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STEPS TOWARD INCREASING Q IN MIRROR SYSTEMS*

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ABSTRACT

Experiments such as the 2XIIB experiment at Livermore have established the ability of mirror systems to confine high temperature, high density plasmas at central beta values exceeding unity. Given these results the next tasks for the mirror approach are to explore means for increasing the energy gain factor Q and to scale up the plasma volume, both of these requirements deriving from economic constraints. This report will discuss means for increasing Q, including recent improvements in the tandem mirror concept and design studies of the field-reversed mirror in the context of upcoming and proposed scaled-up mirror experiments.

Key words: Mirror fusion systems; tandem mirror, thermal barrier, field reversed mirror, mirror fusion test facility.

I) INTRODUCTION

The magnetic mirror approach possesses some inherent advantages with respect to fusion power. Its linear geometry, its natural diverter action, and its potential for operation at very high beta values all represent very desirable features from an engineering standpoint. Over against these favorable attributes is the problem of the low value of the power gain factor, Q, that characterizes conventional mirror systems. Given the broad base of physics understanding that now exists concerning mirror confinement, the U.S. mirror program is now tackling the next critical tasks en route to mirror fusion power plants. These tasks are:

- Extending present mirror physics understanding to encompass two alternative approaches to solving the problem of low Q - the tandem mirror and the field-reversed mirror.
- Scaling up the size of mirror experiments, more nearly to approach the scale of a practical system.

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In performing the above tasks technological issues assume an importance approaching the importance of the physics issues. These technological issues include the problems of initiating and maintaining the plasma entities involved, for example the high temperature plasmas required for the end plugs of the tandem mirror. The technologies required for this purpose include, for example:

- Neutral beam injection at high power density, proved out for mirrors in the ZKTB experiment at Livermore.
- Electron and ion cyclotron heating of mirror plasmas, demonstrated in work at Oak Ridge National Laboratory and elsewhere.
- High-field superconducting magnet coils. Demonstrated for mirror systems in the Livermore Baseball II experiment; now being scaled up in the Livermore MFTF system under construction.
- High speed vacuum pumping, using titanium gettering and cryopumping technologies. These techniques, developed at Livermore and at other fusion laboratories, are essential to the success of mirror systems.

On the conceptual side, the response to the problem of low Q in mirror systems has been, as mentioned, the development of the tandem mirror idea and the reemergence of the concept of field reversal (anticipated in the ASTRON concept of Christofilos), put forth in the idea of the field reversed mirror. These concepts are outlined in another paper at the symposium (Coensgen, Simonen, and Turner, 1979). In this paper we will discuss some new developments in the tandem mirror idea, the thermal barrier, proposed by Baldwin and Logan (1979) at Livermore. We will also discuss some aspects of the field-reversed mirror idea as visualized at Livermore for fusion power applications. Finally, we will outline work in progress and in planning for a large mirror facility, MFTF-B, that is intended both to test the new TM ideas and to provide a facility in which scaled-up FRM tests can be made.

II) TANDEM MIRROR WITH THERMAL BARRIER

The tandem mirror concept (Dimov, Zakaidov, and Kishinevsky, 1976; Fowler and Logan, 1977) attacks the problem of low Q by what is essentially a scaling approach. In the TM fusion occurs in a large-volume solenoid "plugged" at each end by electrostatic barriers. In a properly scaled TM the plasma confinement time should be determined by the mean time it takes ions of the central plasma to diffuse upward in energy until they can escape over the electrostatic barriers. In the TM these barriers are created by the ambipolar potentials of the conventional mirror cells located at each end of the TM. As far as Q is concerned the issues here are therefore:

1. The height of the ambipolar potential barrier.
2. The power per unit of plasma volume in the plugs required to maintain the ambipolar potential.
3. The volume of central plasma relative to that of the plug plasmas. This ratio, taken together with items 1 and 2, determines Q .

Design studies of the original TM idea showed that while the objective of increased Q (to 5 or more) relative to conventional mirror systems could be achieved, there were some drawbacks. For example, to create the desired

ambipolar potential in the end plugs by neutral beam injection alone required both the introduction of beams with energies of 500 keV to 1 MeV, and the need for high plasma densities. These requirements in turn triggered the need for very high magnetic fields (15 T) in the plugs. Overall, to achieve high Q under these conditions seemed to imply the necessity for high total power output, of order 1000 MWe.

While the virtues of the TM as first proposed remain substantial, it would be clearly advantageous to find means for reducing both the technological requirements of the plugs and the size - hence the electrical power output of the system. This desire was the motivation for the thermal barrier idea.

The first step toward this idea is the recognition that if it were possible to increase the electron temperature in the plugs beyond that attained by energy transfer from the plugs' ions alone, the plug ambipolar potential would increase. This result is evident from the usual equation for the magnitude of ambipolar potential difference between the plug plasma and the central cell plasma in terms of the density ratio n_p/n_c and the electron temperature in the plug (here the same as that in the central cell):

$$e\phi_c = kT_e \log_e \left(\frac{n_p}{n_c} \right). \quad (1)$$

The problem here arises from the fact that in order to raise the temperature of the plug electrons it is also necessary to heat the electrons in the central cell, there being free communication between the electrons in both plasmas. The idea of the thermal barrier is to interpose another short mirror cell between each plug plasma and the central plasma. In this intermediate cell the plasma density is actively depressed relative to that in either the central cell or in the plugs, leading in turn to a local value of the ambipolar potential that is less positive (i.e. relatively negative) with respect to the plug and central plasmas. This negatively dipping potential then acts as an electrostatic barrier to the electrons, impeding the flow of thermal energy between plug and the central cell region. It is now possible to apply ECRH to the plugs, thereby raising their electron temperature, without having to raise the central electron temperature correspondingly.

The variations in magnetic field, plasma potential, and particle density in a TM with a thermal barrier are shown schematically in Fig. 1. Given that the barrier functions to isolate the two plasma regions we may write, following Baldwin and Logan (1979), that the plasma densities in the three regions (plug, barrier and central cell) will be related through the equations:

$$n_b = n_c \exp(-e\phi_b/kT_{ec}) = n_p \exp \left[-e(\phi_b + \phi_c)/kT_{ep} \right]. \quad (2)$$

From Eq. (1) and (2) we therefore find,

$$n_p = n_c \exp \left[-e\phi_b/kT_{ec} + e(\phi_b + \phi_c)/kT_{ep} \right]. \quad (3)$$

Equation (2) shows that generation of the negative potential dip ϕ_b requires $n_b < n_c$, i.e. the barrier cell must be depleted of ions. On the other hand, as can be seen from Eq. (3), once the thermal barrier is in place it is not required that n_p should be greater than n_c in order to generate the

Fig. 1 Thermal Barrier

confining potential ϕ_c . Depending on parametric values n_p/n_c will always be reduced relative to the higher values required for a conventional TM, as reflected in Eq. 1. This result is of great economic significance, since it permits a major reduction in the complexity of the plugs and in the overall size of the TM system (an example case will be given in Section VI).

Although electrons from the central cell region and from the plug are repelled from the barrier, ions from the central cell that are not reflected by mirror action before they reach the plug mirror field are free to traverse the cell in the course of being reflected by the positive potential of the plugs. Thus even if no ions were to be trapped within the plug mirror cell there would be present a minimum ion density contribution from passing particles originating from the central cell. This contribution may be estimated, by particle flux conservation, to be

$$n_c(b) = n_c \left[\frac{1}{\pi^2} \left(\frac{kT_{ic}}{e\phi_b} \right)^{\frac{1}{2}} \frac{B_b}{B_c} \right], \quad (4)$$

where B_b is the (depressed) value of B in the center of the barrier region and $B_c > B_b$ is the strength of the central solenoid field, as shown in Fig. 1. To this density must be added the density of transiting ions that may become trapped in the barrier region. If no active means of removing these trapped particles were to be taken collisions would fill in the barrier until n_b reached equality with n_c and the barrier potential difference ϕ_b would vanish. The second requirement for the implementation of the barrier idea is to introduce means for preventing the accumulation of trapped ions in the barrier

region insofar as is possible.

Various means of achieving the pump-out of the ions trapped in the barrier cell are being considered. These include

- Transit-time heating of the longitudinal component of the trapped ions' energy by r.f. modulation of the barrier field.
- Periodic "purging" of the barrier cell by raising up the field between the barrier mirrors.
- Employing the transverse drift motions of trapped ions to cause them to be lost on bounding surfaces.
- Charge-exchanging of trapped ions with neutral beams injected nearly parallel to the field lines in the barrier region.

The last process mentioned, charge exchange with a neutral beam, appears to be one where both the requirement that detrapping should compete with collisional trapping rates and that the power needed should be acceptably low can be satisfied.

It should be emphasized that the thermal barrier idea is of sufficiently recent origin that its various ramifications are only beginning to be explored. One of these is for example the question of what effect the imposition of the barrier fields will have on the overall MHD stability of the TM plasma. Pearlstein (1979) has calculated that there will be a negative effect, albeit one which is weakened by increasing the mirror ratio B_0/B_z . Pressure-weighted MHD stable solutions can still be found, but central beta values may have to be reduced somewhat to avoid ballooning instabilities.

III) THE FIELD-REVERSED MIRROR - DESIGN STUDIES

The second main component of the U.S. mirror program is the investigation of field-reversed systems. The status of experimental work on field reversal in the U.S. has been reviewed in a companion paper in this symposium (Coensgen, Simonen and Turner, 1979) and will not be repeated here. Two key issues are now being addressed in this work. They are:

- Creating and maintaining field-reversed entities at fusion temperatures.
- Establishing plasma and confining field configurations that lead to MHD stability of the field-reversed entity.

In the FRM program at Livermore it is proposed to use high energy neutral beams both to aid in the initiation of field reversal and to maintain it in steady state, when this is required. The present experimental program at Livermore is geared to exploring the feasibility of this approach.

Looking toward the eventual application of the FRM idea for fusion power studies have been made at Livermore of the characteristics that a FRM might have. One study, commissioned by the Electric Power Research Institute, concentrated on one particular aspect of the FRM, its extremely efficient use of the confining field, and the compact fusion systems that this quality might thereby permit. A conceptual design was made of a single-cell FRM that would produce 20 megawatts of fusion power, yielding a net 2.5 megawatts of electrical power, more as a

demonstration unit than as a economically viable power plant. Fig. 2 is an artist's drawing of such a FRM; Table I summarizes some of its parameters. (Carlson and Schultz, 1979).

Fig. 2 Single-cell field-reversed mirror reactor.

TABLE I Parameters of the Single Cell FRM

	Megawatts
Fusion Power	20
Gross electric power	
From blanket ($M = 1.2$, $\eta_T = 0.35$)	5.9
From end leakage ($\eta_{DC} = 0.5$, $\eta_T = 0.35$)	5.2
Total	11.1
Recirculated power	
Injector input power ($\eta_I = 0.7$)	5.3
Copper coil power	3.3
Total	8.6
Net electric power	2.5

In the same EPRI-sponsored study previously referred to another possible approach to a FRM fusion power system is discussed. This idea, called a moving-ring FRM, involves the formation and subsequent compression of field-reversed plasma entities. Compression is accomplished by moving these entities into a converging field. Following compression and the resultant release of fusion energy the field-reversed entity would be decompressed by allowing it to move now into a region of diverging field lines at the exit end of the device.

If the moving-ring FRM could be perfected it would have several advantages as compared to a static system, including direct conversion of the plasma energy (by magnetic decompression), facilitated disposal of the reaction products, and physical separation of the functions of creating the FRM plasma, heating it and extracting energy from it.

IV) THE FIELD REVERSED MIRROR - SOME PHYSICS CONSIDERATIONS

As previously mentioned, one of the key issues in the FRM is the question of MHD stability of the field reversed entities. In the MHD limit (aximuthal mode number m approaching infinity) Newcomb (1979) and others have shown that in the axially symmetric case all such equilibria are unstable. However the experiments of Linford (1978) at Los Alamos and similar experiments in the Soviet Union (Eskov and co-workers, 1975), seem to show that elongated field-reversed entities can be stable against MHD modes for times greatly in excess of the usual MHD growth times. Elongated equilibria theoretically stable against MHD radial fluting modes have also been found by Barnes and Saylor (1978) of Los Alamos. It has also been conjectured by several investigators that finite-orbit stabilization effects could play an important role, stabilizing high m number modes, and therefore perhaps leading to overall stability in optimally-shaped FRM plasmas. Taken together these data and calculations, though not conclusive, encourage the belief that MHD-stable equilibria can be created and maintained once viable startup techniques are developed.

To illustrate the fusion potential of the FRM we will here employ a theoretical model, the so-called Hill's Vortex model, that though not wholly realistic, serves to demonstrate the salient features of a FRM - its compactness and its extremely efficient use of the confining field.

The starting point for finding the Hill's Vortex equilibrium solution is the Grad-Shrafranov equation (Grad and Rubin, 1958; Shrafranov, 1966), a partial differential equation relating the flux function, ψ , to the circulating plasma-diamagnetic current $j_{\theta}(r)$. This equation is

$$\frac{\partial^2 \psi}{\partial z^2} + \frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r} \frac{\partial \psi}{\partial r} = \frac{-8\pi^2}{c} r j_{\theta}(r) \quad . \quad (5)$$

The azimuthal current $j_{\theta}(r)$ may also be expressed as a function of ψ through the relation

$$j_{\theta} = C(\psi)r + D(\psi) \frac{1}{r} \quad , \quad (6)$$

where

$$C(\psi) = 2\pi c \frac{dp(\psi)}{d\psi} , \quad (7)$$

$$D(\psi) = \frac{1}{c} \frac{dI^2(\psi)}{d\psi} . \quad (8)$$

Here $p(\psi)$ is the scalar plasma pressure and $I(\psi)$ is the axial current threading through the region and producing a toroidal field component ($I(\psi)$ is assumed zero in the FRM case here considered, i.e. no toroidal field component is assumed).

The Hill's Vortex solution is found by setting $D(\psi) = 0$, $C(\psi) = \text{constant}$, i.e. $j_\theta(r) \sim r$ within the plasma, while $C(\psi) = 0$ outside the plasma.

Inside the plasma the flux function for a Hill's Vortex solution can be written as

$$\psi = \psi_0 \left(\frac{r^2}{R^4} \right) (2R^2 - r^2 - 4\alpha^2 z^2) . \quad (9)$$

Here R and α are parameters determining the physical size and the ellipticity (elongation), respectively, of the field-reversed entity. The case $4\alpha^2 \ll 1$ corresponds to a long cigar-shaped equilibrium.

We shall here adopt the special case of a spherical plasma boundary, since it illustrates many of the important features of the FRM, at the same time permitting analytic calculations of such parameters as fusion power density. While not necessarily realistic from the standpoint of MHD stability, based on the Los Alamos work there may exist Hill's-Vortex-like solutions that are MHD stable for the reasons cited earlier.

For a spherical plasma boundary, of radius a , where the field-reversed entity is immersed in a uniform vacuum magnetic field $B_z = B_0$, the solutions take the form (inside and outside the plasma)

$$\psi = \frac{-3\pi B_0}{2a^2} r^2 \left[a^2 - (r^2 + z^2) \right] , \quad (r^2 + z^2) < a^2 , \quad (10)$$

$$= B_0 r^2 \left[1 - \frac{a^3}{(r^2 + z^2)^{3/2}} \right] , \quad (r^2 + z^2) > a^2 . \quad (11)$$

Field lines of this solution, corresponding to $\psi = \text{constant}$ surfaces, are shown plotted in Fig. 3. We may also use the solution above to determine the variation of magnetic field within the plasma, thus the degree of field reversal achieved. At the midplane ($z = 0$), for example,

$$B = B_z = \frac{1}{2} \left(\frac{1}{r} \frac{\partial \psi}{\partial r} \right)_{z=0} , \quad (12)$$

$$= \frac{3B_0}{2} (a^2 - 2r^2), \quad r \leq a.$$

When evaluated at $r = 0$, $B(0) = -(3/2)B_0$, i.e. the field reversal factor $B(0)/B_0 = -(3/2)$.

The plasma pressure profile may also be evaluated, using Eq. (6). Thus we find $p \sim \psi + \text{constant}$;

$$p = \frac{B_0^2}{8\pi} \left\{ \left(\frac{3 \cdot 15}{4} \right) \left(\frac{r^2}{a^2} \right) \cdot \left[1 - \left(\frac{r^2}{a^2} + \frac{z^2}{a^2} \right) \right] \right\}. \quad (12)$$

The maximum value of p occurs at $z = 0$, $r = a/\sqrt{2}$, at which point

$$p_{\max} = \left(\frac{3 \cdot 15}{16} \right) \left(\frac{B_0^2}{8\pi} \right) \approx 2.8 \left(\frac{B_0^2}{8\pi} \right). \quad (13)$$

This last result illustrates a salient feature of field-reversal, the fact that the self-confining forces of field-reversed equilibria can lead to very high beta values relative to the vacuum field. Here $\beta_{\max} = 2.8$ for the spherical case; elongated equilibria would have somewhat lower values of β but values that would also be greater than 1.

Fig. 3 Plot of field lines in spherical Hill's Vortex field-reversed configuration. Figure courtesy of G. Miley, University of Illinois.

In Fig. 4, B_z/B_0 , B_z^2/B_0^2 and $\beta = p(r)/(B_0^2/8\pi)$ at $z = 0$ are plotted as a function of r/a . Note that the null point in B_z^2 , occurring at $r/a = 1/\sqrt{2}$ coincides

with the maximum point of p , as might have been expected intuitively. That is, $P_{\max}$ occurs at the low point in the self-excavated magnetic well created by the field-reversed entity.

Fig. 4 Plots of B_z/B_0 , B_z^2/B_0^2 and β_0 (evaluated at $z = 0$) as a function of r/a in spherical hill's Vortex field-reversed configuration.

We may use the analytic solution for plasma pressure, Eq. (12), to calculate the volume-averaged fusion power density for a field-reversed entity composed of fusion plasma and compare this result with other volume-averaged cases, for example, tokamaks. Using Eq. (12) and performing the indicated integrals,

$$\overline{n^2} = \frac{\int n^2 dV}{\int dV}, \quad (15)$$

$$\overline{n^2} = n_{\max}^2 \left[\frac{2^1 \cdot 2^2 \cdot 2^3 \cdot 2^4}{5 \cdot 7 \cdot 9 \cdot 11} \right] = 0.296 n_{\max}^2, \quad (16)$$

where $n_{\max}$ is the value of n at the point where $p = p_{\max}$. Carrying out the same average for a parabolic density distribution in a plasma of cylindrical cross-section (for example as in a tokamak), there results

$$\overline{n^2} = n_{\max}^2 / 3 = 0.333 n_{\max}^2. \quad (17)$$

We may therefore use these two results to obtain a rough measure of the relative efficiency of utilization of the external magnetic field in the two situations, i.e. FRM and tokamak. The fusion power density, P_f , varying as $n^2 \langle \sigma v \rangle$, therefore varies according to the relationship

$$P_f \sim \beta^2 B_0^4 \left[\frac{\langle \sigma v \rangle}{T_i^2} \right], \quad (18)$$

(ignoring the effect of T_e on beta,. We have therefore, for the same value of B_0 and, for now, the same T_i :

$$\frac{P_f(\text{FRM})}{P_f(\text{toroid})} = \frac{0.296 \beta_{\max}^2(\text{FRM})}{0.333 \beta_{\max}^2(\text{toroid})}. \quad (19)$$

If we now put in the value $\beta_{\max}(\text{FRM}) = 2.8$ and $\beta_{\max}(\text{toroid}) = 0.10$ as being representative of the maximum values likely to be achieved, we find

$$\frac{P_f(\text{FRM})}{P_f(\text{toroid})} = 700. \quad (20)$$

There thus exists, potentially, a very large gain in fusion power density for a FRM relative to low beta toroidal systems, reflecting a far more efficient use of the confining field. This efficient use of the confining field, inherent to the FRM, might be utilized in various ways, as follows:

- For the design of highly compact FRM's, as in the EPRI-sponsored design previously mentioned (Fig. 2).

- To allow the use of lower confining field intensities than required in toroids. At a field intensity only 30 percent of the toroid field (for example 3 T instead of 10 T), the power density in the Hill's Vortex case would still be almost 6 times as great as that for the toroid at the same ion temperature.
- To permit operation at high ion temperatures in order to improve the confinement (against classical losses) and to operate closer to the peak value of $\langle \sigma v \rangle$. At $T_i = 100$ keV, for example, the power density ratio (from Eq. 18) is 56:1 evaluated relative to a toroid operating at 20 keV and the same value of B_0 .
- To permit operation with advanced fuels, for example D-Helium-3, that require high ion temperatures and/or have lower $\langle \sigma v \rangle$ values than DT. For example, as calculated using Eq. (14), (16) and (17), at the same B_0 a FRM based on the case discussed above operating at $T_i = 200$ keV with D-He-3 would have a predicted power density ratio about 5 times that of the DT toroid operated at 20 keV.

In addition to the question of fusion power densities there are other quantitative issues that will enter into the attempts to implement the FRM idea. One of these issues has to do with the minimum number of particles required to effect field reversal through the action of their diamagnetic currents. In the FRM as visualized at Livermore, where the lion's share of the diamagnetic current is assumed to be carried by the energetic ions, it is possible to estimate this number. One such estimate can be derived from a "long layer" theoretical model of a FRM plasma (Post, 1978) which may be roughly representative of a realistic FRM configuration. According to this model the number of ions required per centimeter of length of the FRM is given by the expression

$$N = N_0 \left[\lambda \left(\frac{a}{a_0} \right)^2 \left(1 - \frac{s}{a} \right) \right] \text{ cm}^{-1} \quad (21)$$

where

$$N_0 = \frac{1}{2} (Mc^2/e^2) = 0.65 \times 10^{16} \text{ cm}^{-1} \text{ for deuterons.}$$

The quantity (a/a_0) is the ratio of the outer radius of the FRM plasma to the gyroradius of the ion in the vacuum field; from the theory it is required that $a/a_0 \gg 2.0$ for strong field reversal. The quantity s/a is the ratio of the inner to the outer radius of the FRM plasma; normally $s/a \ll 1$. The quantity λ , a parameter given by the theory, is essentially a "beta" factor for the outer boundary of the FRM plasma. For a long layer where $a/a_0 \gg 2.0$ and $s/a \ll 1$, λ approaches 1. Specifically,

$$\lambda = \frac{\frac{1}{2} n(a) M v^2}{(B_0^2/8\pi)} \quad , \quad (22)$$

i.e. it is equal to the kinetic energy density of the ions at the outer boundary of the FRM divided by the energy density of the vacuum field.

Putting in the value $a/a_0 = 5$, a rough lower limit for that parameter in a strongly field-reversed FRM, and taking $\beta_0 = 1$, we find

$$N \approx 1.6 \times 10^{17} \text{ cm}^{-1}.$$

We may use this number to estimate the minimum neutral beam injection current required to maintain an FRM plasma. Thus if the mean lifetime of the ions in the FRM plasma is, for example, 0.1 sec, the above requirement for N implies the need for a trapped neutral beam current (deuterons) of about 27 amperes per meter of FRM plasma. Provided such a field-reversed entity can be initiated the technical requirement of supplying the neutral beam currents to maintain it against classical losses appear to be well within the capabilities of present-day sources.

To complete the example above with respect to other fusion parameters we note that the radial density profile for this field-reversal model is given by the expression

$$n(r) = \frac{1}{2} n_0 \cdot \left(\frac{\beta}{\beta_0} \right)^2 \cdot \left(\frac{1}{r^4} \right) \text{ cm}^{-3} \quad (23)$$

As shown previously the beta value at $r = a$, as measured with respect to the vacuum field, approaches unity for $(a/a_0) \gg 1$. We therefore see from Eq. (23) that for $r \leq a$, beta, varying as r^{-1} will be given by

$$\beta(r) = \beta(a) \left(\frac{a}{r} \right), \quad r \leq a, \quad (24)$$

i.e. the mean value of beta will be larger than 1 in this FRM model, as it was in the Hill's Vortex model. In fact one finds for the fusion parameters $\overline{n^2}$ and $\overline{n}$ the values

$$\overline{n^2} = n^2(a) \left[2 \log_e \left(\frac{a}{s} \right) / \left(1 - \frac{s^2}{a^2} \right) \right], \quad (25)$$

$$\overline{n} = n(a) \left[2 / \left(1 + \frac{s}{a} \right) \right]. \quad (26)$$

Taking $(s/a) = 0.2$ for example, one finds

$$\begin{aligned} \overline{n^2} &= 3.4 [n(a)]^2, \\ \overline{n} &= 1.7 n(a), \end{aligned}$$

i.e. the reactivity of this field-reversed column is approximately 3.4 times that of a constant density $\beta = 1$ plasma column. This then is another example of the efficient use of the confining field in FRM systems.

In the earlier example with $a/a_0 = 5$, if we now take $B_0 = 5$ T and $a_0 = 1.0$ cm (60 keV deuterons), we find from Eq. (23)

$$n(a) = 10^{15} \text{ cm}^{-3};$$

$$n(b) = 5 \times 10^{15} \text{ cm}^{-3}.$$

$$n = 1.7 \times 10^{15} \text{ cm}^{-3}.$$

For this example the plasma column diameter $2a = 10$ cm and the DT fusion power released would be approximately 560 watts/cm^3 or 4.4 MW per meter of plasma column. These figures and those given in the earlier example are of course only rough indices of the kinds of fusion parameters that might be achieved if FRM fusion systems become a reality.

In addition to the caveat concerning the MHD stability of FRM plasmas there is another important caveat concerning the above example and the neutral beam current requirements that were mentioned. In the above the estimates given are based on the tacit assumption that the current-cancelling effects of the electrons can be neglected. Baldwin and Fowler (1978) have estimated however that partial cancellation of the ion diamagnetic currents by the electrons might double the neutral beam current requirements, in order to maintain the required net diamagnetic current. This increased requirement should still be well within present source capabilities, provided again that reasonably long ion lifetimes are achieved.

V) SCALED-UP MIRROR EXPERIMENTS - MFTF AND MFTF-B

In order to proceed further toward the fusion goal with the mirror approach it is necessary to scale up the size and power level of mirror experiments. From the physics viewpoint scale-up is needed to round out and to confirm theoretical extrapolations. These extrapolations concern the stability of mirror plasmas and the improved confinement that is predicted to occur as the plasma ion and electron temperatures are increased. From the standpoint of engineering and technology it is important to increase the size, the power level and the confinement time of mirror plasmas so that these parameters more nearly approach those expected in fusion power plants. To these ends construction work has been underway since October 1977 on a large new mirror facility, MFTF. Recently, growing interest in the tandem mirror idea has led to consideration of enlarging this facility so that it could be operated as a tandem mirror, as well as meeting its original objective of providing a scaled-up facility within which mirror and FRM physics and technology issues could be tested. Given continued encouragement from the TMX tandem mirror experiment at Livermore a formal proposal to implement the MFTF-B plan will be made. The MFTF facility now being constructed is discussed in a paper at this symposium (Coensgen and Simonen, 1979).

The scale of MFTF-B and its relationship to the presently-authorized MFTF can be discerned from Fig. 5, which depicts a conceptual design of MFTF-B. On the right of the figure is the large MFTF mirror cell now under construction; in the center and left are the proposed central chamber and a second mirror cell, a duplicate of the present MFTF cell. Note that the overall length of MFTF-B is approximately 60 meters and that of its central solenoid is approximately 20 meters. The bore of the central solenoid is approximately 4.4 meters. These dimensions are large enough to provide a significant test of the scaling laws of the TM principle. Fig. 6 shows how MFTF-B would be located within an existing building at Livermore, enlarged at one end to accommodate the solenoid and second TM plug.

Fig. 5 MFTF tandem configuration (MFTF-B)

With the emergence of the new thermal barrier idea thought has been given to the possibility of including thermal barriers as an option in MFTF-B. Fig. 7 shows a side view of an MFTF-B coil system with the inclusion of a pair of barrier coils. Also shown below the drawing is a plot of the magnetic field strength on the magnetic axis for this particular configuration. Studies are underway aimed at optimizing the field distribution from the standpoint of MHD stability. Fig. 8 shows the general coil arrangement in perspective.

The predicted effect of the thermal barriers in upgrading the performance of a TM of the size of MFTF-B is remarkable. Table II compares the predicted performance of MFTF-B with (high Q mode) and without (two-component mode) its thermal barriers activated. As will be noted, the inclusion of the thermal barriers is predicted to raise the Q value by an order of magnitude - to or beyond the $Q = 1$ breakeven point.

Returning to the question of the physics issues that are to be addressed in MFTF/MFTF-B, these may be divided into two kinds. There are first those that have to do with the physics of the plugs. These are primarily the issues of stabilization of high frequency modes and of maximizing the ambipolar potential (which requires a high T_e). The second class of problems concerns issues of MHD stability and radial transport in the central cell of the TM. Here it is hoped that theory, as guided by results from the Livermore TMX and from other tandem mirror systems (AMBAL-1 in Novosibirsk, Phaedrus at the University of

TABLE II Approximate Parameters for Two Operating Scenarios for MSTF-B

	Two-component mode	High-Q mode with thermal barriers
End plugs:		
E_{inj} (kV)	80 (0.5 s)	150 (30 s)
n_p (cm ⁻³)	10^{14}	10^{13}
T_e (keV)	1	100
r_p (cm)	20	40
B_p (T)	2	2
Center Cell:		
E_{inj} (kV)	80 (0.5 s) ^b	80 (0.5 s)
n_c	3×10^{13}	3×10^{13}
T_e (keV)	1	10-20
T_i (keV)	0.3	10-20
B_c (T)	0.5	1.5
L_c (uniform) (m)	25	15
n_{t0} (cm ⁻³ s)	$1-2 \times 10^{17}$	10^{14}
Power gain ^a :		
$Q_{effective}$	0.1	1

^aAs if a DT plasma; the actual experiments will use pure deuterium.

^bThe 150-keV beams needed for the high-Q mode might also be used in the two-component mode for short pulses (0.5 s).

Fig. 6 MSTF-B in extended Building 431 with cutaways to reveal arrangement of machine components and subsystems in the building.

Fig. 7 MFTF-B coil system and field plot with barrier field included

Fig. 8 Perspective view of MFTF-B coil system with barrier coils included.

Wisconsin, and Gamma 6 at Tsukuba University in Japan) will provide an initial data base upon which to build.

Important though the MHD and radial transport issues are, these are less central to the success of the TM than the issues of high frequency instabilities and electron temperature. These questions have been discussed in the companion paper to this one at this symposium (Post, 1979) and will only be touched on briefly here.

Fig. 9 Theoretical curve showing downward trend in stabilizing stream density vs R_p/a_i .

The key issue is likely to be the question of stabilization of ion cyclotron instabilities, the most important of which is the drift cyclotron loss cone (DCLC) mode. The DCLC mode is a azimuthally propagating electron drift wave driven unstable at or near the ion cyclotron frequency. Its virulence depends upon the steepness of the radial density gradient of the plasma, proportional to the dimensionless parameter $(R_p/a_i)^{-1}$, where R_p is the radial scale length of the plasma and a_i is the mean ion orbit radius. In the Livermore 2XIIB experiment the theoretically predicted stabilization of the DCLC mode by a

Fig. 10 MFTF 80 keV - 80 "Amp" Neutral Beam

warm plasma stream was demonstrated. Because of its small plasma radius ($R_p/a_i \approx 3$), and hence its steep radial density gradient, 2XIIB required a warm plasma stream density equal to several percent of the density of the hot plasma, leading in 2XIIB to an unacceptably large depression of the electron temperature (to ~100 eV, down from the value of 500 eV - 1 keV for an isolated mirror plasma). However the same theory that predicted stabilization in 2XIIB shows that by scale-up, i.e. by increasing R_p/a_i , the fractional amount of warm plasma required for stabilization should drop to tolerably small values. Fig. 9 illustrates this trend as calculated from the theory (Baldwin, Berk and Pearlstein, 1976). Since R_p/a_i in MFTF/MFTF-B can be as high as 20 or more, it is seen that the reduction in the required fractional density of warm plasma fraction is marked.

In MFTF/MFTF-B there exists yet another possibility for minimizing the cooling effects of warm plasma. Because of the large number of independently steerable neutral beam sources that will be employed (24 80 keV 50 ampere beam modules in MFTF, see Fig. 10), it is possible to build the plasma up with a flat-topped radial distribution, i.e. one in which there is little or no radial gradient within the plasma body. Such a radial distribution, as calculated from a Fokker-Planck buildup code, is shown in Fig. 11. Under these conditions appreciable amounts of warm plasma stabilization would be required only at the periphery of the plasma; the interior should require little or none.

With the size, power, and flexibility built into the design of MFTF/MFTF-B it will be possible to make realistic tests of the above and of other plasma

Fig. 11 Calculated plasma density profile in MFTF from BUILDUP code.

stabilization techniques in a way not possible in 2XII-B or in TMX, owing to their much smaller size.

MFTF is also planned as a test bed for FRM studies, provided upcoming experiments in the Livermore Beta II facility (2XII-B modified) or other field-reversal research pave the way. With its central field of 2 T, MFTF could, for example, in principle contain a 50 keV ion temperature Hill's Vortex-like plasma with a peak ion density (calculated using Eq. 13) of about $3 \times 10^{14} \text{ cm}^{-3}$, a volume of 50 liters (at $a/a_0 = 10.0$, for example, to take some advantage of finite-orbit stabilization effects) and a DT-equivalent fusion power yield of about 500 kilowatts. At this level its FRM plasma would be of a size comparable to that visualized for the single cell FRM of the EPRI study (Fig. 2).

VI) TANDEM MIRROR POWER PLANT STUDIES

Conceptual studies of the application of the tandem mirror principle to fusion power generation have been underway since the idea's first inception. Prior to the introduction of the thermal barrier idea those studies seemed to have pointed to the following conclusions:

- A modest-sized low Q tandem mirror could be designed as a driver for a fusion-fission hybrid "fuel factory" having reasonable technological demands (beam energies, magnetic field, etc.).
- A pure fusion $Q = 5$ to 10 tandem mirror could be designed but would require extrapolated technology (500 keV - 1 MeV neutral beams, 15 T magnets). It would be large in size and would not be economically viable except at the 1000 Mwe level.

With the introduction of the thermal barrier idea, however, a major improvement in Q and in the economic picture emerges. Carlson (1979) has performed conceptual point design studies illustrating improvements, in Q , in less demanding technology, and in reduced power output that could result from the use of thermal barriers. Fig. 12 from Carlson's studies shows an artist's conception of such a TM power plant, and Table III lists some of its design parameters. The thermal barrier idea is clearly worthy of further investigation.

Fig. 12 500 MWe Tandem Mirror Power Plant with thermal barriers.

TABLE III Thermal Barrier Tandem Mirror Reactor
Preliminary Parameters for a Unoptimized Design

Fusion Power = 1770 MW (3160 MW for larger version)
Estimated net power = 500 MWe (1000-1100 MWe for larger version)
Plasma Q = 11 (20 for larger version)

Central Cell

Length = 56 m (100 m for larger version)
B = 2.8 T
Coil outer diameter = 6.8 m
Plasma radius = 1 m, $\beta = 0.75$ (satisfies MHD criterion)
First wall radius = 1.4 m
Neutron loading = 2.9 MW/m²

Plug (each)

Yin Yang coil set
Plasma radius = 0.75 m, $\beta = 0.6$ (satisfies DCLC criterion)
 $B_0 = 4$ T, $B_{\text{mirror}} = 6$ T, $B_{\text{max}} = 8$ T
Coil set outer diameter = 6.5 m
Neutral beam injection = 2 MW at 400 keV (5A)

Thermal Barrier (each)

Barrier coil: Solenoid, 4.5 m long, 3.5 m outer diameter,
 $B_0 = 12$ T, $B_{\text{max}} = 12.5$ T
B at barrier minimum = 1.2 T
ECRH heating = 54 MW at 60 GHz
Barrier pump beams = 27 MW at 40 and 90 keV

Direct Converter

Circular cross section, 100 W/cm² power density
Diameter = 18 m (22 m for larger version)

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