c) will disappear and plasma will be diverted out of the tandem mirror ends. In this case $e\delta\phi/kT_c \approx 2.3$ and $V_{\nabla B}/V_E \simeq 1/A$.

It may be hoped, however, that the radial potential gradient will be less than T_c, since for the central-cell plasma classical cross-field transport is ambipolar, without a radial field. Radial transport code calculations, assuming classical transport, in fact show only a small radial E-field development[6]. It should be noted that the radial electric field in the vacuum region between the plasma and the B-cell wall may be eliminated by floating the B-cell wall at the proper potential. If it is desired to enhance B-cell plasma loss the ellipticity of this region may be enhanced by adding two Ioffe coils to the B-cell.

In this configuration, as in the previously discussed configuration, flux tube recircularization takes place after the flux tube leaves the B-cell and enters the central-cell. It is expeditious to recircularize at high fields so that magnetically confined central-cell ions do not sample the quadrupole fields, and are not subject to neo-classical and resonant transport mechanisms[6].

Another magnetic field configuration of interest is indicated in Fig. 3b. Here the elliptic flux tube coming out of the plug is recircularized within the B-cell so that the B-cell midplane flux tube has a circular cross-section. The dashed curves in Fig. 4 indicate "window-frame" coils that could be used to obtain this magnetic topology. This arrangement would allow a small class of ions (with pitch-angles near to 90°) to be mirror-trapped in the B-cell, and thereby create the situation $g_b > 1$. Interest in this configuration derives from the fact that some trapped plasma may be required for stability.

The B-cell concept tends to create a possible two-stream unstable situation when $1 < g_b < 2$. This question has been examined in Ref. 1 and they find that achievement of stability should be possible for g_b close to 1. Further investigation is required at low g_b, particularly when a local stable region is present at the B-cell midplane.

III. Conclusions

We propose here a "passive" method of creating a desired thermal barrier between the central-cell and plug electrons in a tandem mirror. Creation of this barrier region involves only a judicious choice of magnetic field topology. This method has the further advantage of preferentially eliminating high-Z ions from the central-cell.

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Figure Captions

1. Axial distributions for a typical tandem mirror of (a) magnetic field amplitude, (b) plasma potential, (c) plasma density.

2. The additional cross field loss rate of alpha ions in the B-cell normalized to the alpha end loss vs. the B-cell mirror ratio divided by the filling factor (g_b). Also shown is the B-cell potential normalized to the central cell ion temperature.

3. Possible flux tube configurations that could be used to create a drift unstable B-cell: (a) elliptic cross section cell, (b) elliptic cell recircularized at midplane.

4. Schematic $Z - \theta$ plane plot of the current topology to creat elliptic B-cell. Currents shown by dashed lines could be used to create configuration b of Fig. 3.

THERMAL BARRIER

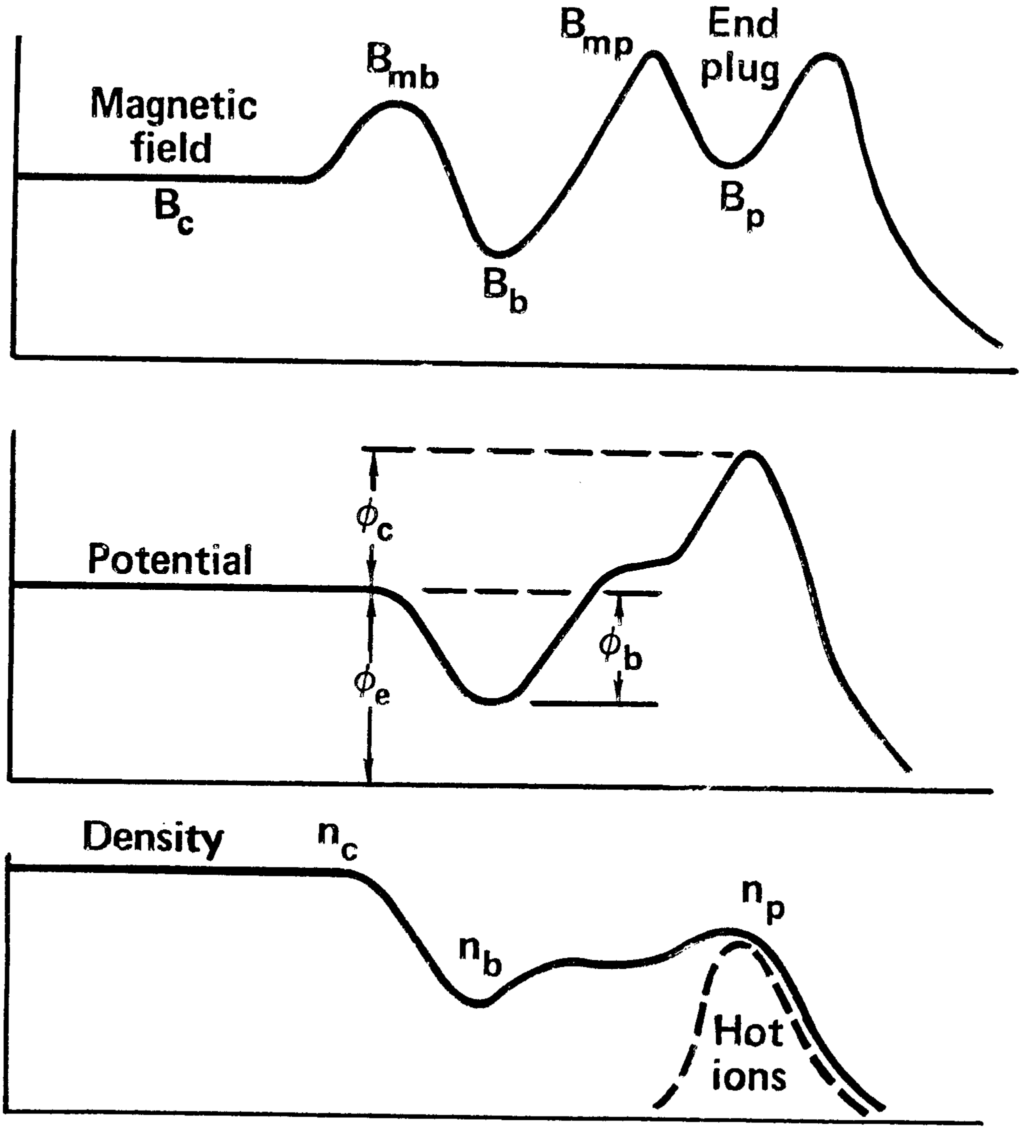

Figure 1

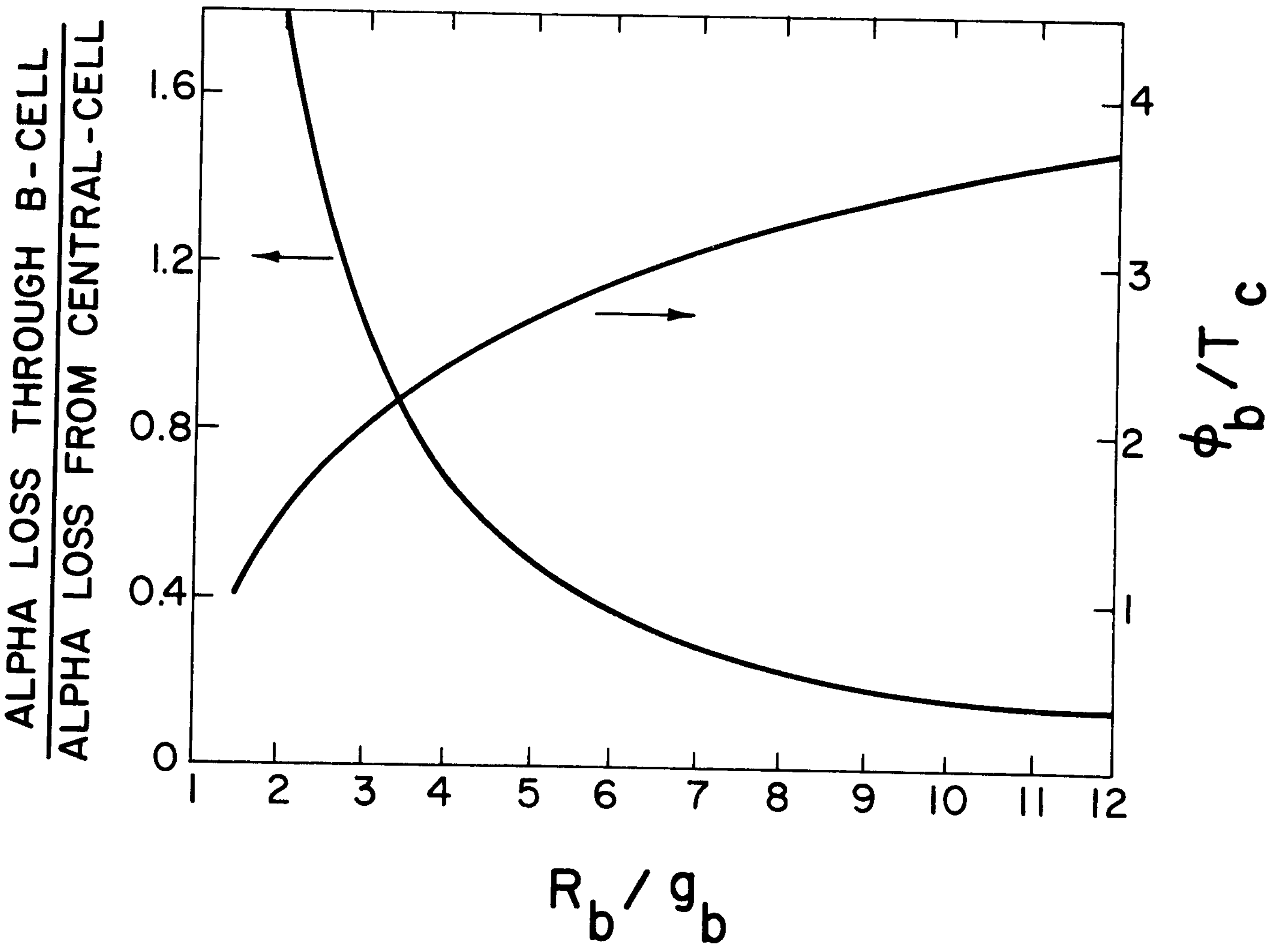
ALPHA LOSS THROUGH B-CELL / ALPHA LOSS FROM CENTRAL-CELL
0
0.4
0.8
1.2
1.6
1
2
3
4
5
6
7
8
9
10
11
12
R_b / g_b
1
2
3
4
ϕ_b / T_c

FIG. 2

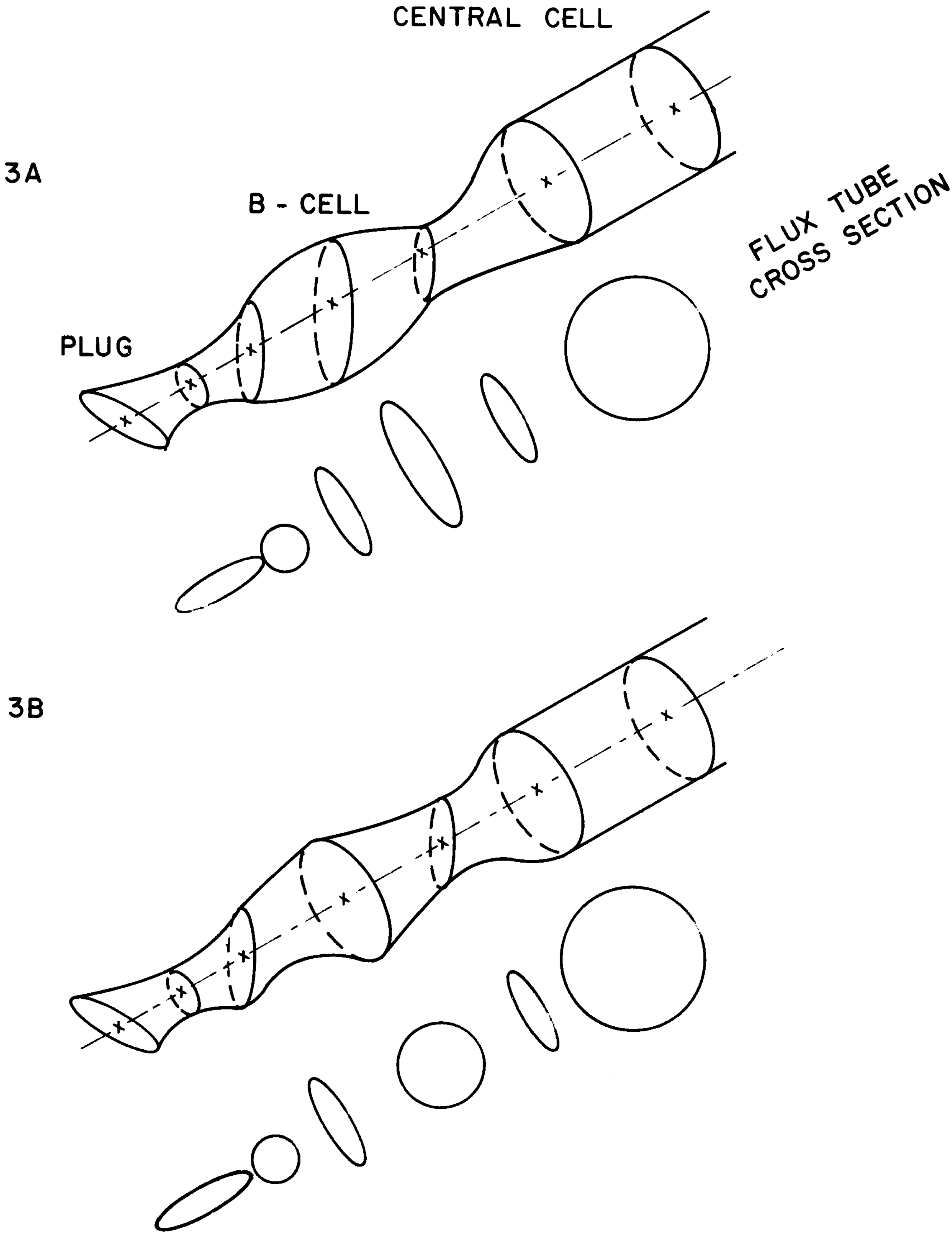

FIG. 3

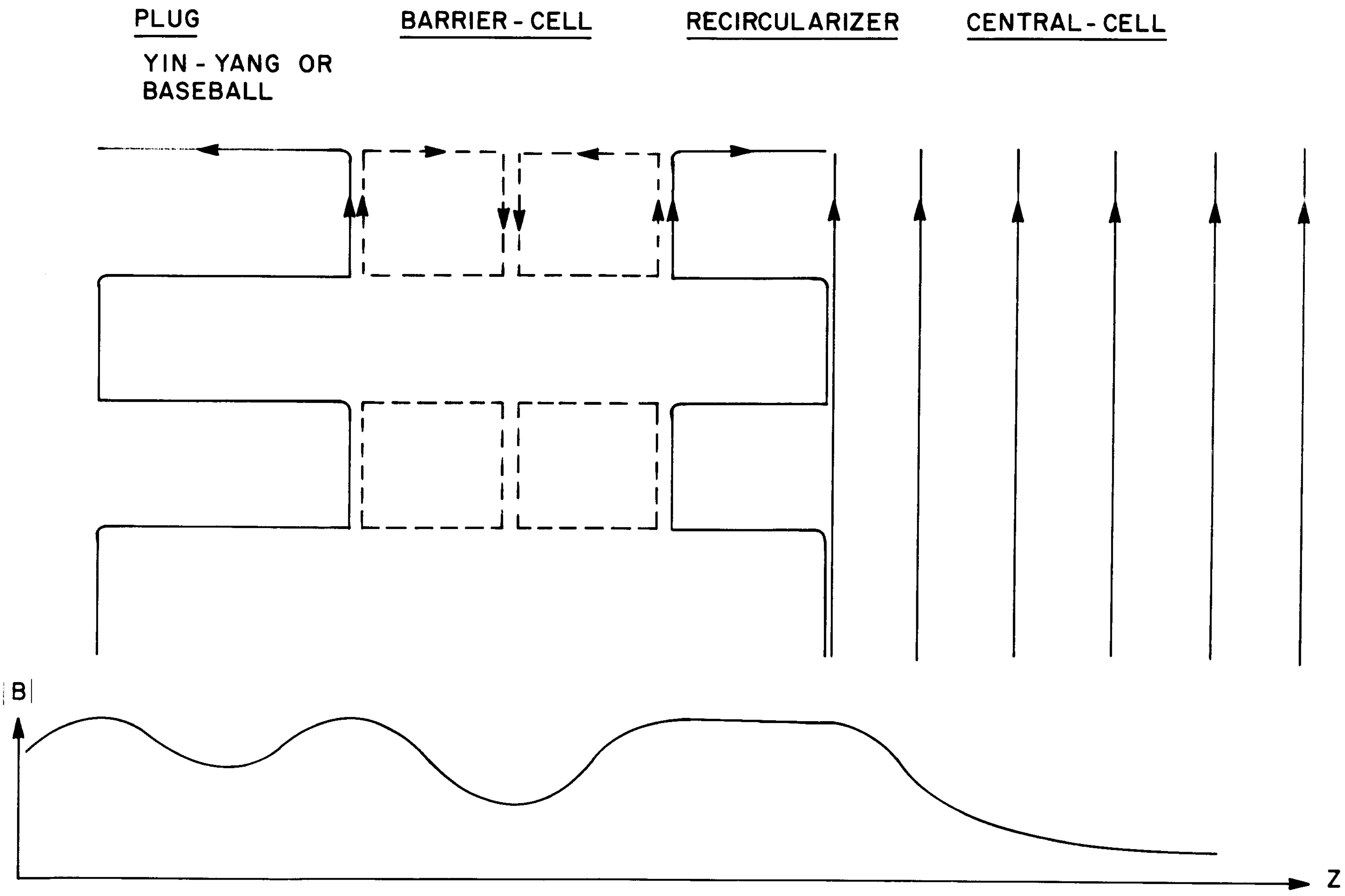

FIG. 4. COIL TOPOLOGY, Z - θ PLANE