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AXISYMMETRIC SLOSHING ION TANDEM MIRROR PLUGS

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Abstract

By injecting neutral beams close to the loss cone of a deep, axisymmetric mirror cell and locally heating electrons, an ambipolar potential can be established having a minimum at the midplane and a strong off midplane peak on one side of the midplane. Such a mirror cell could serve as a plug for a tandem mirror machine, thus eliminating the problems associated with non-axisymmetry of ion orbits. A minimum-B cell outside of this axisymmetric cell could then be added as an MHD anchor.

I. INTRODUCTION

It has recently been shown that the addition of a thermal barrier[1] to a tandem mirror[2,3] can greatly enhance its viability as a fusion reactor. As presently pictured the thermal barrier would consist of the addition of a mirror cell between the tandem mirror central cell and plug, in which an accumulation of mirror trapped ions is prevented by some pumping scheme[1,4]. This would result in a dip in density and potential in the barrier cell region and it is thought that this potential dip could, to a significant degree, isolate the plug and central cell electrons.

The tandem geometry considered to date then consists of a uniform field central cell region (where in a reactor the fusing plasma is confined), bounded by a non-axisymmetric barrier cell and quadrupole end plugs which serve as the electrostatic plug to central cell ions and as the MHD "anchor" for the system. Use of an auxiliary mirror cell outside of the plugs[5], the so-called "A-cell," has also been considered to prevent a large potential drop within the plugs and therefore enhance plug-ion confinement. (The A-cells are probably not necessary in a tandem containing a thermal barrier.)

A source of a number of potential difficulties in tandem mirror operation is the non-axisymmetry of the system. This results in enhanced central cell radial losses due to neo-classical and resonant particle transport[6-8], field errors[9] and MHD equilibrium axial currents[10] as well as increased difficulty and expense in the magnetic design of the system.

In this paper we describe a scheme that would allow for axisymmetric ion confinement. The proposed arrangement would have the tandem mirror central cell bounded at each end by a large mirror ratio ($R \sim 10$) axisymmetric mirror that would serve as both the electron thermal barrier and ion plug. All confined ions remain within the limits of this plug. An outer quadrupole plug is then added to each end to serve as MHD anchor and a potential divider cell.

The possibility of creating the desired density and potential profiles in the axisymmetric plug is examined in Section II by means of a Fokker-Planck simulation. In Section III we will discuss issues related to stability and Section IV contains conclusions.

II. BARRIER-PLUG CELL

It has been noted[11] that a mirror confined distribution of ions that are peaked at a pitch angle near to the loss cone will exhibit a dip in both density and potential at the mirror midplane. These ions may be characterized as "sloshing" ions and this situation has been observed in experiments.[12] In the discussion of the barrier concept[1] it has been proposed that a similar potential depression could be maintained by the "pumping" of ions that try to fill in the potential trough. One means that has been suggested to accomplish this pumping[13] is injection of neutral beams at an angle so as to be within the barrier-cell loss cone, relying on charge exchange to replace "trapped" with "passing" (untrapped) ions.

It has recently been suggested that a mirror cell located outside of a quadrupole plug can serve the functions of both electron thermal barrier and plug to central cell ions.[14] We will consider a situation in which both the thermal barrier and the ion plug are similarly created within a deep axisymmetric mirror cell which adjoins each end of a tandem mirror central cell. Neutral beams are injected near to the cell midplane at close to the loss cone angle. These beams serve not only to fuel, but more importantly, their charge exchange interactions serve to maintain the sloshing character of the confined ions and the accompanying midplane density and potential dip. For this potential inversion to be significant, a high mirror ratio ($R \geq 5$) well is required of this cell. Once a midplane potential minimum and off-midplane peaks are established, electrons which are locally trapped within the outer half of this plug can be heated by some means such as ECRH which will increase the potential in this region proportional to the local electron temperature.

The resulting hot electron high potential region can serve to plug the central cell of a tandem mirror. The ability to maintain this local hot electron species depends on the thermal insulation provided by the midplane potential depression.

As an example of such a mirror cell we will consider machine parameters consistent with the Phaedrus tandem mirror experiment. Corresponding to this experiment, the neutral beams have primarily 6 keV energy (75% at 6 keV, 15% at 3 keV and 10% at 2 keV).[15] In this energy range charge exchange dominates over impact ionization by approximately a factor of 3 and so beams injected near the mirror midplane and at a small angle to the field direction (close to the loss cone but in the trapped region of velocity space) should provide both fueling and charge exchange pumping.

We have studied the behavior of such a mirror cell by use of a Fokker-Planck code which includes axial dependence in the bounce-average approximation.[16] Finite beta field reduction is accounted for in the long-thin approximation $(B^2 + 8\pi P_\perp = B_{vac}^2)$. Table I shows the basic parameters chosen and results of these calculations. We consider a large mirror ratio cell (R = 10) with neutral beams injected at 30° to the field direction (loss cone angle is 18°). Three calculations are shown: one with low electron temperature (T_e = 50 eV), one with high electron temperature (T_e = 600 eV), and a run to observe the importance of charge-exchange ionization of the beams in which charge-exchange sources are set equal to zero.

For the low T_e case the density rises a factor of 2.5 in moving away from the midplane and an associated off-midplane potential peaking of 75 eV is observed. In the high T_e case (which represents electron heating by a process such as ECRH) the potential is seen to rise to 867 eV above the midplane value. (It should be pointed out that the potential is solved by equating the Fokker-Planck calculated local ion density with the electron density obtained through a Boltzmann relation

$$\phi(z) = \phi(z=0) + T_e \ \ell n\{n_i(z)/n_e(z=0)\}. \tag{1}$$

This gives an accurate result for potential throughout most of the mirror but becomes inaccurate near the mirror throats where the proper solution must be obtained by an analysis similar to that of Pastukhov's.[17])

Figure 1 shows contours of the equilibrium midplane ion distribution function in velocity-pitch-angle space. Notice the peaking of the distribution function near the loss cone boundary.

Figures 2a and 2b indicate the potential profiles for the low and high electron temperature cases. To maintain the high temperature case a considerable amount of ECRH is required. We estimate the power needed to balance the energy flow from the heated electrons (confined in an electrostatic well of depth $\Delta\phi$) into the central cell electrons (of temperature T_{ec}) following Ref. 13:

$$P_e \approx \frac{n_p^2}{(n\tau_{ee})} (T_e - T_{ec}) \exp(-\Delta\phi/T_e), \tag{2}$$

$$\text{with } n\tau_{ee} = 8.2 \times 10^9 [T_e(\text{keV})]^{3/2}/\ell n \ \lambda_{ee} \quad \text{cm}^3/\text{sec}.$$

The ion density profile along the mirror axis is shown in Fig. 3 for the low T_e case. Also shown for comparison is the density profile that results from a zeroing of the charge-exchange source term. In this situation a much weaker off midplane peaking is observed, indicating the significance of the role played by charge exchange.

The effect of varying the neutral beam injection angle is indicated in Table II. In this series of calculations the electron temperature and neutral beam current was held fixed (the actual source strength is proportional to density). As the injection angle is brought to near the loss cone angle the off midplane density peaking is seen to rise while the confinement parameter, $n\tau_p$, deteriorates. For injection at greater than 45°, high midplane beta causes onset of the mirror mode and calculations would require decreasing the beam injection current. Injection at an angle near to 30° appears to offer a large midplane density depression without an intolerable degradation of confinement.

In a tandem mirror we would heat the electrons on the outer half of the sloshing ion plug and the resulting magnetic field and density profiles might be expected to be as indicated in Fig. 4. The central cell ions which enter the plug can trap within the potential well of the plug and must also be pumped. The trapping rate depends upon central cell ion temperature and in a near term experiment auxiliary central cell ion heating will be required to prevent this trapping from exceeding the charge-exchange pumping rate. Otherwise additional pumping beams (aimed into the loss cone) would be required to maintain the barrier density depression .

If an additional minimum-B cell is added to the outside of the plug to serve as MHD anchor to the tandem mirror (Fig. 4) the density and potential will exhibit a dip between the plug and the anchor. Ideally we would like the potential minimum between the plug and anchor to equal the minimum at the plug midplane. This potential dip would then serve to thermally insulate the hot plug electrons from the anchor. On the other hand the presence of the anchor will increase the confinement of the beam injected ions by reducing the potential drop at the mirror throat, thereby acting as an A-cell.

III. STABILITY OF THE TANDEM MIRROR

To attain an overall average minimum-B stability of the tandem mirror a minimum-B cell is added to each of the outer ends of the system. This requires addition of a recircularizing section and a quadrupole coil to each end of the tandem as shown in Fig. 5. Although previous studies have shown that flute stability does not appear to be difficult to achieve at central cell betas of up to 0.5 in such a system, high beta pressure driven ballooning modes are seen to be more limiting to the central cell beta.[18]

Although the field topology for this proposed tandem is similar to that of systems already studied[13,18], the location of the recircularizing region within the high field, low beta section between the anchor and plug should increase ballooning mode stability. Furthermore, this configuration allows for the tailoring of the magnetic field topology within the axisymmetric plug so as to optimize beta. For example coil #5 (Fig. 5) could be run as a bucking coil so as to generate a separatrix outside of the last confined flux surface. This would tend to limit the plug bad curvature to a more localized region near the plug midplane where the plasma pressure is a minimum and thereby reduce the weighting of the bad curvature region within the plug.

With respect to microstability the plug should be stabilized due to the penetration of central cell ions into most of this region as well as the presence of some cold plasma trapped within the potential well. The anchor would gain stabilization from the central cell loss stream, and to this end its density (and dielectric constant) should be minimized. It is important to note that the anchor stabilization stream can be fed into the region between the plug and the anchor (see Fig. 4). The stabilization current would thus leave through the anchor without entering the plug or central cell.

If the sloshing ion distribution and associated midplane potential depression were desired solely for the purpose of obtaining microstability by electrostatic trapping of cold plasma[11] only a small density inversion would be required and the high mirror ratios considered thus far would not be necessary. In a typical calculation of 60^{o} injection into a mirror ratio 2.5 well (T_e = 50 eV, mean ion energy = 2.8 keV) the resulting midplane density (n_o) was 6.4×10^{12} and the density peaked at $B/B_o = 1.25$ at $n_{max} = 1.1 \times 10^{13}$. The partial filling of this density depression with warm plasma could be sufficient for microstability.

IV. DISCUSSION

We have shown that axisymmetric ion confinement can be made possible in a tandem mirror, including a thermal barrier, by using near loss cone injections into deep mirror plugs. Large mirror ratios are required to produce the desired potential profiles and charge-exchange of the neutral beams is seen to play a crucial role in maintaining the desired potential profile. For reactor applications some of the charge-exchanged neutrals will reionize within the plasma and the resulting reduction in charge exchange pumping requires careful consideration. Furthermore the constraint of keeping the beam energy below a level such that charge exchange ionization remains significant (about 100 keV for deuteron beams) is severe, and additional pump beams or other pumping means may be required. (Charge exchange on the sloshing ions is enhanced by their beam-like character but this does not hold true for the cooler central cell ions that must also be pumped.) Alternatively fueling beams can be injected perpendicularly at the potential peak which permits reduction of their energy and separate neutral beams for charge exchange pumping or another pumping scheme such as use of RF could be utilized.

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Table I

	Low Electron Temp.		High Electron Temp.
Plasma Radius	15 cm	15 cm	15 cm
Max Magnetic Field	1.0 T	1.0 T	1.0 T
Min Magnetic Field	0.1 T	0.1 T	0.1 T
Loss Cone Angle	18°	18°	18°
Mirror Coil Spacing	2.5 m	2.5 m	2.5 m
Beam Injection Angle	30°	30°	30°
Impact Ionization Beam Current	24 A	18 A	16 A
Charge Exchange Beam Current	73 A	0	50 A
Electron Temperature	48 eV	48 eV	600 eV
Mean Ion Energy	3.6 keV	1.5 keV	5.0 keV
beta	0.19	0.12	0.27
Midplane Density (cm^{-3})	$5x10^{12}$	$5x10^{12}$	$5x10^{12}$
Maximum Density (cm^{-3})	$2.4x10^{13}$	$9.2x10^{12}$	$2.0x10^{13}$
$\phi_{max} - \phi_{midplane}$	75 eV	30 eV	860 eV
ECRH Power	0	0	720 kW

Fokker-Planck results for 6 keV hydrogen neutral beams (including half and one-third energy components) injected at 30° angle into an R = 10 mirror cell.

Table II

	I	II	III
Injection Angle	20°	30°	45°
Midplane Density (cm^{-3})	5.3×10^{10}	1.5×10^{12}	1.1×10^{13}
$\int n(z)dz$ (cm^{-2})	3.0×10^{13}	3.2×10^{14}	1.5×10^{15}
Peak to Midplane Density Ratio	21.3	6.1	2.6
Potential Depression (eV)	153	90	48
Midplane Beta (%)	0.3	5.2	50
$n\tau_p$ (cm^{-3}-sec)	3.7×10^{9}	2.5×10^{10}	3.9×10^{10}

Fokker-Planck results for 6 keV neutral beams of fixed current injected at varying injection angles. T_e held fixed at 50 eV.

Figure Captions

1. Equilibrium ion distribution function contours in velocity space (pitch angle vs. speed) at the mirror midplane for $T_e = 50$ eV case.

2. Ambipolar potential vs. distance along field line from midplane for (a) $T_e = 50$ eV, (b) $T_e = 600$ eV. To correct for inaccuracy of calculation at $z \gtrsim 90$ cm minimum potential is set at -300 eV.

3. Ion density vs. normalized magnetic field magnitude at equilibrium for $T_e = 50$ eV case. Also shown is the density profile with charge-exchange ionization turned off. (Source strength adjusted to give same midplane density.)

4. Schematic modulus-B, electron density and potential profiles for a tandem mirror containing the axisymmetric plug-barrier cell.

5. Schematic of magnetic field components and flux tube shape for an axisymmetric plug tandem mirror.

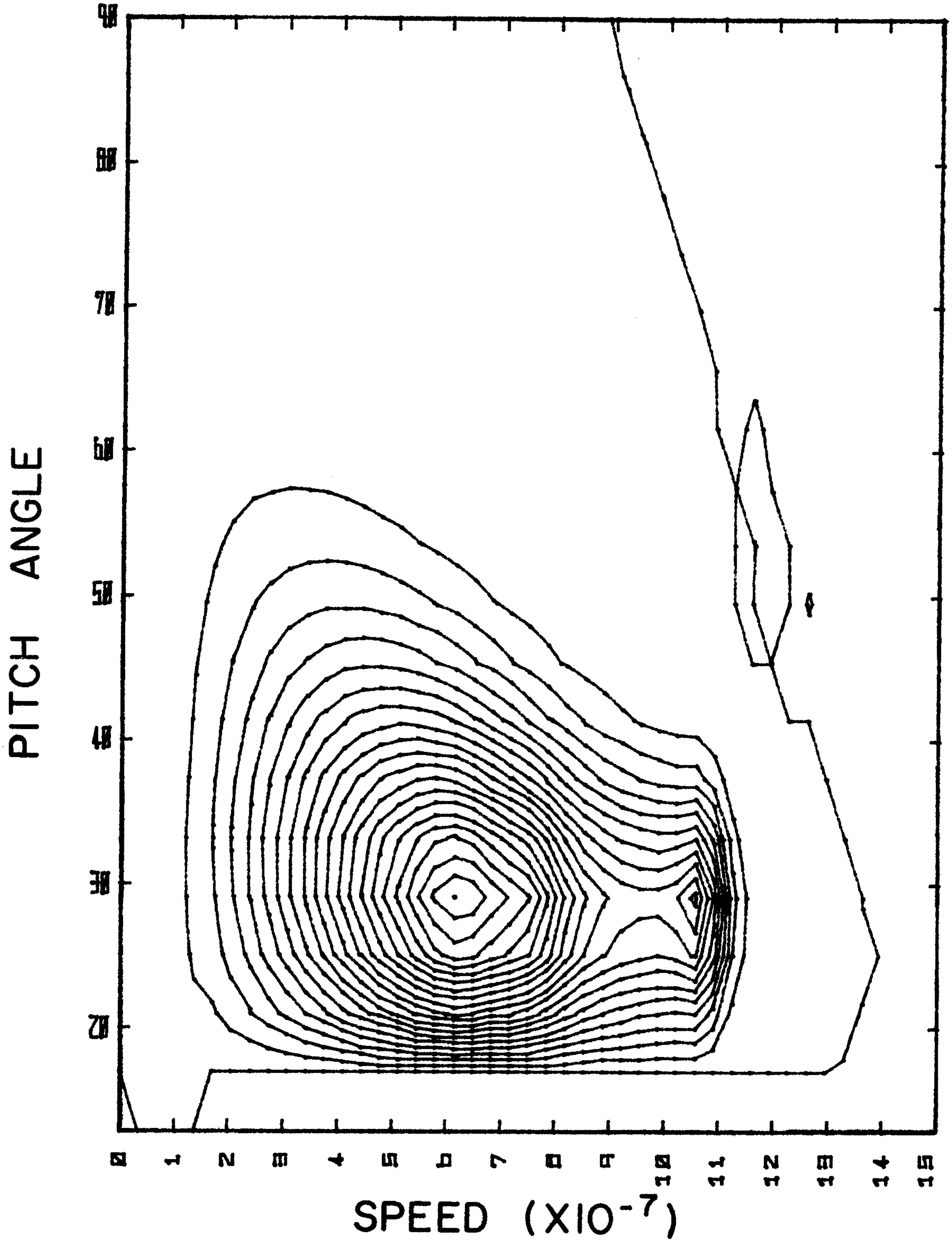
PITCH ANGLE
90
80
70
60
50
40
30
20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
SPEED (X10^{-7})

FIGURE 1

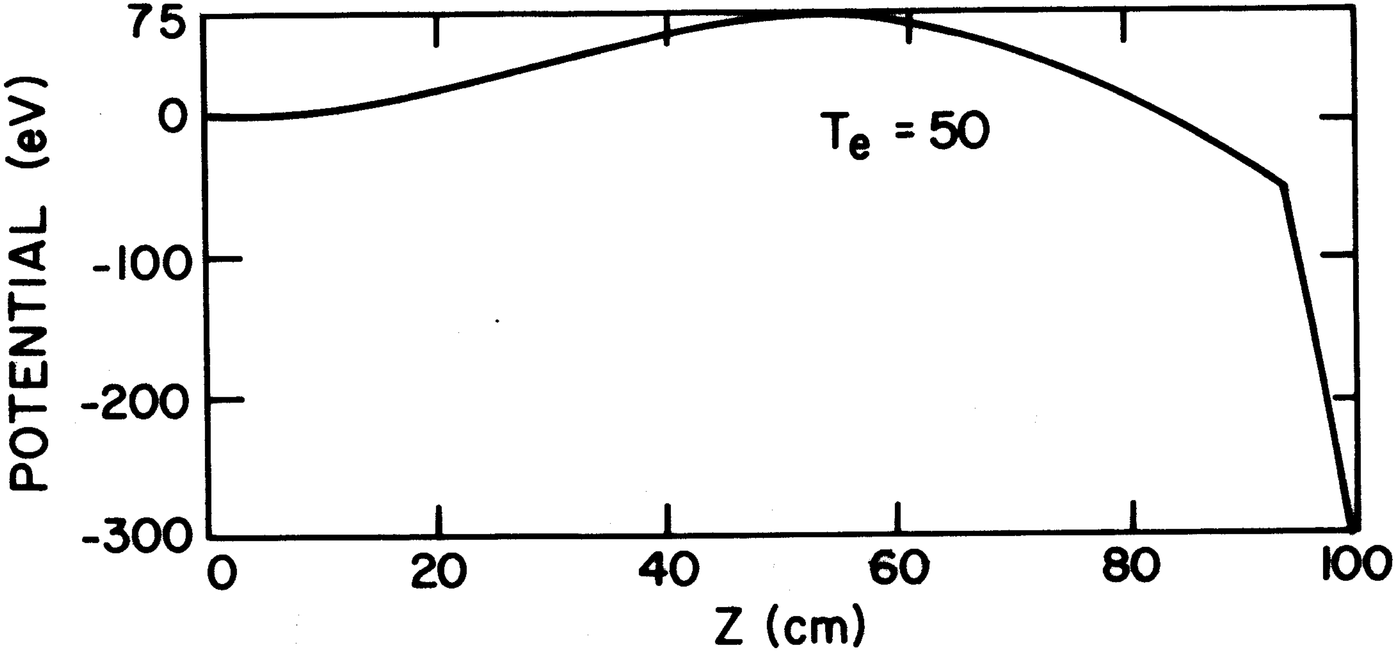

FIGURE 2a

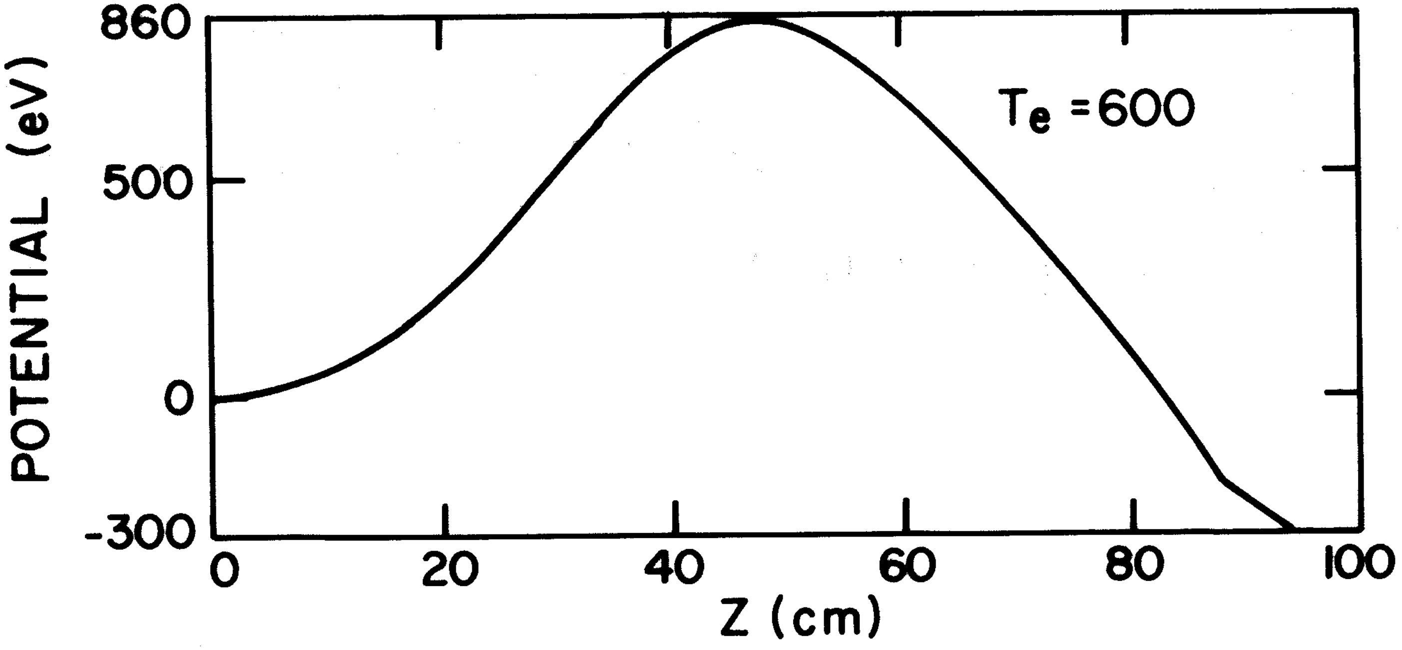

FIGURE 2b

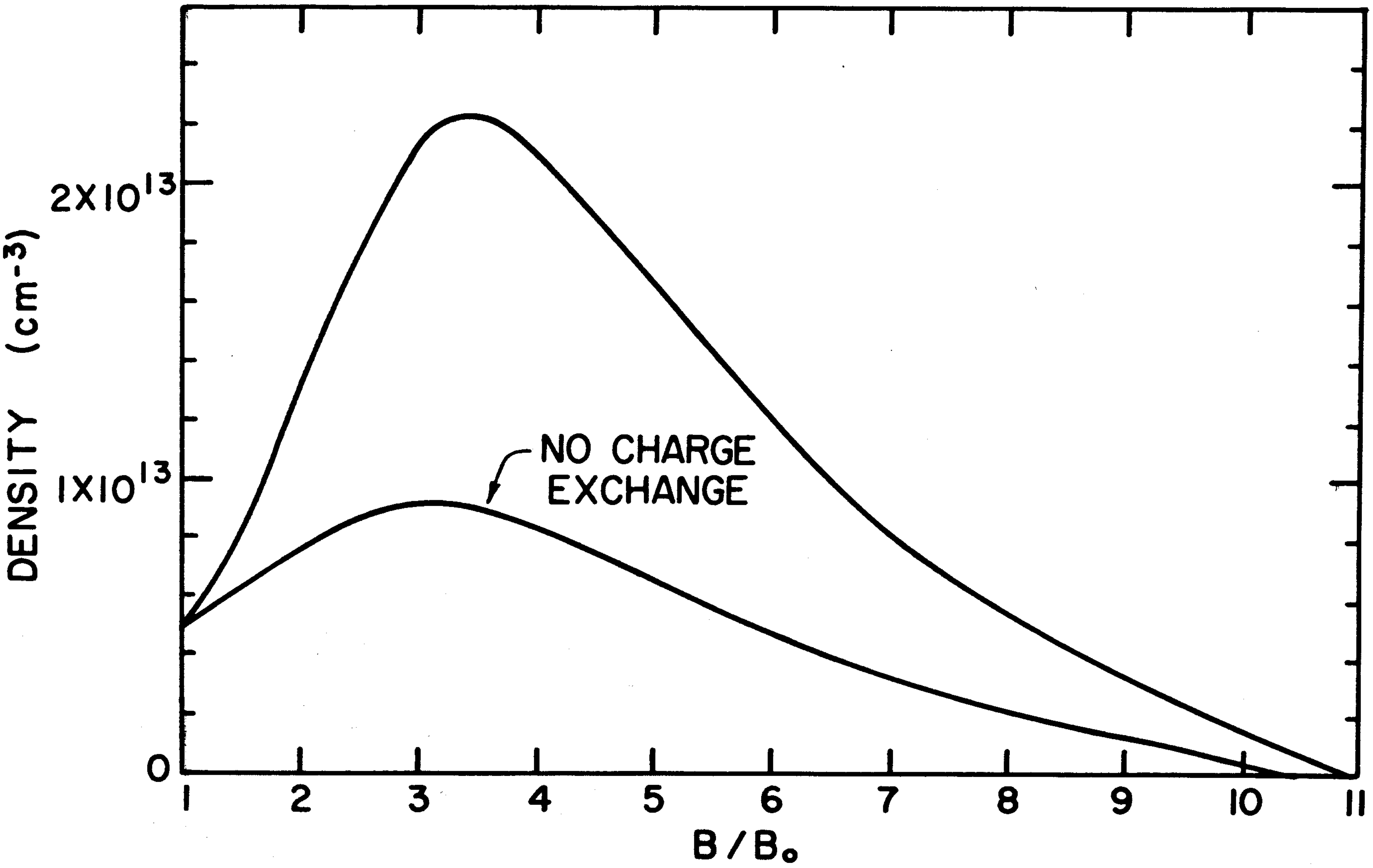
DENSITY (cm-3)
2X10^13
1X10^13
0
NO CHARGE EXCHANGE
1
2
3
4
5
6
7
8
9
10
11
B/B₀

FIGURE 3

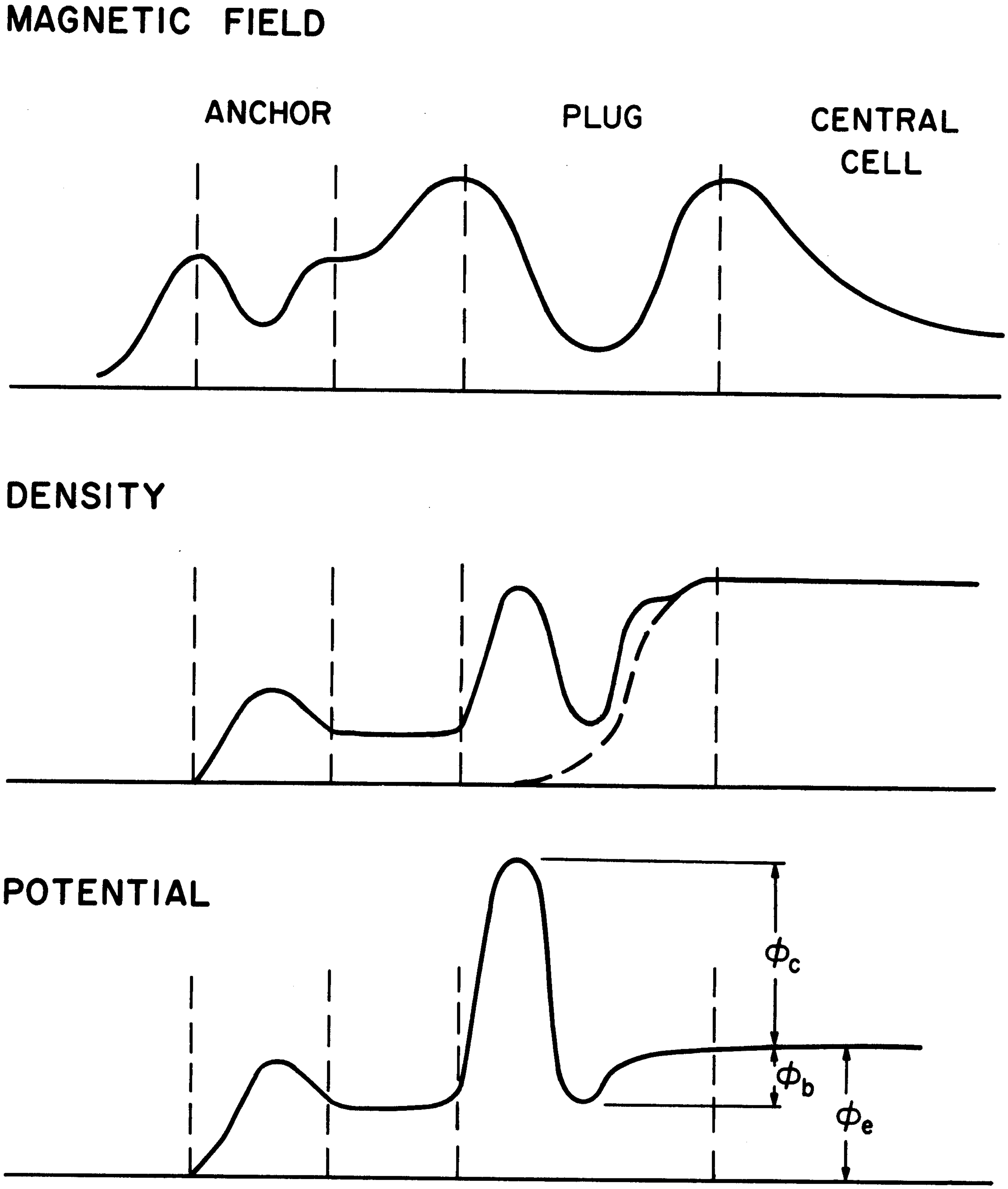
MAGNETIC FIELD
ANCHOR
PLUG
CENTRAL CELL
DENSITY
POTENTIAL
ϕ_c
ϕ_b
ϕ_e

FIGURE 4

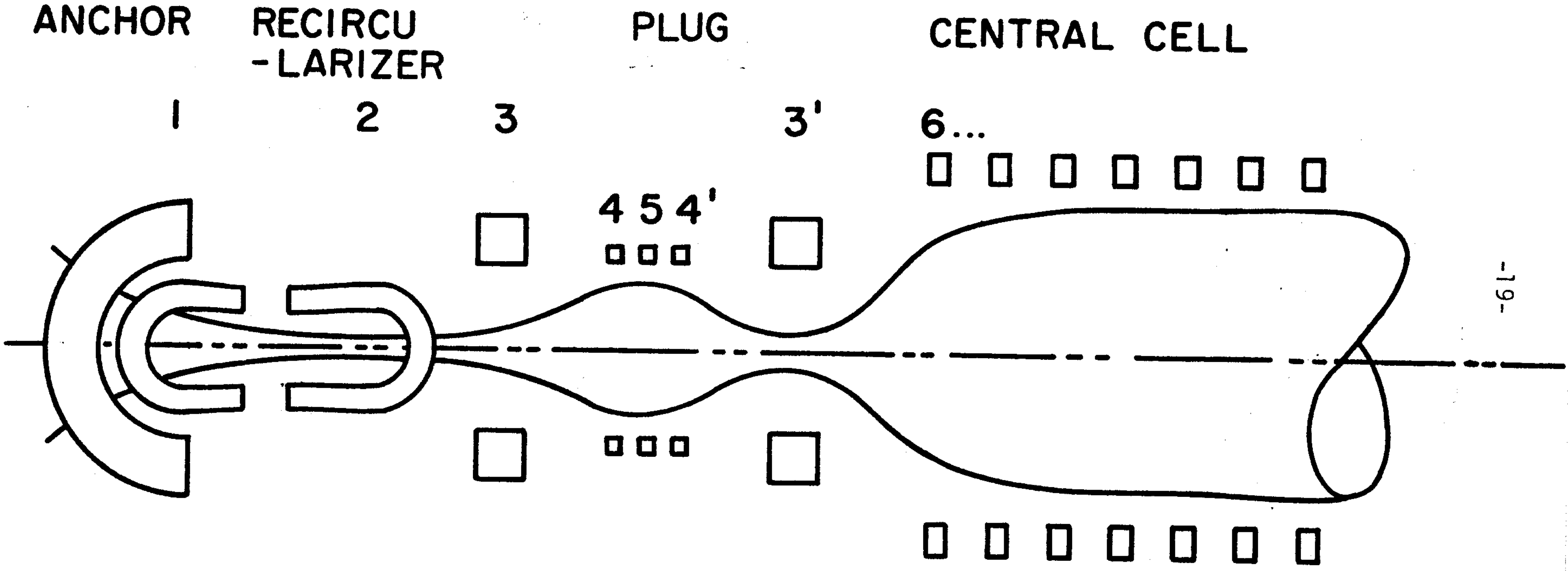

FIGURE 5