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PLASMA SURFACE INTERACTIONS IN Q-ENHANCED MIRROR FUSION SYSTEMS*

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Two approaches to enhancement of the Q (energy gain) factor of mirror systems are under study at Livermore. These include the Tandem Mirror[1,2] and the Field Reversed Mirror. Both of these new ideas preserve features of conventional mirror systems as far as plasma-wall interactions are concerned. Specifically in both approaches field lines exit from the ends of the system and impinge on walls located at a distance from the confinement chamber. It is possible to predict some aspects of the plasma/surface interactions of TM and FRM systems from experience obtained in the Livermore 2XIIB experiment. In particular, as observed in 2XIIB,[3] effective isolation of the plasma from thermal contact with the ends owing to the development of sheath-like regions is to be expected. Studies presently underway directed toward still further enhancing the decoupling of the plasma from the effects of plasma surface interactions at the walls will be discussed, with particular reference to the problem of minimizing the effects of refluxing secondary electrons produced by plasma impact on the end walls.

[1] G. I. Dimov, V. V. Zakaidakov, M. E. Kishinevsky, "Open Trap With Ambipolar Mirrors," Proceedings Sixth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Federal Republic of Germany, October 1976, Vol. III, pp. 177-187.
[2] T. K. Fowler and B. G. Logan, "The Tandem Mirror Reactor," Comments Plasma Phys. Cont. Fusion 11, 167 (1977).
[3] J. F. Clauser (To be published).

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Plasma Surface Interactions in Q-Enhanced Mirror Systems

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I. Introduction

Following experimental successes achieved in the 2XIIB facility mirror research at LLL has entered a new phase, one in which the goals have shifted from the qualitative to the quantitative. The ability of mirrors stably to confine dense fusion plasmas having been demonstrated, attention is now being turned toward a practical, quantitative, issue: how best to employ mirror principles to achieve fusion power. Here the central issue is the confinement quality factor, Q, (ratio of fusion power released by the plasma to plasma heating power input). As limited by practical bounds on the strength of the magnetic field at the mirrors Q has a theoretical maximum value of about 1.5 for a conventional mirror operated with a 50-50 deuterium-tritium plasma (created by neutral beam injection) at an ion temperature of 100 keV. The high recirculated power fraction implied by such a low Q value would represent a severe economic penalty for a pure fusion power plant. Our response to this, an essentially economic, constraint has been to undertake the study of two improvements on the conventional mirror, the Tandem Mirror (TM) and the Field Reversed Mirror (FRM). Both offer the possibility of enhancing Q at the same time retaining many of the advantages and many of the physics and technology aspects of the conventional mirror.

This report will review those aspects of plasma surface interactions that are special to mirror systems, particularly those systems of the Q-enhanced type.

II. Q-Enhanced Mirror Systems

Q-enhanced mirror systems of the TM and FRM variety, having many features in common with conventional mirror systems, will exhibit similar characteristics as regards plasma surface interactions.

In brief review, the Tandem Mirror,[1,2] as shown schematically in Fig. 1, consists of two small-plasma-volume conventional mirror cells, between which is a large central mirror cell. Maintained by neutral beam injection at high plasma density and high ion temperature, the end mirror cells develop a naturally-arising high positive "ambipolar" potential; this potential acts as an electrostatic barrier which enhances the confinement of a lower density reacting plasma in the central cell. In the TM the Q factor, determined by the ratio of fusion power produced in the central cell to the power required to maintain the end plugs, can be much higher than that of a conventional mirror.

The Field Reversed Mirror, as proposed at LLL, is shown schematically in Fig. 2. According to our present concept, tangentially aimed neutral beams would be used to initiate and maintain a plasma state in which diamagnetic currents (principally ionic in origin) would create a field-reversed internal region between the mirrors. In a FRM Q-enhancement arises from the fact that internally-trapped plasma must diffuse across the closed field lines within the FRM before reaching lines that escape through the mirrors. If the FR region is several (5 or more) ion orbit gyroradii across, a substantial increase in Q is predicted, relative to the conventional mirror.

Particularly in the case of the FRM there are unanswered questions as to equilibrium and stability; our present and planned experimental program is aimed at finding answers to these questions.

questions relating to the end regions and end walls, where the most important phenomena are those associated with particle transport along the field lines to the end walls.

In an approximate way we can describe the processes of longitudinal thermal conduction (from the plasma to the end walls) in terms of phenomena in three domains: Region I, which might be called the "mirror sheath", is that region, usually characterized by steep positive density gradients, lying just inside the mirrors. Here the ambipolar potential climbs rapidly to its maximum value, providing the electrostatic well within which the electrons of the central plasma are confined. Region II is the transition region between the mirrors and a Region III near the end walls. In Region II the magnetic field intensity falls off and its flux tubes expand as the end wall is approached. Region III is then the final transition zone between the outward-flowing plasma in Region II and the vacuum chamber surface (and/or other structures) upon which that plasma finally impinges.

Phenomena occurring in all three of these regions can play an important role in the overall confinement picture. Furthermore, phenomena occurring in the three regions are intercoupled. An example, later to be discussed, concerns secondary electrons emitted in Region III. If not prevented from doing so, their flow back along the field lines through Region II into Region I provides a mechanism for cooling the central plasma. Similarly, neutral gas released by recombination in Region III, if not pumped away, can appear in Regions II and III, causing cooling through ionization and charge exchange and the production of additional cold electrons in Region II. These electrons can then exchange energy with the central plasma.

emission coefficient, i.e. the number of secondary electrons emitted, from whatever process, per plasma electron incident on the wall.

$$F(\Gamma) = (\pi\mu/8)^{1/2}\left\{\ln\left[(1-\Gamma)^2/2\pi\mu\right] + (5-\Gamma)/(1-\Gamma)\right\} , \qquad (2)$$

where $\mu = m_e/M_i$.

Three limiting cases may be distinguished:

a) In the absence of space charge effects (no sheath) $F \to 1.0$, corresponding to free thermal effusion; $F < 1.0$ therefore reflects the insulating effect of the sheath in reducing thermal effusion.

b) In the limit $\Gamma \to 0$ sheath insulation is greatest, F being given from Eq. (2) as:

$$F(0) = (\pi\mu/8)^{1/2}\left[\ln(1/2\pi\mu) + 5\right] . \qquad (3)$$

In a deuterium plasma $\mu \simeq (1/3670)$ and $F(0) = 0.12$. Thus the sheath reduces thermal conduction by a factor 8 relative to free thermal effusion.

c) For $\Gamma > 0$ the sheath is perturbed by refluxing secondary electrons and F increases. With increasing Γ a virtual cathode forms in front of the wall limiting the increase in F so that it reaches a maximum value, at $\Gamma = \Gamma_c$, beyond which F does not increase.

Here

$$\Gamma_c = 1 - 8.3\,\mu^{1/2} . \qquad (4)$$

Here T_0 is determined primarily by thermal conduction, the effect of the sheath is unimportant, and the result is rather insensitive to the heating power, varying only as the $2/7^{th}$ power. For example a 10-fold increase in P would result in less than a two-fold increase in T_0.

b. When τ_0/τ becomes of order F/3, sheath effects become important and T_0 rises. In this limit

$$T_0 \approx \left[1.9 \times 10^{13} \; PL/Fn_0\right]^{2/3} \quad eV . \qquad (9)$$

As will be discussed neither limiting case can account for the observations in 2XIIB, where it is found that the thermal isolation of the central plasma is much higher than that predicted by either Eq.(8) or Eq.(9). These equations may however be applicable to Regions II and III, where classical conduction probably dominates.

Closely related to the Hobbs and Wesson result, Eq. (8), is a theoretical treatment of theta-pinch end losses by Morse.[7] In his model Morse provides for three plasma regions: a central region of length $2L_2$ where ion-electron energy transfer occurs, and two "passive" end regions, each of length L_1, where only electron thermal conduction is operative, out to the end walls, where $T_e = 0$. He does not, however, include secondary emission effects, considered by Hobbs and Wesson. Morse's result for T_e can be written as:

$$T_e = \left\{5.7 \times 10^{-36} \left[n_e^2 L_1 L_2 \overline{W}_i (\ln\Lambda)^2/A\right]\right\}^{1/5} \; eV \qquad (10)$$

In sum, the simple F-P model predicts an energy loss rate in which the escape of each electron through the loss cone transports energy from the interior of the plasma of order $e\phi_0 + kT_e$, i.e. the $W_\parallel$ needed to escape out of the well plus an average $W_\perp$ equal to kT_e.[9] Thus the expected average energy loss per escaping electron is 5 to 6 kT_e.

L. Hall[10] has considered a generalization of the above model, including the effect of particle exchanges with plasma external to the mirrors and with secondary electrons emitted at end walls. In his notation the longitudinal energy loss rate, through the electron channel, is proportional to kT_e, i.e. $P_L \sim \eta kT_e$. Thus for the simple F-P case where the only electrons involved are those originating from the contained plasma $\eta \approx$ 5 to 6. However, as will be discussed later, in 2XIIB η is found experimentally (by analysis of energy balances) to be considerably higher. The discrepancy can be explained by Hall's modified F-P treatment: Each additional cold electron introduced from Regions II or III on field lines connecting to Region I can, upon being trapped in Region I, allow the escape of another hot electron from the central plasma, in this way enhancing the loss rate above that for an isolated plasma. Each new cold electron drawn into and subsequently trapped in the Region I ambipolar well gains an energy $e\phi_0$. To maintain charge neutrality the trapping of the new electron prompts the release of a hot plasma electron. Upon climbing the potential well this electron loses energy $e\phi_0$ but carries out a net kT_e per exchange, the end result of which is to increase η. As observed in 2XIIB, increased cooling drops T_e below the F-P value $T_e/T_i \approx 0.1$. However even though enhanced over the simple F-P model the observed cooling rates are much lower than those predicted assuming classical electron thermal conduction as calculated by Hobbs and Wesson.

Fig. 5, prepared by B. G. Logan,[11] shows the axial variation of hot plasma density, and of the cold plasma as it penetrates through the ambipolar barrier into Region I, after being produced in the gas box in Region II. Fig. 6, prepared by T. Simonen et al.[12] shows the observed variation of the central T_e with injected neutral beam current. The electron heating power, P_{ie}, depends on beam current; in these experiments hot ion density is proportional to beam current.

Fig. 7, prepared by J. F. Clauser[13] shows the relative insensitivity of T_e in Region II (as measured by Langmuir probes) to that in Region I. He finds an approximate scaling law; $T_e(\text{ext.}) \propto \left[T_e(\text{internal})\right]^{1/2}$. These data bear on the question of the degree of isolation of the central plasma from that in Region II.

Finally, Fig. 8, also prepared by Clauser shows an intriguing but as yet not understood dependence of the central T_e on mirror ratio, R. The variations in R were achieved by varying the field strength of the external guide field relative to the strength of the confining field (produced by a Yin-Yang coil pair), neutral beam and stream gun parameters being held constant insofar as possible. The data seem to show that increasing R has a strong effect on T_e, T_e in fact appearing to be roughly proportional to $(R_{vac} - 1)^{3/2}$, indicating that mirroring effects are influential in the confinement and possibly in the degree of thermal isolation of the central plasma from Regions II and III. What remains to be resolved is whether it is the <u>external</u> mirror ratio, i.e. that seen by particles attempting to penetrate from outside the mirrors, that controls, instead of the interior mirror ratio, which affects the containment of the hot plasma.

Taking F at its minimum value (Eq. 3) of 0.12, and, from Table I, $n_0 = 1.5 \times 10^{20}\ m^{-3}$ yields $T_0 \approx 41$ eV. Again the classical model disagrees, even if no allowance is made for secondary electron emission.

If we now compare with Morse's model, Eq. (10), a somewhat higher T_e is obtained, but one still much lower than the 140 eV achieved in 2XIIB. Taking $L_1 = 3$ m, $2L_2 = 0.5$ m, $\ln(\Lambda) = 15$ and other parameters as before, one finds $T_e \approx 68$ eV. Again, because of the relative insensitivity (as the 1/5th power) of T_e to the plasma parameters, no reasonable change in these could produce agreement.

B. Modified Fokker-Planck Model

From the 2XIIB data it is possible to estimate the value of η in Hall's modified F-P mode. Knowing the loss rate of the ions, $\dot{n}_i = n_i^2 / (n\tau)_i$, the usual assumption of charge balance would yield the rate of loss of primary electrons. The observed rate of energy loss can then be formally related to the central electron temperature by writing it as ηkT_e. An η value significantly greater than the F-P value of 5 to 6 implies the presence of additional losses, in Hall's model associated with electrons coming from Regions II or III. Thus we write formally

$$P/\dot{n}_i = P \cdot (n\tau)_i \,/\, n_i^2 = \eta kT_e \qquad (11)$$

In practical units, solving for η

$$\eta = 6.3 \times 10^{18} \left[(n\tau)_i \,/\, n_i^2\right] \left[P/T_e\right] \quad , \qquad (12)$$

We see that even though the mirror-confined plasma in 2XIIB is far better insulated from its surroundings than would be predicted on the basis of classical electron thermal conduction, it still does not operate in a regime that would permit it to conform to the F-P results for an isolated plasma. Assuming that the modified F-P model is the correct one, the implication is that there exists an unacceptably high rate of exchange of electrons between Region I and Regions II and III. We will in a later section outline some of the measures being taken to reduce this exchange so that the F-P values of η and T_e/T_i for an isolated plasma can be approached. According to this model what is needed is a reduction in the density of plasma in Region II and a suppression of refluxing secondary electrons from Region III. Both issues are being addressed in our experimental program. Encouragement that these problems can be solved can be derived from 2XII results (before the beams and stabilizing streams were added). In some of these experiments, where the external plasma density was low, values of $\eta \approx 8$ were found, nearly as low as the classical value $\eta \approx 6$. These were, however, somewhat unstable plasmas with $n\tau$ values below classical. Additional encouragement can be derived from results from the Livermore Baseball II experiment where close agreement between both $(n\tau)_i$ and T_e/T_i as compared to the F-P result for an isolated plasma was seen.[14] In plasma decay measurements at densities (of order 10^{15} m^{-3}) below the threshold for the DCLC mode, $(n\tau)_i$ and T_e/T_i -- as deduced from measurements of ϕ_0/T_i -- were found to agree within experimental error with the F-P results for an isolated plasma. Owing to the care taken in Baseball II to achieve clean vacuum conditions the environment of the plasma was indeed conducive to achieving effective isolation from the end regions.

unknowns. Nevertheless, because little or no streaming plasma should be required and because the field lines of the reversed field region do not connect directly to those exiting through the mirrors we believe the FRM should not suffer from the cooling effects now observed in 2XIIB.

One problem, already mentioned, can clearly be solved subject only to economic constraints. By expanding the flux lines of the field outside the mirrors of a TM or a FRM particle fluxes at the boundary walls can be reduced to levels low enough to insure adequate life against sputtering and blistering. At the same time the physical separation between the end wall and the confinement zone can be made large enough to inhibit the refluxing of neutral gas resulting from recombination at the end walls, thereby correspondingly reducing the density of secondary plasma in Region II.

There is an additional motivation for expanding the field, namely direct conversion, under study at LLL for several years.[17] The electrostatic direct converters we have studied would not only act to improve the fusion energy balance, but as discussed later, could also act to prevent the refluxing of secondary electrons.

VIII. Means for Reducing the Refluxing of Secondary Electrons

Stimulated by the considerations outlined in the previous sections efforts have been initiated at LLL aimed at controlling the refluxing of secondary electrons both in 2XIIB and in new experimental facilities, now under construction. These new facilities, TMX and MFTF, the Tandem Mirror Experiment and the Mirror Fusion Test Facility will employ systems specifically aimed at this problem, as well as addressing related problems (such as wall heating) associated with plasma surface interactions at high power levels. Fig. 9 shows an artist's drawing of TMX, a facility due for completion in late 1978. The large MFTF facility, a major scaleup over 2XIIB, primary ion lost is thereby amplified by a factor of order γ . If $\gamma >> 1$ this could lead to a marked cooling effect.

Secondary electrons emitted by electron bombardment can in principle lead to a more catastrophic effect, cascading of the primary flux. Shearer[18] has used a simple model to illustrate this possibility: Consider fluxes f_i of singly charged ions, f_e of electrons, resulting in returning electron fluxes from the wall of f_i and f_e. In equilibrium the net current to the wall must vanish, i.e.

$$0 = +ef_i - ef_e - \left[-e\gamma f_i - e\delta f_e\right] \qquad (13)$$

rearranging terms,

$$f_e/f_i = (1 + \gamma) / (1 - \delta) \qquad (14)$$

so that $f_e > f_i$. Taking $T_i = \alpha T_e$ ($\alpha > 1$ due to the ambipolar and wall sheath potentials) then the energy flux to the wall is given by

$$E_w = f_i kT_i + f_e kT_e = f_i kT_e \left[\alpha + (1 + \gamma)/(1 - \delta)\right] \qquad (15)$$

If $\gamma = \delta = 0$ we would recover the simple F-P result, i.e. the energy loss flux is entirely accounted for by the exit fluxes. If $\delta << 1$ and $\gamma > 1$ there would be a simple amplification of the energy loss. But as $\delta \to 1$ it can be seen that Eq. (15) becomes singular. For $\delta > 1$ this model predicts that a regenerative process will set in limited finally only by space charge effects. We do not believe that the parameters in 2XIIB are such as to permit regeneration to occur but increases in T_e or other circumstances could lead to such a possibility if no measures were taken to control the refluxing of greatest midway between the wires. As evaluated by Barr[20]

$$V_{1/2}/V_g = \left[(\pi d/a) - \ln(2)\right] \Big/ \left[(\pi d/a) - \ln(2\pi r/a)\right] \ , \ r/a << 1 \ . \qquad (17)$$

Here d is the separation between the plasma of the grid wires and the end wall and r is the grid wire radius. For a typical case (d/a = 1., $r = 10^{-4}$ m, a = .01 m) $V_{1/2}/V_g \approx 0.4$, i.e. the potential midway between the wires is only 40 percent of V_g. Thus we can roughly estimate the required voltage as $V_g \approx -(460)/0.4 \approx -1200$ volts.

The ion density at the grids in TMX is actually about an order of magnitude higher than that believed required for a TM fusion power plant. This augurs well for the use of some kind of grid array in such a system.

Closely related to the above ideas is the work at LLL on direct conversion. Electrostatic direct converters such as we have studied would have the inherent ability to suppress refluxing electrons from the ion collectors. At these collectors the electric fields, decelerating for incident ions, are therefore also decelerating for emitted electrons. At the same time the measures employed to separate and collect the electrons from the incident plasma can be used to prevent the refluxing of secondary electrons from the electron collectors. Direct converters therefore play a dual role in Q-enhanced mirror systems, acting not only to recover particle kinetic energy (thereby reducing the energy dissipated as heat) but also acting as effective suppressors of refluxing secondary electrons.

B. Aligned Fins

Another approach to the refluxing problem has been studied by C.C. Damm and G.D. Porter.[21] They propose that ions of the emerging plasma

Taking $\phi(o)/kT_e = 1.$ and $n_h/n_{eo} = 0.5$, $S_f = 0.15$, i.e. about an order of magnitude reduction in secondary refluxing is predicted even when n_h constitutes only one-half of the total incident plasma density. They also treat details of the collection of secondaries on the fins. Their conclusion: Assuming adequate vacuum pumping can be provided (to keep down the local gas density at the fin array), aligned fins offer an attractive solution to the twin problems of refluxing electrons and dissipation of particle energy at the ends of mirror systems. The pumping required here implied is simply stated: Pumping speeds must be high enough to satisfy the inequality $n_o\sigma_{ioniz.}L \ll 1$. If $L = 1$ metre this implies $n_o \ll 10^{20}\ m^{-3}$. It should be possible to satisfy this requirement with proper design.

C. Multipole Magnetic Grids

That the "picket-fence" idea proposed early on in fusion research could help to solve the refluxing problem has occurred to many. Thus far the various studies at LLL have been preliminary in nature, differing mainly in their proposed modus operandi.

Shearer[18] proposes the use of a multipole field, generated by a grid of current-carrying wires (adjacent wires carry oppositely directed currents), located behind the end wall. Here the action of the multipole field is to repel a portion of the incident plasma (some of which would be background plasma), thereby reducing the production of secondary electrons. Post[22] has considered aspects of another multipole embodiment. Here the grid wires would be placed in front of the exit surface. Thus, in addition to their action in repelling incident particles from the background plasma (as in Shearer's scheme) the grid would perform an additional function: Given sufficiently strong currents in the grid wires all flux lines emerging from the end wall are forced to

$$I > I_{min} = 1.25 \times 10^6 \, wB_0 \, (1 + \alpha^2) \text{ amperes,} \qquad (21)$$

where $\alpha = x/(w/2)$. Next for an array of N pairs of wires the ratio of the field at the wall between the innermost pair and that of single pair is given by

$$D = \sum_{n=1}^{N} B_n/B_1 = - \sum_{n=1}^{N} (-1)^n \left\{(2n - 1)\,(1 + \alpha^2)/[\alpha^2 + (2n - 1)^2]\right\} . \qquad (22)$$

As an example, for $\alpha = 1$ and $N = 8$, $D \sim 0.57$. Thus if we require the flux condition to be satisfied when $B_0 = 0.01$ T and $w = 0.05$ m, we find from Eq. (21) Eq. (22) $I_{min} = 2200$ amperes. Carried in rectangular water-cooled copper bus bars 2 cm^2 in area the joule heating power dissipation by the grid array would be approximately 10 kW/m^2 of endwall; this should be acceptably small compared to other losses. Figure 13 illustrates the field line pattern for a grid array of the type described above. The case shown corresponds to $I \approx I_{min}$ at $\alpha = 1$. The plane $x = w/2$ is shown (solid line). Also shown (dashed line) is a position for the end wall more appropriate for the r.f. enhanced scheme.

From the field calculations which give the mirror ratio between the wall and the field maxima for each magnetic line shown it is possible to estimate the suppression factor, F, i.e. the fraction of secondary electrons that would escape, assuming isotropic electron emission, ignoring plasma-related effects, and not including the effect of r.f. enhancement. For the example shown ($\alpha = 1$) $F \approx 0.22$.

- New facilities, TMX and MFTF, are under construction. In these it will be possible to test both the new approaches to confinement and means to minimize the deleterious effects of plasma surface interactions and background plasma.

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TABLE II

Maximum Secondary Emission Coefficients,
δ_{max} and V_{max}, for Various Metals

Metal	δ_{max}	V_{max}
Aluminum	1.0	300
Copper	1.3	600
Gold	1.4	800
Iron	1.3	400
Molybdenum	1.3	400
Nickel	1.3	500
Platinum	1.8	700
Silver	1.5	800
Tantalum	1.3	600
Titanium	0.9	280
Tungsten	1.4	650

14. A.H. Futch, C.C. Damm, J.H. Foote, A.L. Gardner, J. Killeen, Physics of Fluids 14, 1542-1554 (1971).

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18. J.W. Shearer (Private communication).

19. G.W. Hamilton (Private communication).

20. W.L. Barr (Private communication).

21. C.C. Damm, G.D. Porter (Private communication).

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23. D.E. Baldwin (Private communication).

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TANDEM MIRRORS WITH AMBIPOLAR BARRIERS AT THE ENDS

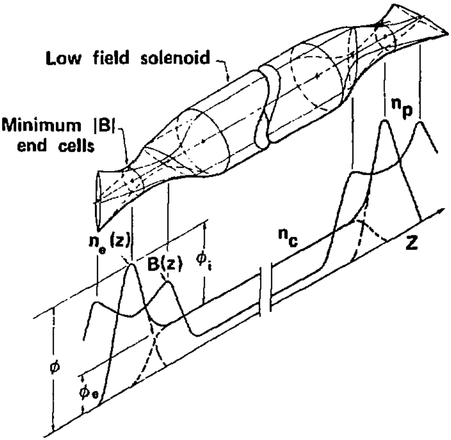


Figure 1

2XIIB

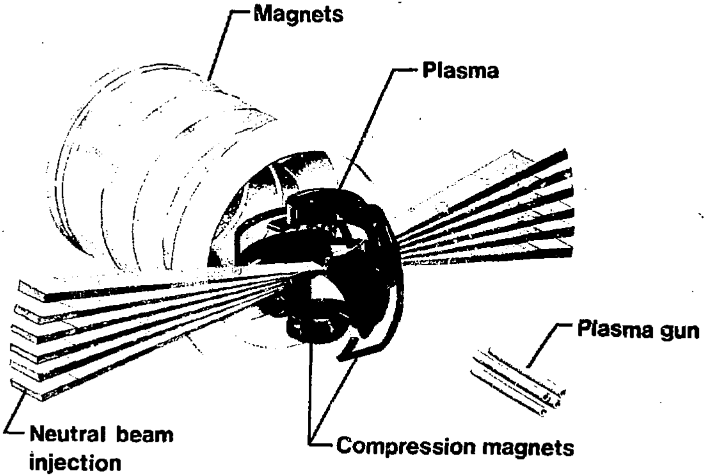
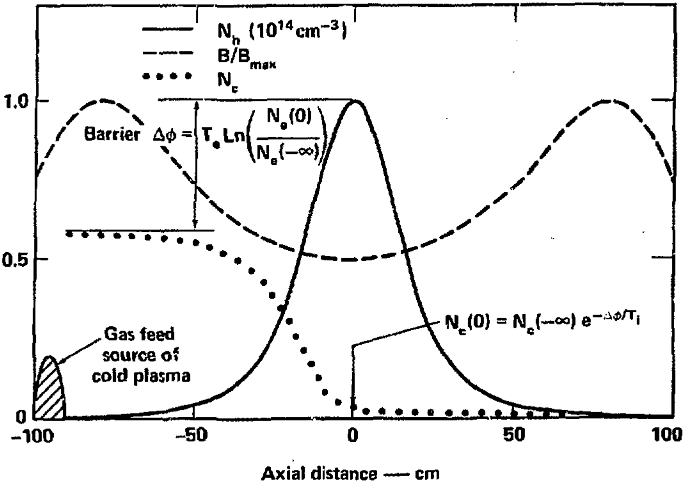


Figure 2



N_h (10^{14} cm^{-3})
B/B_{max}
N_c
1.0
0.5
0
Barrier $\Delta\phi = T_e \, Ln\left(\frac{N_e(0)}{N_e(-\infty)}\right)$
$N_c(0) = N_c(-\infty)\, e^{-\Delta\phi/T_i}$
Gas feed
source of
cold plasma
-100
-50
0
50
100
Axial distance — cm

Figure 5

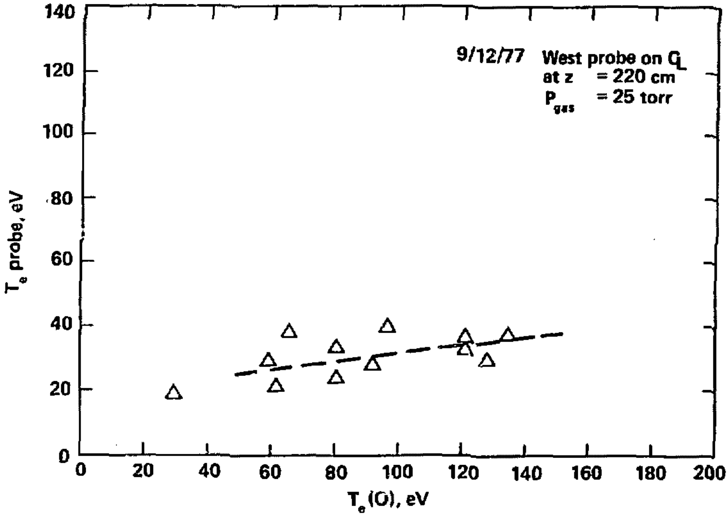

9/12/77
West probe on ℄
at z = 220 cm
P_{gas} = 25 torr
T_e probe, eV
T_e(O), eV
0
20
40
60
80
100
120
140
160
180
200

Figure 7

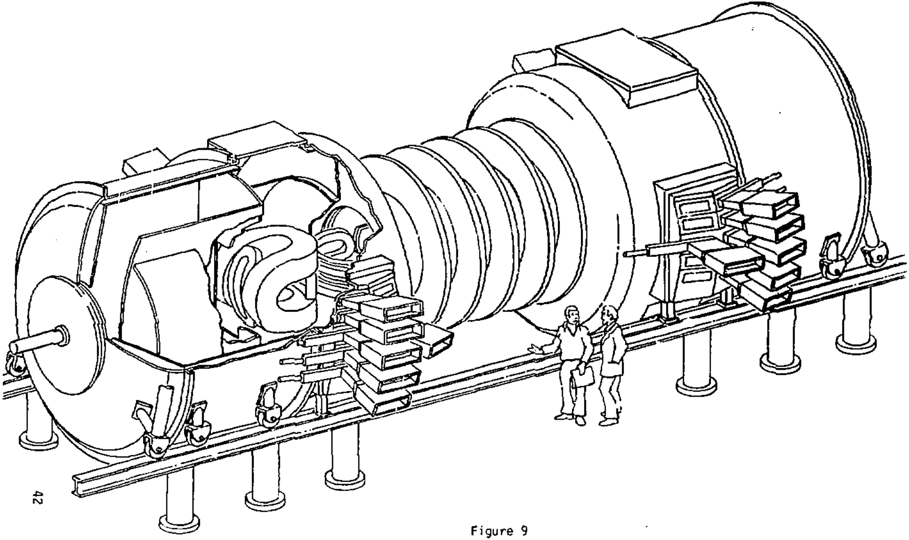


Figure 9

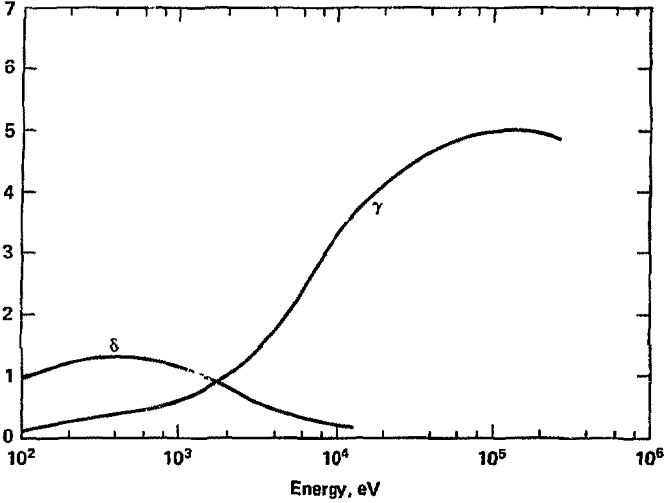


Figure 11

SECTION OF FLUX LINE PLOT FOR MULTIPLE MAGNETIC GRID ARRAY

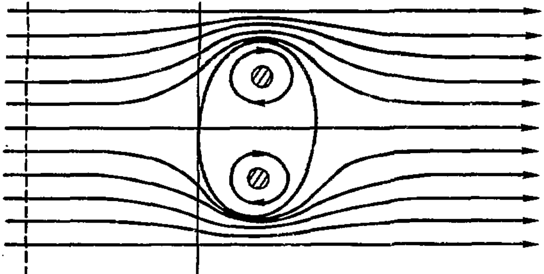


Figure 13

III. General Characteristics of the Plasma-Surface Problems in Mirror Systems

Both conventional and Q-enhanced mirror systems share an important feature in common: Field lines on which plasma is trapped or onto which it diffuses exit through the mirrors. Once beyond the mirrors these lines may be guided and expanded so as to impinge on large-area surfaces located at a substantial distance from the confinement region. The practical advantages of this circumstance are considerable. Depending on the amount of field expansion, energy fluxes onto the end chamber surfaces can be greatly reduced relative to those just outside the mirrors. Not only is this advantageous in extending all lifetimes against sputtering and blistering, but it can greatly ameliorate the twin problems of vacuum pumping and the refluxing of gas from the walls into the confinement region.

The above are advantages of the "natural diverter" action of mirror systems. But the very fact of the connectedness of field lines inside and outside the confinement region requires the minimization of the deleterious plasma cooling effects associated with plasma thermal conduction along the field lines. As later discussed, while 2XIIB has shown that thermal isolation along its field lines is far greater than that predicted from classical electron thermal conduction, substantial cooling effects are nevertheless evident. That plasma surface interactions play a role in this cooling is to be expected.

It is posssible to arrange, through the diverter action of the mirrors, that the radial boundary of the hot plasma lies well inside the radius of the chamber wall. Plasma surface interactions at the side wall are less important in mirror systems than they are in tokomaks where the plasma may touch the wall or a radial limiter. The radial "first wall" problem in mirror systems has been studied experimentally and theoretically[3-5] and is believed to be understood and under control. This paper will therefore concentrate on

IV. Theoretical Models of Longitudinal Energy Transport

Several theoretical models have been developed in the past to explain longitudinal energy losses from open-ended systems, not only mirror systems but also linear theta-pinches and similar devices. As will be shown, no single model adequately describes the 2XIIB results, but comparisons are nevertheless informative as an aid in uncovering the mechanisms at work.

A. The Hobbs and Wesson Model and the Morse Model

In connection with theta-pinch and cusp confinement studies Hobbs and Wesson[6] treated the problem of electron thermal conduction, including the influence of boundary sheaths and secondary electron emission at the bounding walls. Their calculations give heat flow rates and steady-state electron temperatures as a function of plasma heating rates, plasma lengths, and plasma density. As will be seen their model does not fit the 2XIIB data, but some of the mechanisms they discuss are undoubtedly present in 2XIIB in Regions II and III.

Based on their model, Hobbs and Wesson show the following:

1. The heat transmission, Q, through the boundary sheath at the wall can be written as

$$Q = \frac{1}{4}\, n_0\, \bar{v}_e \left[(2kT_e)\, F(\Gamma) \right] , \qquad (1)$$

where $\bar{v}_e = (8kT_e / \pi m_e)^{1/2}$, the thermal velocity of the (maxwellian) plasma electrons, and n_0 is the plasma electron density. The function $F(\Gamma)$ quantifies the insulating effect of the sheath potential (which retards the free flow of electrons) as modified by secondary emission at the wall; Γ is the effective secondary

$\Gamma_c = 0.85$ for a deuterium plasma at which point

$$F(\Gamma_c) = 0.33 + 2.2\mu^{1/2} = 0.37 \qquad (5)$$

Thus the maximum effect (in this model) of secondary emission at the wall is to increase thermal effusion by about a factor 3 relative to the case where $\Gamma = 0$.

2. The central electron temperature for a plasma slab located between two boundary walls at $X = \pm L$ metres is given by

$$T_0 = \left\{5.5 \times 10^{-4} PL^2 + \left[(9 \times 10^{-6} L)/(2F\tau)\right]^7\right\}^{2/7}, \text{ eV} , \qquad (6)$$

where P is the heating power input to the electrons in watts/m^3 and τ is a characteristic heating time defined through the equation (with appropriate units)

$$P\tau = \left(\frac{3}{2}\right) n_0 k T_0 . \qquad (7)$$

Again two limiting cases are to be distinguished:

a. When τ is sufficiently long compared to the electron transit time, $\tau_0 = L/\bar{v}_{e0}$, i.e. $\tau_0/\tau << F/3$, then the second term in (6) is negligible and

$$T_0 = \left[5.5 \times 10^{-4} PL^2\right]^{2/7} \text{ eV} . \qquad (8)$$

where A = 2 (deuterons) and $\bar{W}_i$ is the mean ion energy in eV.

Although in some of its aspects it is a more realistic model for 2XIIB than the Hobbs and Wesson model, Morse's result also does not agree with the *2XIIB data.*

B. <u>Modified Fokker-Planck Model</u>

An entirely different model of heat conduction out the ends of a mirror system is provided by the results of calculations using the so-called Fokker-Planck equation. This equation describes the collisionally-induced velocity-space diffusion and subsequent escape through the mirrors of plasma particles trapped between mirrors. In this model energy flow through the mirrors is to be determined by the self-consistent evaluation of the loss rates of electrons and ions as they diffuse into their respective loss-cones (hyperboloids in velocity space), as determined by the combined effect of the mirrors and the positive ambipolar potential that arises to balance electron and ion loss rates in steady state.

In its most-often-used form the F-P equation is solved simultaneously for the electrons and ions, with loss-cone angles determined by the mirror ratio and the ambipolar potential, ϕ_0.[8] Equating the loss rates of electrons and ions (required for a steady state) yields a self-consistent value for ϕ_0 of order 4 to 5 kT_e in magnitude, i.e. only the most energetic electrons with $W_{\parallel} > 4$ to 5 kT_e can escape. Another result: in steady state the electron temperature T_e is much lower than the ion temperature; $T_e/T_i \approx 0.1$ typically. That T_e does not approach equilibrium with T_i in steady state results from two circumstances: 1) Each plasma electron introduced by neutral beam injection is trapped at near-zero energy. 2) Ion-electron collisional energy transfer rates are relatively slow as measured on an ion-ion collision time scale (which sets the time scale for mirror confinement).

V. Summary of 2XIIB Results

We here summarize briefly recent 2XIIB data relating to the effects of plasma and surface-related phenomena (external to the mirrors) on energy and particle confinement within the mirror cell. Fig. 3 is a schematic drawing of 2XIIB; Fig. 4 is a photo of the actual experiment. For our present discussion the most relevant features are: 1) The high current neutral beam source array and the titanium gettered tanks within which the sources are mounted, and; 2) the large end tanks where exiting field lines terminate on titanium gettered walls.

Plasma buildup in 2XIIB is accomplished by impinging the neutral beams on a seed plasma produced by streaming plasma guns located at the far end of one of the end tanks. To stabilize the plasma against high frequency instabilities these same stream guns are employed and/or a baffled gas box located in Region II outside one of the mirrors is used. Energetic ions and electrons exiting from the plasma in Region I pass through the gas box, ionizing the gas within it thereby producing a low temperature plasma. A portion of this plasma penetrates into Region I, providing the stabilizing effect. Needless to say, this is a two-edged sword: The stabilization is achieved at a price, namely, it also provides a reservoir of cold electrons than can cool the central plasma by the mechanisms discussed by Hall.

Table I presents a set of typical 2XIIB experimental parameters showing progress achieved between 1975 and 1977 through improvements in beam and vacuum technique and other changes. For our purposes the most significant data are those concerning n_e, T_e and $\overline{W}_i$, electron density, electron temperature and mean ion energy (all in the central plasma). Note particularly the high central beta values achieved (1.7 in Table I; >2.0 in recent experiments).

VI. Comparison Between Theoretical Models and 2XIIB Data

A comparison between 2XIIB data and the theoretical models gives insight into the energy transport processes at work.

A. Classical Electron Thermal Conduction Model

We first compare the measured 2XIIB central T_e value with that which would be predicted using the Hobbs and Wesson results, equations (8) and (9). Even a rough comparison reveals the incompatability of their model with the high T_e values observed. First compare with Eq. (8).

$$T_o = \left[5.5 \times 10^{-4} \, PL^2\right]^{2/7} \quad . \tag{8}$$

The heating power P can be estimated from the fraction of the neutral beam trapped by ionization (as opposed to charge exchange on the beam which results in little net heating). A typical value (probably an upper limit) is 2×10^6 watts. The plasma volume is, typically, about 4 liters. Thus estimated $P \approx 5 \times 10^8$ watts/m^3. From Figure 5 we can estimate $L \approx 0.5$ m. Eq. (8) then gives $T_o \approx 24$ eV. To reach a T_e value of 140 eV, as observed under some conditions in 2XIIB would require by Eq. (8) that the heating power be increased by a factor $(140/24)^{7/2} = 480.$! Clearly the 2XIIB data cannot be explained by classical electron thermal conduction between Regions I and II.

Even if we use the Eq. (9) Hobbs and Wesson result (assuming that this might apply in some sense) agreement with 2XIIB is not obtained. Here

$$T_o = \left\{1.9 \times 10^{13} \, PL/Fn_o\right\}^{2/3} \quad \text{eV} \tag{9}$$

with P in watts/m^3, T_e in eV, $n\tau$ sec-m^{-3} and n_i in ions (electrons) per m^3. From Table I we take n_i = 1.5 X 10^{20}m^{-3}, T_e = 140 eV, and $(n\tau)_i$ = 10^{17} sec-m^{-3}. P may be estimated, as before, at 5 X 10^8 watts m^{-3}. We find, from Eq. (11), $\eta \approx 100$. Taken literally this result implies that for the operating conditions for which the above data were taken there existed a substantial degree of enhancement of the rate of energy transport by hot electrons, relative to the simple case of an isolated plasma. The discrepancy is also evidenced by the depression of T_e relative to simple F-P values. In 2XIIB $T_e/T_i \approx 0.016$, a factor of 6 below the value for an isolated plasma. Although valid in the case of an isolated plasma the tacit assumption made here in arriving at an η value, namely that only the electrons of the central plasma are involved in losses through the electron channel, is misleading. In the presence of external sources of electrons the total flux of excaping hot electrons, enhanced as a result of exchanges with influxing electrons from Regions II and III, can be much higher than the rate as calculated by normalizing it to the hot ion loss rate. The value of η found will be correspondingly reduced.

There are external sources of electrons which could stimulate losses through the electron channel . First, for these experimental runs gas box stabilization was used in which the neutral gas "current" introduced was of order 600 amperes equivalent. Introducing this into the electron balance results in dropping the calculated η value in 2XIIB to about 14. Second, as later discussed, it is possible that substantial numbers of secondary electrons are being formed in Region III and drawn into Region II. The presence of a flux of secondaries could account for the remaining discrepancy between η values of order 14 and the value for an isolated plasma.

VII. Control of Plasma Surface Interactions in the TM and the FRM

It is essential for the success of the Tandem Mirror idea, and probably also for that of the FRM, that the electron temperature in these devices should not be unduly influenced by plasma and surface phenomena external to the confinement zones. Fortunately it appears that the adverse mechanisms now operative in 2XIIB can be eliminated or at least greatly reduced in both the TM and the FRM.

Consider first the role of the streaming plasma used in 2XIIB to stabilize a particular high frequency mode, the DCLC (Drift Cyclotron Loss Cone)[15]. Note that there are two effects in a TM that can reduce the need for this plasma stream. First, the scaling laws for the DCLC mode show that as the plasma diameter as measured in ion gyroradii is scaled up the fractional density of stabilizing plasma needed drops markedly.[16] As can be seen from Table I the plasma in 2XIIB is only 2 to 3 orbit radii in radius, whence the requirement for a substantial stabilizing stream. Second, it appears that, inherent to its operation, there will exist an outward-flowing stream of plasma coming from the central cell that can supply a stabilizing effect for the end cells. If these two effects are adequate to suppress the DCLC mode in the end cells (The central cell will not suffer from loss cone instabilities since the plasma contained therein approaches a maxwellian distribution), then the problem in a TM should mainly be one of preventing the accumulation of plasma or neutral gas in Region II, and of suppressing the generation and/or the refluxing of secondary electrons born in Region III. Means to accomplish this end will be discussed in the next section.

For the FRM, once a field reversed state is achieved the plasma trapped therein should approach a maxwellian distribution, i.e. one not subject to the DCLC or other loss-cone modes. To be sure we are only now beginning to explore the FRM idea; its confinement and stability problems are largely due for completion in 1981-82, is shown in Fig. 10. MFTF will address physics problems related both to the TM and the FRM, at a level of size and input power not far below that expected in a mirror fusion power plant.

Several approaches to the control of secondary electrons are presently under study. Among these are:

- Electrostatic grids.
- Fins aligned with the exiting magnetic field lines.
- Magnetic multipole grids.

Before discussing these specific approaches we will review the nature of the secondary emission problem. Secondary electron emission under particle bombardment occurs from all solid surfaces. Uncontaminated metal surfaces generally exhibit the lowest secondary emission coefficients; gas-laden surfaces usually exhibit higher coefficients. The fraction, δ, of secondary electrons emitted from a clean metal surface upon electron impact rises to a maximum at 300-800 eV incident energy; $\delta_{max} > 1$ for most metals. Table II lists δ_{max} and V_{max} for several metals for impact at normal incidence. δ increases at oblique incidence.

The electron emission coefficient, γ, for release of electrons upon ion bombardment is of order 0.1 for metals at low ion impact energies but rises to 5 or more for W_i of order 10 keV or higher. Contaminated surfaces may exhibit much higher yields. Figure 11, based on Figure 3 in Hall[10] illustrates trends of both δ and γ for a typical clean metal surface.

Consider first the effects arising from ion impact. Energetic ions escaping from Region I release electrons upon bombarding an end wall. Returning, these electrons can exchange with electrons in the hot plasma, resulting in a net release of kT_e per exchange. The electron cooling per secondary electrons. (In 2XIIB the end walls are coated with titanium for which $\delta < 1.0$ - see Table II - and kT_e is relatively low compared to V_{max}.)

A. Electrostatic Grids and Direct Convertors

Suppressor grids, long employed in electron tubes, could be adapted to the problem at hand. Here matters are complicated by ionic space charge and power dissipation limits. Hamilton[18] has considered the use of grids in connection with the design of TMX and MFTF. Figure 12 illustrates schematically how such grids may be employed in TMX.* In establishing the dimensions and grid potentials the depression of potential between the grid wires caused by ion space charge and by fringing field effects must be taken into account. As to the former Hamilton gives an inequality to be satisfied in order for a repelling field to exist between the wires.

$$|V_g| > 2.3 \times 10^{-9} n_i a^2 \quad \text{volts,} \tag{16}$$

where V_g is the potential of the grid wires, a is the grid wire separation (in metres) and n_i is the incident ion density, ions/m^3. In an example for TMX where the maximum expected value of external density $n_i = 2 \times 10^{15} m^{-3}$ and a = 0.01 m Eq. (15) gives $V_g > 460$ volts. If, in addition, fringing field effects are considered V_g must be increased correspondingly, to compensate for the depression of potential.

*Dimov[7] is also considering the use of such grids in a TM under design at Novosibirsk.

stream, after magnetic expansion, should be collected on a venetian-blind-like set of metal fins that are aligned with the magnetic field lines as they exit through the fins. The width of the fins parallel to the field lines is made large enough (typically 50 cm in an example case for MFTF) to insure that transiting ions will impact them at some point along their helical trajectory. At the same time the spacing between fins is made small enough to insure collection of the lowest energy emerging ions ($W \approx e\phi_0$). The fins collect electrons emitted by ion impact through the action of the magnetic field parallel to their surface. They also act to reduce the refluxing electron current resulting from particle impact on the wall behind the fins.

Damm and Porter take into account the plasma sheath that develops on the fins and end wall, as modified by the collection of ions on the fins, of length L. They also take into account the presence of a background plasma of density n_b. Assuming a linear decrease in hot ion density n_h, with distance into the fin structure, they find

$$n_i = n_b + n_h (1 - z/L) \tag{18}$$

$$n_e = n_{eo} \exp \left\{ \left[\phi(o) - \phi(z) \right] / kT_e \right\} . \tag{19}$$

Imposing quasi-neutrality and the Child-Langmuir limit on current emission from the sheath at z = L they find a suppression factor owing to the introduction of the fins

$$S_f = \left\{ 1 + \left[kT_e/\phi(o) \right] \ln (1 - n_h/n_{eo}) \right\}^{3/2} (1 - n/n_{eo}) \quad . \tag{20}$$

pass between the grid wires at a field maximum. Thus a strong mirroring effect will act on the isotropically emitted secondary electrons originated at the end wall. Secondaries generated by particle impact on the grid wires will be trapped by the wire's magnetic field and returned to its surface. In considering a similar problem Hall[10] has pointed out that subtle considerations as to the plasma potential near the grid wires must be taken into account.

Variations on the basic multipole idea include charging the grid wires negatively, thereby achieving a combined electrostatic-magnetic effect. Another variation proposed by Baldwin[23] and by Post would be to use the grids and end wall as an r.f. transmission line to apply r.f. electric fields in the region between the wires and the wall. If resonant with the electron cyclotron motion over a region near the back plate, these r.f. fields (at frequencies of order 300 Mhz for a 0.01 T magnetic field at the wall) would enhance the mirroring action of the multipole field. This scheme is similar to the r.f. confinement systems considered by Watson.[24] With proper design it should be possible to take into account the effects of the sheath at the wall, thereby retaining effectiveness up to higher values of plasma density and electron temperature than would be possible without employing r.f. enhancement.

An estimate of the grid wire currents required to satisfy the flux condition mentioned earlier is readily made. An equivalent sufficient condition is that the x-points of the field separatrices should lie on the end wall surface. This condition is first stated by inspection for a single pair of wires and then generalized to N pairs of wires.

For a single pair, spaced w metres apart and located x metres from the end wall the critical condition is

IX. Conclusions

- The problem of plasma surface interactions in both conventional and Q-enhanced mirror systems is mainly concerned with phenomena arising in the end regions, namely those regions, usually far removed from the central plasma, where field lines that have emerged through the mirrors finally terminate on the end walls.

- High beta, high ion temperature MHD stable plasmas have been created and maintained confined in 2XIIB; these achievements provide a data base for the evaluation of energy loss processes and their relationship to plasma surface interactions.

- Comparison of 2XIIB data with two theoretical models: a) classical electron thermal conduction and, b) a modified Fokker-Planck model shows that the former does not fit the data while the latter does, if electron exchanges between the confined plasma and the region external to the mirrors are taken into account.

- There are reasons to believe that both the Tandem Mirror and the Field Reversed Mirror should be much less subject to energy exchange between the central plasma and the end regions than is now the case in 2XIIB.

- Several alternative approaches to the problem of reducing the refluxing of secondary electrons, a potentially serious source of cooling, are under study, together with studies of means to reduce the density of secondary plasma external to the mirrors.

TABLE I

Typical 2XIIB Parameters

	1975	1977
Machine parameters		
Neutral beam		
Aim	Head On	Tangential
Voltage (kV)	20	20
Current (A)	300	500
Duration (ms)	10	10
Stabilizing stream	Plasma gun	Gas box
Magnetic field		
Field strength B_{vac}(T)	0.67	0.67
Mirror ratio	2:1	2:1
Duration (ms)	10	10
Length mirror-mirror L (m)	1.50	1.50
Plasma parameters		
Density $n_i(m^{-3})$	5×10^{19}	1.5×10^{20}
Ion energy $\bar{W}_i$(keV)	13	13
Electron temperature (eV)	85	140
Beta $= 8\pi n W_i/B_{vac}^2$	0.6	1.7
Field reversal parameter $\Delta B/B$	0.3	0.7
$n\tau_E$ $(m^{-3}s)$	7×10^{16}	1×10^{17}
Plasma size		
Radius R_p (m)	0.07	0.06
Length L_p (m)	0.20	0.16
Volume (m^3)	5.5×10^{-3}	3.2×10^{-3}
Vacuum gyro radius a_i (m)	0.035	0.035
R_p/a_i	2.0	1.7
L/a_i	43	43

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Figure Captions

1. Schematic of the Tandem Mirror.
2. Field Configuration of the Field Reversed Mirror Sustained by Neutral Beam Injection.
3. Schematic of 2XIIB.
4. Photograph of 2XIIB Facility.
5. Density Distributions of Central Plasma and of External Plasma as Created by Gas Box.
6. Variation of Electron Temperature with Neutral Beam Current.
7. Trend of External T_e with T_e of Main Plasma.
8. Trend of T_e of Main Plasma vs Mirror Ratio.
9. Drawing of TMX Facility.
10. Cutaway Drawing of MFTF.
11. Trends of Electron and Ion-Induced Secondary Emission vs Energy of Bombarding Particle.
12. Schematic of Secondary-Emission-Suppressing Grids Designed for Use in TMX.
13. Portion of Field Line Plot of Magnetic Grid Field.

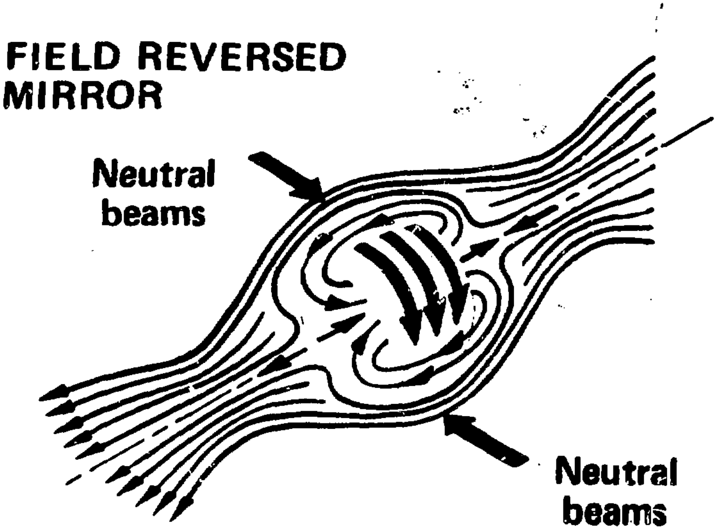

Figure 2

2XIIB

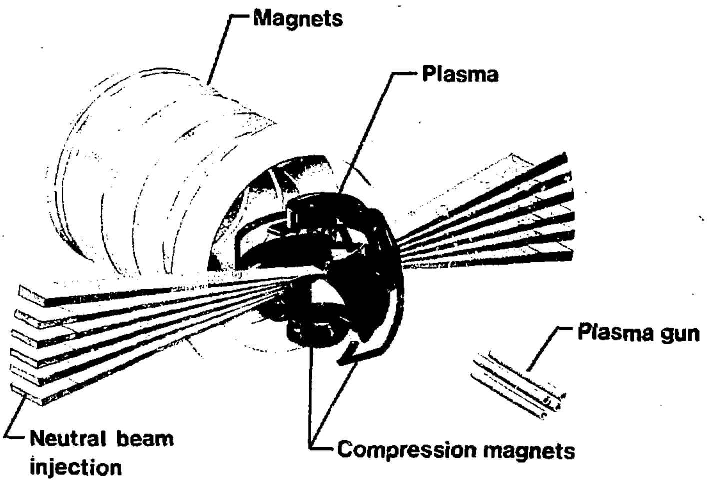

Figure 2

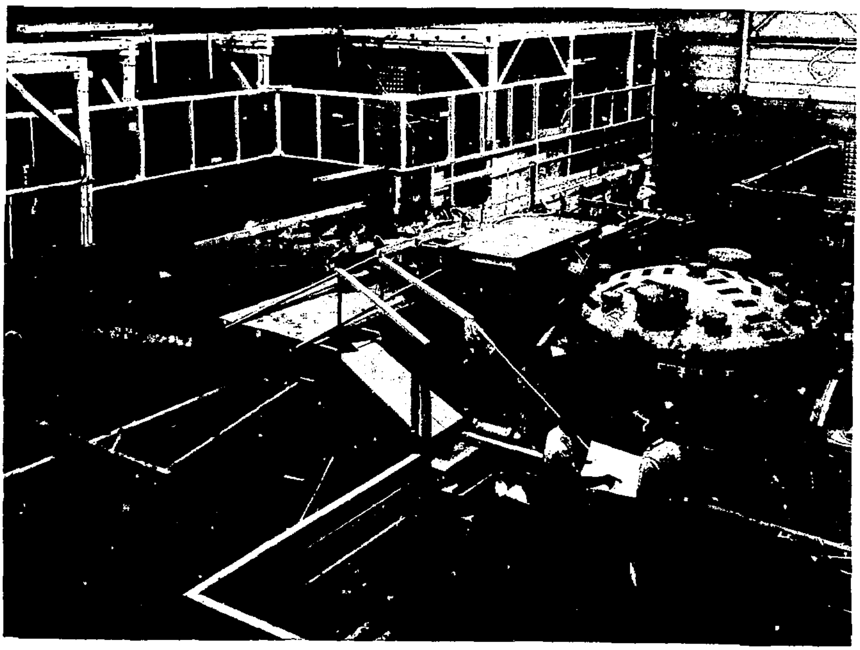

Figure 4

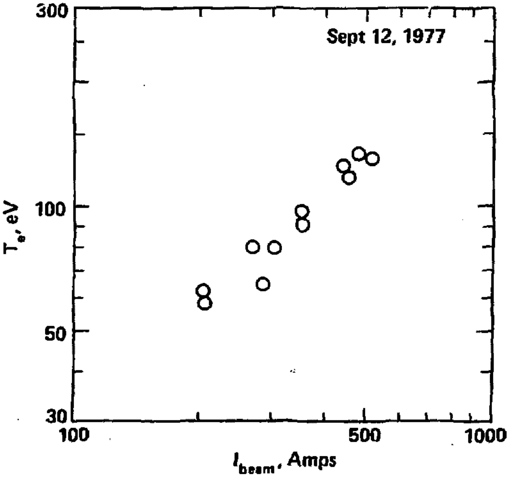

Figure 6

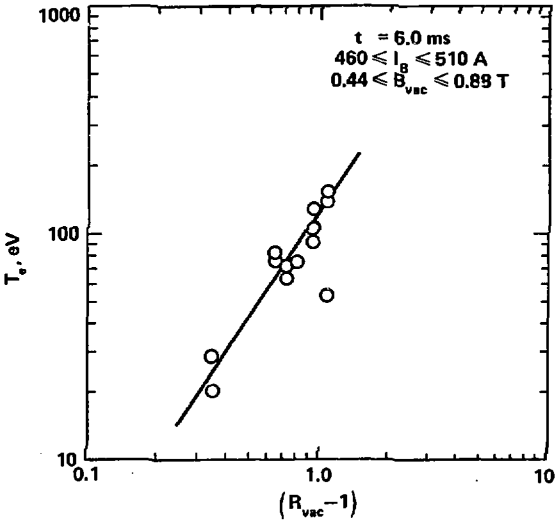

Figure 8

MFTF

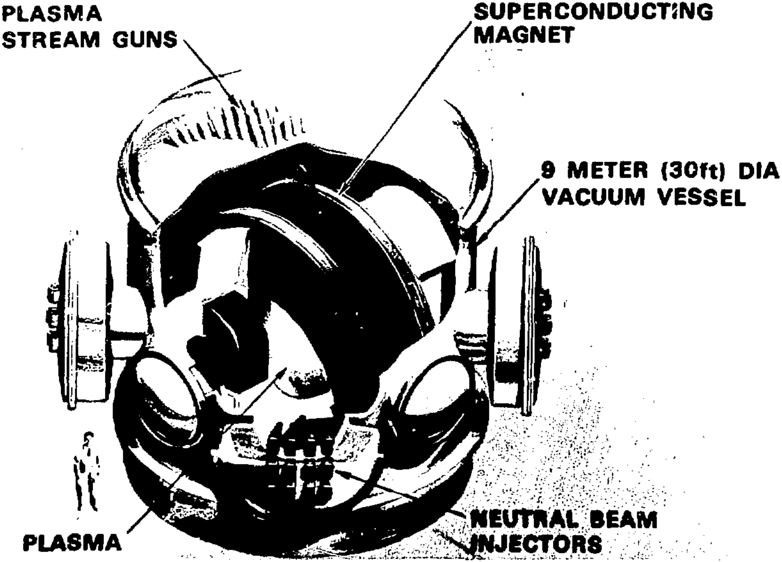

Figure 10

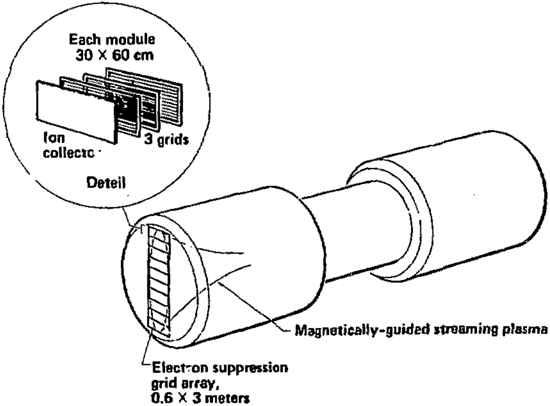
Each module
30 × 60 cm
Ion
collecto
3 grids
Detail
Magnetically-guided streaming plasma
Electron suppression
grid array,
0.6 × 3 meters

Figure 12