Tandem Mirror Sloshing - Electron Plugs

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Abstract

By a proper usage of ECRH heating in minimum-B tandem mirror plugs thermal barriers can be created which thermally insulate hot plug electrons from both the central cell and the outside environment. This arrangement can be utilized in an axisymmetric, outboard anchor plug arrangement or a minimum-B plug. In the axisymmetric arrangement ICRF can serve as a pump for preventing ions from accumulating in the thermal barrier potential depression whereas in the minimum-B plug unconfined drift orbits should prevent such an accumulation.

Introduction

The tandem mirror concept has been shown to be greatly improved by the utilization of a so-called "thermal barrier,"[1] a region of potential depression located between the ion plug and the central cell which tends to produce a thermal separation of the central cell from the plug electrons. Since the ion plugging potential scales as the plug electron temperature it is desirable to be able to have relatively hot electrons localized in the plugs.

We have recently explored the use of "sloshing-ions" in the plugs [2] for creation of axisymmetric ion confinement. A sloshing-ion cell has also been analyzed in detail by Logan for the proposed MFTF-B experiment [3].

In this paper we discuss a new possibility, the use of sloshing-electrons. By sloshing-electrons we mean creation of a population of hot magnetically confined electrons. We require that these electrons be shallowly trapped in the tandem mirror end plugs so that their bounce points all occur near the outer mirror throat at a position close to the ECRH resonance surface. The result would be a hot electron density component that peaks at the resonance surface and has a minimum at the plug midplane. Viewed at the midplane these electrons appear to be counter-streaming or sloshing.

There is a large literature dealing with ECRH heated hot electron mirror plasmas. In particular, the INTEREM experiment [4,5] has observed sloshing electron profiles using fundamental frequency ECRH heating.

In this paper we will show that creation of a sloshing electron population has important advantages for use in tandem mirror plugs. Best utilization can be made in either of two plug configurations:

1) an axisymmetric arrangement similar to that described in ref. 2 but having improved operation due to the natural imposition of a thermal barrier between the axisymmetric cell and outboard "anchor" as well as between the axisymmetric cell and central cell. Furthermore the pumping of the barrier could be accomplished by use of ICRF.

2) a single cell minimum-B end plug that should permit a significant degree of passive pumping.

In section II we will describe the basic configuration in more detail and section III contains an example of plasma parameters achievable in a near term experiment.

II. Sloshing Electron Cell Concept

Consider the magnetic field shown in fig. 1a. The magnetic field of strength B_c in the central cell rises to a peak B_m at the edge of the central cell. The flux tube then maps into the end plug having a field minimum B_a and an outer field maximum B_p. Fig. 1 will be referred to throughout the text for notation.

Electrons are heated at the resonant layers located at b or b' to create a magnetically trapped hot sloshing-electron component that peaks in density at the resonance zone. If the density of hot electrons at b, $n_{eh}(b)$, is sufficiently high it will throttle the flow of cold electrons into the plug region thus creating a thermal barrier.

Neutral beams injected perpendicularly and at the plug midplane will cause the ion density to rise at the midplane. The associated electron density rise requires that the electrostatic potential increase proportionally to the local electron temperature. The electrons (termed "warm" electrons) that are locally trapped in the midplane potential depression will be heated by the hot sloshing-electrons. If need be auxiliary electron heating could also be applied. For sufficiently warm midplane electrons the potential $\delta\phi_c$ will rise to a high enough value to serve as a plug to central cell ions, creating tandem mirror confinement (see fig. 1d). The rise in density between the ECRH resonance layer and the plug midplane will also prevent wave accessibility and therefore heating of electrons whose turning points do not reach the resonance layer. (Haste and Lazar[5] have observed that at high RF power levels electrons that do not reach the resonance layer are nevertheless strongly heated due to relativistic effects.)

The sloshing electron population will peak in density at both an inner and outer layer, defined by the ECRH resonance surface. (The peak to midplane density ratio for the hot electrons, observed in [5], can be as large as a factor of 2.) Therefore both an inner (between plug midplane and central cell) and an outer (between plug and outside environment) thermal barrier is expected to form. If only the inner thermal barrier is desired, the outer one can be allowed to fill with electrostatically trapped ions, thus enhancing microstability.

The high field, B_m, separating the central cell and plug serves to decrease the fraction of central cell ions that enter the plug which permits confinement of high central cell densities without degradation of the thermal barrier. For $B_m > B_p$ (with B_p the outer field peak) hot magnetically trapped electrons will tend to be lost toward the outside of the device. Furthermore these hot electrons will only extend on the inside up to the point p' where $B(p') = B_p$ and therefore for $B_m > B_p$ we expect a limited thermal contact with the central cell.

To prevent ions from trapping and accumulating in the potential depression of the thermal barrier region, some sort of "pumping" is normally required. Since the thermal barrier will form in a region of increasing magnetic field (and not at the field minimum as in previously discussed situations [1-3]) addition of perpendicular energy by some method such as ICRF would serve to detrap these ions. The resulting ions are still magnetically confined and pass through the mirror cell midplane. However, since neutral beams are to be injected perpendicular to the field direction and at the midplane, charge exchange of the detrapped ions on these beams will replace them by ions localized to the beam footprint which do not enter the thermal barrier region.

If the mirror cell under consideration were a minimum-B cell such as a quadrupole arrangement, the barrier trapped ions would have uncompensated quadrupole drifts which would cause them to drift out from the confined flux tube where they could be collected by a limiter. Utilization of this "passive" pumping could significantly ameliorate the difficulty and energy requirement for pumping the barrier [6].

Lastly, the question of microstability should be commented on. Two-stream type electron instability appears from [5] to not be a problem at sloshing electron peak-to-midplane density ratios of less than 2. Furthermore, experimental results of Klinkowstein and Smullin[7] indicate that a hot electron population (not necessarily localized to the midplane region) is stabilizing to the Drift-Cyclotron Loss-Cone instability for as yet uncertain reasons.

III. Example of Sloshing Electron Cell Tandem Mirror

In the example to follow we will use the notation of Logan [3] and follow the analysis presented in this reference. Three species of electrons are assumed to be present: a "thermal" central cell electron species of density n_{ec}, a magnetically trapped "hot" plug electron species, n_{eh}, and an electrostatically trapped "supra-thermal" or "warm" plug species, n_{ew}. For density at location m we use n_m, etc. Similarly for ions we have a "hot" neutral beam injected species, n_{ih}, a streaming "thermal" central cell species, n_{ic}, and a species that traps in the barrier potential depression, n_{it}.

We assume that we desire end plugs to confine a central cell plasma of density $n_c \sim 7 \times 10^{12}$ cm^{-3} and having electron and ion temperature $T_{ec} \sim T_{ic}$ $\sim$ 400 eV. Achieving these parameters will determine source and auxiliary heating requirements for the central cell. The ion confining potential $\delta\phi_c$ $(\equiv \phi_a - \phi_e)$ should be $\sim 2T_{ic} = 800$ eV. The thermal barrier potential is determined as follows: To get reasonable power requirements it was shown in [3] that the ratio of cold electron density at the barrier potential minimum, $n_{ec}(b)$, to total electron density at b, defined to be $F_{ec} \equiv n_{ec}(b)/n_b$, should be in the range of 5 to 20%. We will choose this parameter to be 0.1. This choice will determine the level of ECRH power to be applied at b. For a well pumped barrier we can determine the ion density at the potential minimum, n_b, to be

$$\frac{n_b}{n_c} = \frac{g_b}{R_b} \sqrt{\frac{T_i}{\pi\delta\phi_b}} + \frac{n_{ih}(b)}{n_c} \quad . \qquad (1)$$

$R_b = B_m/B_b$ and g_b is the ratio of trapped plus streaming ion density at b to the streaming density. We use a Boltzmann factor for thermal electrons and since $n_{ec}(b) = F_{ec}\, n_b$ quasi-neutrality gives for $\delta\phi_b$,

$$\exp\left(-\delta\phi_b/T_{ec}\right) = F_{ec}\,(n_b/n_c). \qquad (2)$$

For $F_{ec} = 0.1$ and $n_b = 3.5 \times 10^{12}$ (so as to permit ECRH accessibility) we get $\delta\phi_b/T_{ec} = 3.0$.

Using the result of Cohen et al. [8] we can estimate

$$\delta\phi_a = T_{ew} \ln\left[\frac{n_{ew}(a)}{F_{ec}\, n_b} \sqrt{\frac{T_{ec}}{T_{ew}}}\right] \qquad (3)$$

where $\delta\phi_a(=\delta\phi_b + \delta\phi_c) = 5\, T_{ec}$ (see Fig. 1d). Choosing $\delta\phi_a/T_{ew} \sim 1.5$ and $F_{ec} = 0.1$ we find $n_{ew}(a)/n_b = 0.82$.

If we choose the sloshing electron peak to midplane density ratio to be

$$\frac{n_{eh}\,(b)}{n_{eh}\,(a)} = \frac{(1-F_{ec})n_b}{n_{eh}\,(a)} \sim 1.15 \qquad (3)$$

then since $n_a = n_{eh}(a) + n_{ew}(a)$ we get $n_a/n_b \approx 1.6$. Choosing $n_b \sim 3.5 \times 10^{12}$ cm^{-3} we find $n_a \sim 5.6 \times 10^{12}$ cm^{-3}. This modest rise in density at the midplane is to be supplied by neutral beams.

The hot electron energy and density follow from particle and energy balance. The particle balance equates upward RF driven diffusion of both central cell electrons (present at the ECRF resonance location) and supra-thermal electrons which boil out of the electrostatic well located at the midplane with pitch angle scatter loss [3].

The power required to maintain the warm electron component trapped in the electrostatic well at the midplane represents the power required to heat both the central cell electrons that diffuse into and trap in the well [8] as well as the cold electron current that accompanies the neutral beam injection [3]. The former term dominates and requires about 0.4 kW/cm^3. An estimate of the power transferred from the hot to warm electron species, using the Spitzer equilibration time [9] will yield 0.7 W/cm^3 for an assumed hot species temperature of 10 keV. Therefore the hot species is expected to supply sufficient power to maintain the suprathermal species.

Conclusion

We present here the possibility of plugging a tandem mirror using a cell that utilized ECRH heated "sloshing" electrons. Results appear to be very favorable because of the possibility of employing passive or ICRF pumping in the end plugs. A separate auxiliary heating for the warm electrons may not be necessary and a second thermal barrier on the outside of the plugs will be naturally created. This scheme would accommodate itself to an axisymmetric arrangement with associated gain in central cell cross field transport or to a minimum-B end plug.

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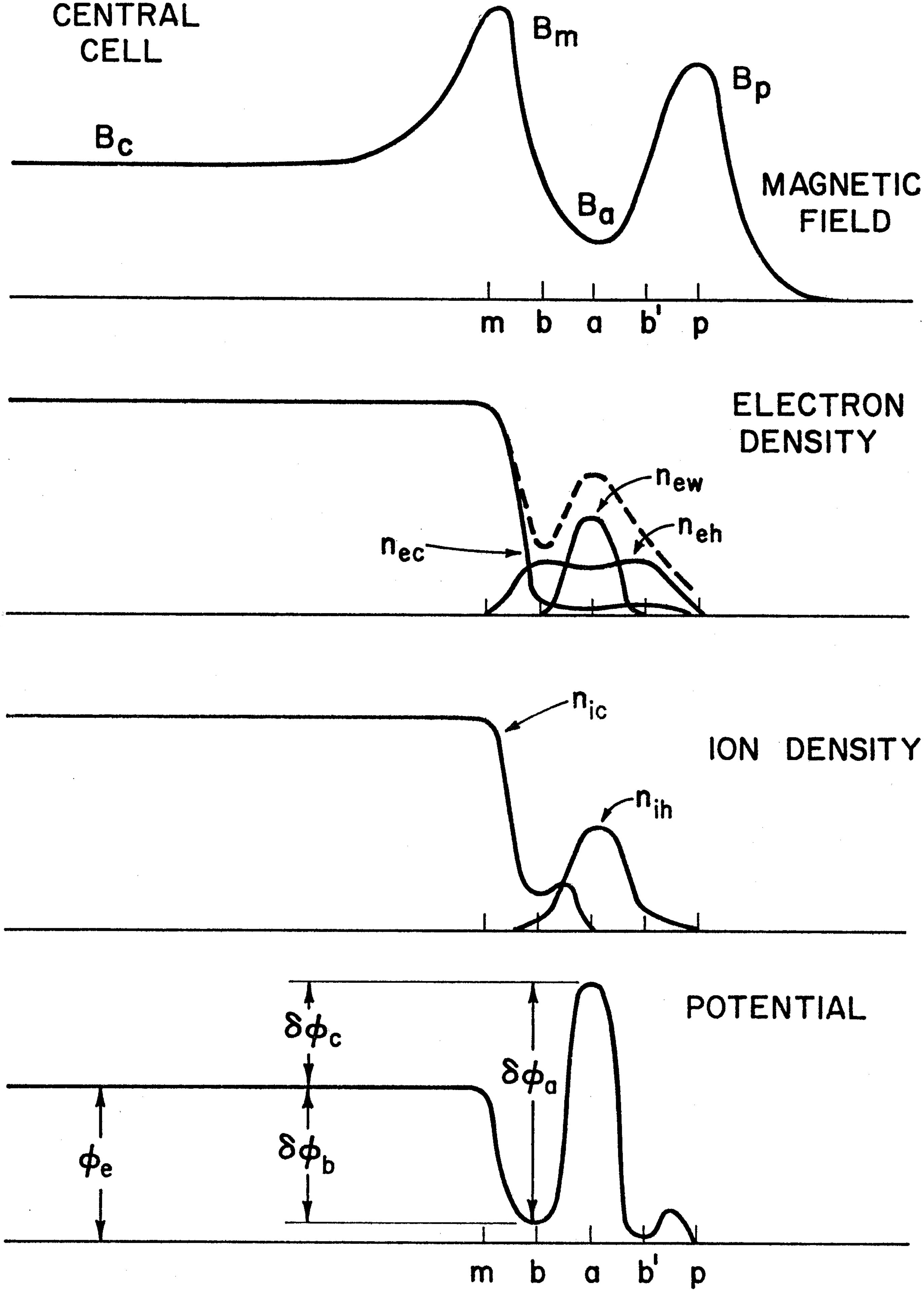
Figure Caption

1a. Magnetic field strength variation along tandem mirror axis for right plug (left plug is symmetric and is not shown).

b. Electron density variation showing the three electron components assumed to be present; magnetically trapped "hot" electrons, n_{ew}, and central cell electrons, n_{ec}.

c. Ion density variation for the central cell species, n_{ic}, and for the neutral beam injected "hot" species, n_{ih}.

d. Potential variation along tandem mirror axis.


CENTRAL CELL
B_m
B_p
B_c
B_a
MAGNETIC FIELD
m
b
a
b'
p
ELECTRON DENSITY
n_{ew}
n_{eh}
n_{ec}
n_{ic}
ION DENSITY
n_{ih}
POTENTIAL
$\delta\phi_c$
$\delta\phi_a$
$\delta\phi_b$
ϕ_e
m
b
a
b'
p