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R.F. Post, J.A. Byers, R.H. Cohen, T.K. Fowler, D.D. Ryutov, L.S. Tung

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PROGRESS TOWARD THE ANALYSIS OF THE KINETIC STABILIZER CONCEPT*

R. F. Post, J. A. Byers, R. H. Cohen, T. K. Fowler,
D. D. Ryutov, L. S. Tung

Lawrence Livermore National Laboratory
Livermore CA, 94550 U.S.A.

ABSTRACT

The Kinetic Stabilizer (K-S) concept [1] represents a means for stabilizing axisymmetric mirror and tandem-mirror (T-M) magnetic fusion systems against MHD interchange instability modes. Magnetic fusion research has given us examples of axisymmetric mirror confinement devices in which radial transport rates approach the classical "Spitzer" level, i.e. situations in which turbulence if present at all, is at too low a level to adversely affect the radial transport [2,3,4]. If such a low-turbulence condition could be achieved in a T-M system it could lead to a fusion power system that would be simpler, smaller, and easier to develop than one based on closed-field confinement, e.g., the tokamak, where the transport is known to be dominated by turbulence. However, since conventional axisymmetric mirror systems suffer from the MHD interchange instability, the key to exploiting this new opportunity is to find a practical way to stabilize this mode. The K-S represents one avenue to achieving this goal.

The starting point for the K-S concept is a theoretical analysis by Ryutov [5]. He showed that a MHD-unstable plasma contained in an axisymmetric mirror cell can be MHD-stabilized by the presence of a low-density plasma on the expanding field lines outside the mirrors. If this plasma communicates well electrically with the plasma in the then this exterior plasma can stabilize the interior, confined, plasma. This stabilization technique was conclusively demonstrated in the Gas Dynamic Trap (GDT) experiment [6] at Novosibirsk, Russia, at mirror-cell plasma beta values of 40 percent. The GDT operates in a high collisionality regime. Thus the effluent plasma leaking through the mirrors, though much lower in density than that of the confined plasma, is still high enough to satisfy the stabilization criterion. This would not, however, be the case in a fusion T-M with axisymmetric plug and central cell fields. In such a case the effluent plasma would be far too low in density to stabilize the plasmas in the plug cells and the central cell.

The K-S resolves this dilemma by employing ion beams injected up the magnetic gradient in the "expander" region outside the outermost mirror in such a way that as they are compressed, stagnated, and reflected they form a "stabilizer" plasma in the expander. Preliminary calculations [1] showed that the power required to maintain the stabilizer beams would be orders of magnitude less than the fusion power generated. This report reviews those calculations and describes additional theoretical and computational work in progress, aimed at confirming and extending the analysis of the K-S concept as applied to axisymmetric tandem mirror systems.

1. INTRODUCTION

The magnetic-mirror approach to fusion has had a long history of development, being one of the first-suggested means for solving the confinement problem of magnetic fusion. This paper is concerned with a possible solution to a problem, the MHD instability of axisymmetric mirror systems, particularly as it pertains to tandem-mirror systems.

The 50-year-long history of research into the confinement of plasma in magnetic fields should have taught us one clear lesson. The lesson is that there is a fundamental difference in the character of plasma confinement between that in so-called "closed" systems, such as the tokamak, the stellarator or the reversed-field pinch, and "open" systems, such as those based on the use of the magnetic mirror principle to provide axial confinement. Closed systems, with no known exceptions, show confinement that is dominated by turbulence-related processes, rather than by "classical," i.e., collision-related, processes. As a result, to achieve confinement adequate for fusion power purposes in, for example, the tokamak requires that it be scaled up in size and power level to the point that its ultimate practicality as an economically viable source of fusion power is open to question. By contrast, from earliest days there have been examples of open systems where turbulence, if present at all, is at such a low level that only collision-related processes play a significant role in determining the confinement. Furthermore, within the class of mirror-based systems, those with axisymmetric magnetic fields, (i..e., solenoidal fields produced by coaxial circular coils), have most clearly attained cross-field transport rates approaching the classical, "Spitzer" [7] rate predicted for such fields. Given this circumstance, in a search for simpler and smaller fusion power systems than those based on closed-field topology, axisymmetric mirror-based systems appear to offer much promise.

Standing in the way of implementing new forms of axisymmetric mirror-based fusion power systems is the long-understood tendency of such systems toward MHD instabilities of the "interchange" variety [8], a type of instability that leads to a coherent drift of the confined plasma column across the confining field. This type of transport of the plasma column across its confining field is to be contrasted with the enhanced-diffusion type of transport associated with the turbulent processes encountered in closed systems. As experiment has shown (for example, in the axisymmetric-field Gas Dynamic Trap at the Budker Institute in Novosibirsk [4]) when the MHD interchange instability is suppressed, the rate of transport of the plasma across the magnetic field can approach the slow diffusion rates expected from inter-particle collisions, namely the Spitzer-predicted rate. The GDT experiment [6], and theory that preceded it [5] represent, in fact, the starting points for the Kinetic Stabilizer concept [1], selected aspects of which will be discussed in this paper.

The stabilization method employed in the GDT is based on the following plasma physics considerations, reviewed briefly here: In an axisymmetric mirror cell for which the ratio of the mean ion orbit radius to the radius of the plasma, r_i/a, is greater than the ratio of the plasma radius to the cell length, so-called "finite-orbit" effects stabilize all but the lowest order MHD interchange mode. This "m = 1" mode corresponds to a simple sideways drift of the plasma column as a whole.

For the m= 1 mode, as with all interchange modes, the source of free energy is the energy of expansion of the plasma that arises from the circumstance that in an axially symmetric mirror cell the volume of a given tube of flux increases if that tube is transported in the radial direction. The geometric origin of this effect lies in the competition between the regions of positive and negative field-line curvature that characterize the magnetic field between the mirrors. As shown by the theory [8] the region of negative field-line curvature (outwardly decreasing field strength) midway between the mirrors always wins (if only slightly) over the regions of positive curvature (outwardly increasing field strength) located near the mirrors.

Better to define the plasma physics issues associated with the stabilization method employed in the GDT (and the one that is to be employed in the Kinetic Stabilizer) it is helpful to consider the interchange instability from the standpoint of plasma currents and particle drifts. Looked at from that aspect, the interchange instability arises from the fact that in regions of negative field-line curvature the particle currents associated with the oppositely directed azimuthal drifts of the ions and electrons, if not canceled by current flow along the field lines from other regions of the plasma, would result in an azimuthally directed electric field in that region. In that azimuthal electric field the ions and electrons would together perform an outwardly directed (**E** x **B**) motion. Stabilization occurs when three conditions are satisfied. The first condition is that there should exist a region or regions of positive field-line curvature down the field lines from the region of negative field-line curvature. The second condition is that these regions should be extensive enough so that the accumulative effect of the electron and ion drifts in them produces canceling currents that are sufficient to overcome the destabilizing charge separation that arises in the regions of negative field line curvature. The third, equally important, condition that must be satisfied is that there should exist a sufficient density of plasma on the field lines between the regions of negative and positive curvature to allow the uninhibited flow of the neutralizing currents that suppress the instability.

Returning now to the situation in the GDT, since the field-line curvature of the field lines emerging outside each mirror is strongly positive it follows that if a sufficient amount of plasma were to be present outside the mirrors, and if this plasma can electrically "communicate" adequately with the interior plasma, it can stabilize the interior, contained, plasma. As the theory shows [5] the plasma in the expander can be orders of magnitude lower in density and pressure and still be sufficiently dense to stabilize the interior plasma.

In the GDT, which operates in a dense and highly collisional plasma region where the mean-free-path for ion-ion collisions is shorter than the length of the plasma, the effluent plasma leaking through the mirrors, even though much lower in density than the interior, confined, plasma, is still sufficiently dense to satisfy the three conditions stated above. As a result it MHD-stabilizes the confined plasma at the remarkably high plasma beta value of 40 percent. However, if we consider the situation that would be encountered in a conventional tandem-mirror fusion system a different picture obtains. Such systems would operate at plasma temperatures and densities where the mean-free-path for ion-ion collisions is long compared to the length of the plasma. In such a case the effluent plasma density would be too low to stabilize the interior plasma and other means must be sought. The long-standing conventional approach to solving the MHD stability problem has been to abandon axisymmetry and to employ multi-pole magnetic-well fields, involving "baseball" or "yin-yang" [9] coils in the mirror cells, following the lead of the classic mirror experiment performed by Ioffe [10] in the 1960's.

Though highly effective in stabilizing MHD modes, the use of non-axisymmetric fields not only introduces transport-producing "bounce-resonant" particle drifts [11], but also increases the complexity of the magnetic field coils of a tandem-mirror system. A consequence of this field-coil complexity is that it severely constrains the field strengths that can be attained in the mirrors and it inhibits the ability of the designer to reduce the volume of the plasma in the plug mirror cells in order to of minimize the power required to maintain the plugging plasmas contained in these cells.

2. THE KINETIC STABILIZER CONCEPT

The Kinetic Stabilizer concept as applied to axisymmetric mirror-based systems has been described in previous papers [1,12]. Its starting point was an earlier concept, the "Kinetic Tandem" [13]. The idea is to create in situ a localized plasma on the expanding field lines lying outside the outermost mirror of an axisymmetric tandem-mirror system. This localized plasma is to be created by the "kinetic" technique of launching directed ion beams from ion sources lying still farther out on the expanding field lines. These ions, aimed at small angles to the local direction of the field lines, would be compressed, stagnated, and reflected at a pre-determined position on the converging field lines, chosen so as to optimize the stabilizing effect of the beam-produced plasma. What was shown in the previous papers is that, when optimally produced, the density of this stabilizer plasma could be many orders of magnitude lower than that of the plug plasma in a tandem-mirror system, and still be effective in MHD-stabilizing that plasma (provided that the three conditions stated above are all satisfied).

The field-line-curvature-related condition that must be satisfied by the Kinetic Stabilizer plasma can be seen from an examination of the MHD stabilization criterion for an axisymmetric mirror system [5], stated in integral form in Equation 1.

$$I_s = \int_{-L}^{L} a^3 \frac{d^2 a}{dz^2} \left[p_{perp.} + p_{par.} + \rho v^2 \right] dz > 0, \text{ Stable} \qquad [1]$$

In this expression the radius of the plasma is represented by the term, a. The integral is to be carried out over the length of the plasma between the ends of the system, located at –L and +L, respectively. The term in the brackets represents the total kinetic pressure of the plasma (a function of position). This pressure term is then multiplied by the plasma radius cubed and the second derivative of the plasma radius (the curvature term) and then integrated over the length of the system to determine the sign of I_s.

As can be seen from Equation 1, regions of the plasma at large radius and where the field-line curvature is strongly positive will make the largest positive (stabilizing) contributions to the integral. The Kinetic Stabilizer takes advantage of this scaling by creating its kinetically produced plasma at an optimally located position on the expanding field lines (the "expander") outside the mirrors. To achieve this optimization the flux surfaces in the expander region can be tailored in specified ways (to be illustrated in a later section).

In order to study the Kinetic Stabilizer in a quantitative manner computer codes employing the Mathematica® platform were written that perform the following functions:

- Generation of the flux surfaces for mirror cells and for the expander
- Calculation of the magnetic compression and localization of ion beams injected into the expander field, with angular distributions that simulate those from actual ion sources.
- Evaluation of the instability integral, Equation 1, both for mirror-contained plasmas and for the beam-produced stabilizer plasma.

In the next section we will present an example (from a previous paper [12]) that illustrates the use of these codes, en route to a discussion of some new results.

3. THE KINETIC STABILIZER TANDEM MIRROR: SPECIAL ISSUES

Of special interest for fusion purposes is the application of the K-S concept to tandem-mirror fusion systems. This application has been discussed in a preliminary way in a previous paper [12]. In that paper it was shown that the use of axisymmetric confining fields should permit the design of practical tandem mirror fusion power plants based on the original TM concept of Dimov/Fowler/Logan. That is, tandem mirror systems that would generate the required plugging potentials by the straightforward means of increasing the plasma density in the plugging cells by an order of magnitude relative to the central cell, while at the same time being able to operate with high central-cell mirror ratios. When one is employing only circular coils to produce the confining fields not only is it possible to increase the fields in the plugging cells far above that possible with yin-yang or baseball coils, but at the same time the plasma volume in these cells can be made much smaller than would be possible with the non-axisymmetric fields. Higher mirror ratios, higher end-cell fields, and small plugging plasma volumes translate to a major simplification (e.g. "thermal barriers" would not be required) and improvement in performance, and should therefore result in major economic advantages.

To briefly summarize the results of the previous T-M calculations, they addressed a "redesign" of an earlier-studied T-M system, called "MINIMARS." [14]. In the calculations the same fusion power parameters were retained as those of the earlier study, but the end plugging region (which had used multi-pole fields and thermal barriers) was replaced by small-volume axisymmetric mirror cells. What was calculated was the estimated power required to maintain the plugs at high plasma density, and the estimated K-S beam power that would be required to stabilize the plug cells. What was found was that the end cells make the largest negative contribution to the stability integral. It follows that if these are well stabilized it will assure that the central-cell plasma will also be stable (assuming that the "communication" between the various plasmas is adequately robust). Note in this connection that the elimination of thermal barriers will improve the communication between the central-cell plasma and the end-cells, thereby reducing some of the concerns that arise when thermal barriers are employed. Table III summarizes the fusion parameters of MINIMARS that were assumed in the K-S example [12].

Table III
Fusion Parameters of MINIMARS

Fusion Power (MW)	1200
Electrical power output (MWe)	600
Neutron wall loading (MW-m^{-2})	2.7
Central-cell magnetic field (Tesla)	3.0
Choke coil field (Tesla)	26.0
Length of central cell (m.)	95.
Plasma radius (m.)	0.42
Ion temperature (keV)	30
Plasma beta	0.6
Mirror ratio of central cell (beta-enhanced)	13.7

In order to calculate the power required by the end cells, that is, the sum of the beam power required to maintain the plugging plasmas, plus that required to power the Kinetic Stabilizers, compromises between competing requirements had to be made. While the power required to maintain the plug plasmas is reduced if their length is made shorter (smaller volume of plasma), the negative contribution to the stability integral increases as the length is shortened. Also, the use of higher ion energies in the plugs reduces their mirror losses, but increases the pressure that must be stabilized by the K-S. In the compromises made 100 keV deuterons were chosen for the plug ions, and the cell length was set at 3.0 m. With these parameters the plug beam power and the K-S beam power were approximately equal, being 8.2 MW for the former (each end) and 5.0 MW for the latter. The total power required to maintain and stabilize the plug cells was still small compared to the 600 MW fusion power output, the "Q" value of which was thus primarily determined by the confinement $n\tau$ value of the central cell.

One important change that was made in the updated MINIMARS example as compared to the previous study was an optimization of the expander. This optimization was accomplished in the following way: Consider a case in which in the expander the flux surface emerging from the mirror resembles a stylized trumpet horn. That is, it is of conical shape (zero second-derivative), changing farther out to a sharply outwardly curving flux surface that shortly changes again to a conical surface for further expansion until the location of the ion sources is reached. The shape of the flux surfaces in such an expander is shown in Figure 5.

With this shape of expander the ion sources are to be aimed to converge at the high-curvature region between the two conical surfaces. In this way their stabilizing effect can be optimized. Further optimization (to be discussed in a later section) arises from moving the location of high positive curvature in or out in the axial direction. Moving the location inward, although it reduces the radius-cubed term in the stability integral, is compensated for by greater magnetic compression of the beams and by an increase in the second-derivative term in the integral, with possible ancillary advantages having to do with "communication" and other issues.

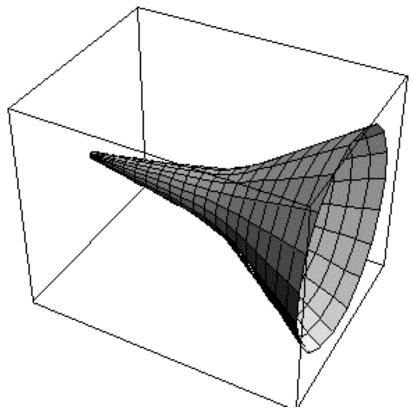

Figure 5: Schematic representation of the flux surface in an optimized expander

4. TANDEM-MIRROR PLUGS: ISSUES AND OPPORTUNITIES

With the previous discussions as background we will now address some new issues and some further avenues for optimization of tandem-mirror systems employing Kinetic Stabilizers.

Since the plug cells represent the largest negative contribution to the stability integral, and thus require the lion's share of the K-S beam power, it is worthwhile to examine ways to reduce the magnitude of this negative contribution, to be accomplished through shaping the flux surfaces in the plug cells. At the same time this type of optimization is going on one must keep one's eye on a particular long-standing issue associated with mirror confinement, namely the Alfvén Ion-Cyclotron (AIC) instability. This instability is driven by the inherent anisotropy of the mirror-confined plug ions. While "warm-plasma" stabilization, normally present naturally in a tandem-mirror system without thermal barriers, is effective on other loss-cone-type instabilities, it is necessary to use special means to avoid the AIC mode. The technique that was developed to suppress this mode is that of "sloshing ions." That is, ions are injected into the mirror cell at an intermediate angle (relative to the field lines) so that they reduce the anisotropy of the trapped plasma. The ability to use sloshing ions to suppress the AIC has been predicted theoretically [15] and demonstrated in tandem-mirror experiments such as TMX –U [16], and Gamma 10 [17]. The fact that the presence of a sloshing ion population does not have a deleterious effect on the confinement of an otherwise isotropic plasma has also been demonstrated in the GDT [3].

In the search for an improved flux surface configuration for the plug cells it was found possible to achieve two objectives at once. The field configuration was calculated from a paraxial expansion (to fifth order in the plasma radius) of the field on axis arising from the superposition of currents in circular loop coils. The field was shaped in such a way that the presence of the sloshing ion population reduces the negative contribution of the plug cell to the stability integral. This long-understood concept takes advantage of the fact that if the sloshing ions are preferentially reflected in regions of the field with positive field-line curvature, the negative contribution of the plasma to the instability integral will be reduced. The presence of collisional randomization in steady-state will prevent the achievement of complete stabilization, but that is not required if the system is to employ

Kinetic Stabilizers. However these stabilizers would now require much less beam power than if the sloshing-ions were not present.

To perform the needed evaluations the stability code was adapted to calculate flux surfaces generated by coaxial, coplanar, circular-hoop coils, the currents in which increase linearly (from a base value) in moving toward the mirrors, starting from the midplane between the mirrors. As shown in an early report [18] this type of coil assembly produces a mirror-cell field the flux surfaces of which are everywhere convex (have positive curvature) with respect to the axis, except for a short region whose length is of the order of the coil radius. Figure 6 shows an example of such a flux-surface contour, as generated by the code

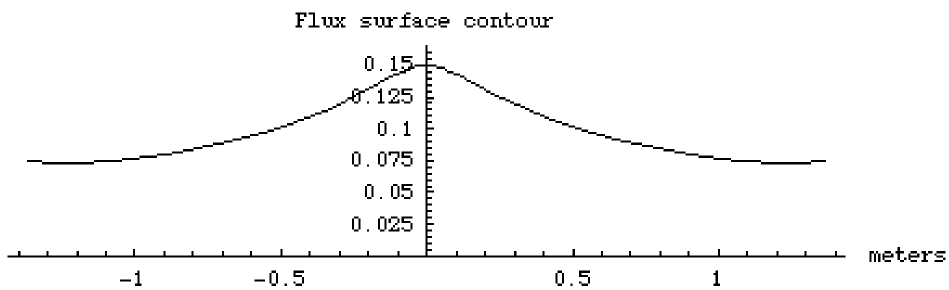

Figure 6: Flux surface associated with an assembly of circular current loops (radius 0.25 m.) the currents in which increase linearly (from a base value) with distance from the midplane (note the change of scale between the y and x axes).

The strength of the magnetic field on the axis of the coil system is shown in Figure 7. Note that the mirror ratio is 4:1 for this choice of values.

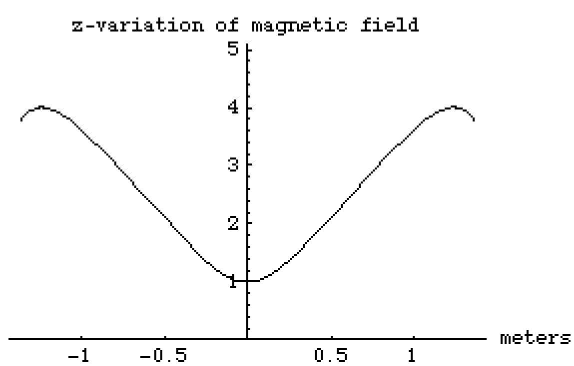

Figure 7: Variation (with distance from the midplane) of the magnetic field intensity on the axis of the coil system producing the flux surface shown in Figure 6

The shape of the flux surface shown in Figure 6 can be seen to be such that it is well-suited for the containment of a sloshing-ion type of distribution in that the sloshing ions will be preferentially reflected in regions of positive field-line curvature. On the other hand, this flux surface would not be expected to be advantageous for the centrally peaked "normal-mode" distributions that would be characteristic of mirror-confined plasmas under usual circumstances.

To illlustrate the gains (reductions in the negative contribution to the stability integral) that could be expected by employing sloshing-ion distributions in mirror cells with flux surfaces of the type shown in Figure 6 comparison calculations of the stability integral were made. First, a "normal-mode" distribution was used together with a Bessel-function type of flux surface (an example of which is shown in Figure 1). The cell length was 2.5 meters, the mirror ratio was 4:1, and the radius of the flux surface at the midplane was 0.15 m. The normal-mode density distribution used is shown in Figure 8.

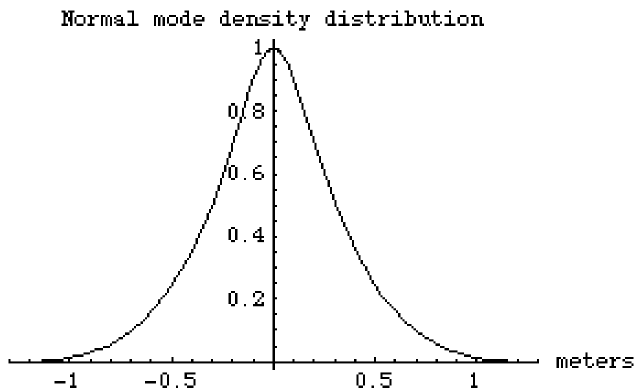

Figure 8: "Normal-mode" density distribution for "Bessel-function" mirror cell

Next, a sloshing-ion distribution, normalized to the same unit peak pressure, was employed in the same cell. Finally, the normalized sloshing ion distribution was employed in the cell the flux surface of which is shown in Figure 6. The length of the cell, the flux surface radius at the mirror, and the mirror ratio were kept the same as for the Bessel-function cell. To represent a sloshing-ion distribution a "normal-mode" distribution was multiplied by a weighting function that approximates the effect of off-angle injection of ions. The resultant normalized axial distribution of the plasma as it was used in the two mirror cells is depicted in Figure 9.

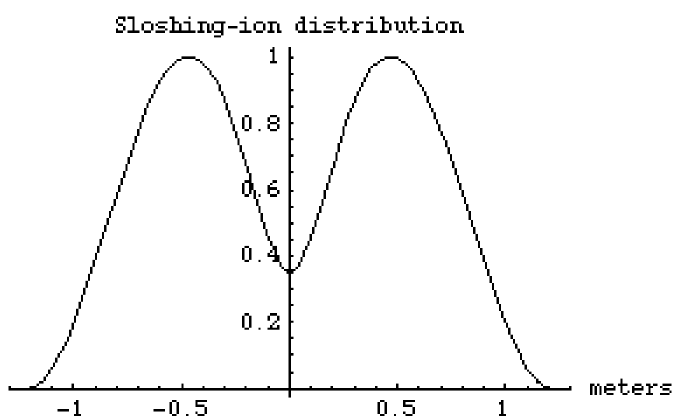

Figure 9: "Sloshing-Ion" axial density distribution .

As noted, the value of the instability integral was calculated for three cases: (1) for the "normal-mode" distribution (Figure 8) in the Bessel-function cell, (2) for a "sloshing-ion" distribution (Figure 9) in the same cell, and (3) for a sloshing-ion distribution in the linear-taper cell of Figure 6 . To illustrate the gains achievable by the optimization of the flux surfaces and by the use of sloshing ions, Table IV gives the value, I_s, of the stability integral for the three cases. The first entry is for the "normal mode" case in the Bessel-function cell.. The second entry is for the "sloshing-ion" distribution in the same cell. The third entry is for the "sloshing-ion" distribution in the "linear-taper-coil" cell of Figure 6 For all cases the mirror ratio was 4:1 and the plasma radius at the mirrors had the same value (.075 m.). All distributions were normalized to unity at their peak pressures so that all would generate the same peak plugging potential in a tandem-mirror system.

Table IV

Cell Type and Density Distribution	I_s	**Ratio**
"Normal-mode" dist. in "Bessel" cell	-3.6×10^{-4}	1.0
"Sloshing-ion" dist. in "Bessel" cell	-3.7×10^{-4}	1.03
"Sloshing-ion" dist. in "taper-coil" cell	-1.4×10^{-4}	0.39

It can be seen from the Table that a substantial reduction in the negative contribution to the stability integral can be achieved by using sloshing ions in a "taper-coil" cell as compared to either "normal-mode" or "sloshing-ion" distributions contained in a "Bessel-function" cell. This reduction comes about as a result of the combined effect of sloshing-ions and the favorable shaping of the field lines that occurs when the cell employs the "linear-taper" configuration for the current in its field coils.

The example given above illustrates the kinds of reductions in destabilizing effect (reflected in reductions in the K-S beam-power requirements) that are possible by shaping the flux surfaces in the end-cells of a tandem mirror employing Kinetic Stabilizers. In a 1988 paper concerning the Gas Dynamic Trap, Mirnov and Ryutov [19] employed variational analysis to determine the optimal shape of the flux surfaces in the mirror cell of the GDT, that is, the shape that minimizes the negative contribution of this cell to the instability integral. Although in the case that they treated the plasma pressure was isotropic (owing to the high collisionality of the GDT operating regime), their analytical approach could also be applied to a "sloshing-ion" pressure distribution. In that way even further gains than those presented here could no doubt be realized, within the limits imposed by engineering requirements in the construction of the field coils.

Although the discussion here has been centered on the optimization of the flux surfaces in the plug cells of a tandem mirror, the analysis by Mirnov and Ryutov [19] shows that the central cell can also be optimized with respect to minimizing its destabilizing contribution to the stability integral. There is however, perhaps another reason for specially shaping the flux surfaces of the central cell. The flux surfaces that were described above and illustrated in Figure 6 are created by circular coils with a linearly increasing current as a function of distance from the midplane. The field lines, as noted, possess "good" curvature everywhere except near the midplane. Although as far as is known the stability analysis has not been performed for this type of mirror field configuration, it seems reasonable that such a shape of flux surface could help in suppressing a class of weakly driven modes of the "trapped-ion" [20] variety. These instabilities have their origin in inadequate electrical communication between the central cell, plug, and expander regions in the tandem mirror. Parenthetically, the elimination of thermal barriers, as proposed here, and the alternative expander designs (discussed in Section VI, below), should go a long way toward eliminating this particular concern.

5. THE EXPANDER: ISSUES AND OPTIMIZATION

The design of the expander presents another opportunity for optimization, previously discussed in Section 4. It also involves some special issues relative to the "communication" requirement mentioned in Section I. As was discussed, the generic requirements for optimization of the expander are to create an expanding flux surface that consists of a combination of conical (zero second derivative) and strong communication between the stabilizer and the plug plasma. A third point: use positive-curvature flux surfaces, chosen to optimally accomplish the magnetic compression, stagnation, and reflection of ion beams injected (at optimally chosen angles of injection) into the expander. In the choice for the location of the positive-curvature region of the expander there are two different approaches that can be taken. The first approach, the one that is illustrated in Figure 5, involves the location of this region at a position that is intermediate between that of the ion sources (located close to the outer end of the expander) and the outer mirror of the plug cell. In this way the stabilizing (positive) contribution to the instability integral arises from a combination of magnetic compression and exploitation of the radius-cubed term in the integrand of the integral. The potential disadvantage of using this means for optimization arises from the "communication" issue as it applies to the region of the expander between the location of the stabilizer plasma and the mirror. Since the distance between these two locations in the expander might be fairly large, and since the density of the stabilizer plasma would be quite low, it would be necessary to insure that a sufficient density of high-conductivity plasma existed between the two to insure the easy flow of the stabilizing currents. This potential problem suggests the examination of an alternative way to optimize the effectiveness of the beam-produced stabilizer plasma, as follows:

First, the expander is to be configured so that its outer conical region extends almost into the mirror region itself, changing abruptly there to a region of high positive curvature. Second, the ion beams are to be directed at smaller angles and with a smaller angular spread, so that they are strongly converged and compressed, being stagnated and reflected in the high-curvature region close to the mirror. In this way, although the radius-cubed enhancement effect is largely lost, stabilization strength is recovered through the greatly increased magnetic compression of the stabilizer beam ions. In an example case, where the magnetic compression factor was approximately 800:1, the value of the stability integral, $I_{s,}$ was found to be +22.0. This value is nearly as large as the value that was obtained by injecting the same current of ions at larger angles into an expander of the shape shown in Figure 5.

Some of the advantages of taking this alternate approach to the expander design are the following: First, the communication distance between the plug-cell plasma and the stabilizer plasma is much smaller than that for the alternative design. Second, the density of the stabilizer plasma, since it is much higher than that for the other case, will itself create a significant local potential peak. The formation of this potential peak will then be expected to result in the trapping of a low-density plasma between this peak and the mirror, still further enhancing the electrical advantage is that the electrons trapped by the potential peak could be heated by directed microwave beams, thus further enhancing the MHD stabiliziing effect of the Stabilizer plasmas.

6. ADDITIONAL OPTIONS

In addition to the mode of operation that involves the injection of ion beams up the magnetic gradient, another optional mode of operation has been studied. This mode of operation could be advantageously employed after the plasma of a tandem-mirror system has been stabilized by the K-S beams and the plasma potentials have been formed. At this point in time, as illustrated schematically in Figure 4, directed gas jets would be turned on, aimed tangentially at the periphery of the plasma at a point near the mirror. The jets would be located on the “down-hill” side of the ambipolar potential peak in the plug cell, for example at a point where the potential with respect to that at the end of the expander is about 1.0 kV. The plasma at the point of injection of the jets would then ionize their atoms, resulting in an accelerated stream of 1.0 keV ions flowing out into the expander. This stream would then take over the stabilization, allowing the stabilizer ion sources to be turned off, thus simplifying the stabilization process.

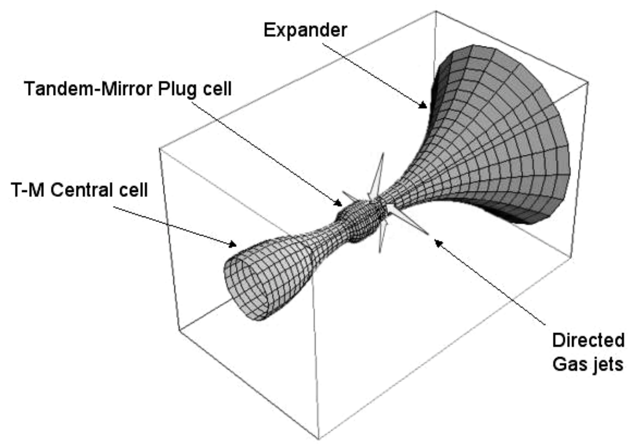

Figure 4: Schematic drawing of gas jet stabilizer beams and tandem-mirror flux surfaces.

The stability integral code, modified to allow the introduction of an ion stream (of krypton ions) originating near the mirror, was run to find the value of the instability integral. In a typical case the value found for I_s (for unit pressure of the ion stream at its origin) was +0.28. This value is about three orders of magnitude greater than the value of I_s for the plug, implying that the kinetic pressure of the ion stream could be three orders of magnitude smaller than that of the plug plasma and still stabilize. When the area of the flux tube near the mirror throat (where the streams are formed) was factored in, in a typical tandem-mirror example it was found that the power extracted by the stabilizer streams was only about 200 kW, thus was far less than the power required to maintain the plug, which itself was much less than the fusion power release.

7. WORK IN PROGRESS

As of the writing of this report there are several other activities in progress in support of analyzing the Kinetic Stabilizer concept. A “legacy” computer codes, FLORA, written during the 1980s as a part of the tandem-mirror program at the Laboratory, is being updated to enable them to be run on modern work stations. FLORA is an initial-value MHD stability code which includes finite-beta capabilities. FLORA has been benchmarked against the codes using the Mathematica platform with close agreement being found at low beta values (where the latter applies). FLORA is now being exercised to examine high-beta cases, where MHD -stable regimes are being found.

Also being investigated are the plasma “communication” issues. These issues refer to the necessity of insuring sufficient conductivity in the region between the plug cell and the stabilizer plasma peak to avoid the so-called “trapped-ion” mode or other communication-related effects.

In progress is the writing of a transport code that will include both axial and radial transport, including the radial potential distribution of the plug cells. Based on preliminary results from another code, the new code is expected to be able to examine ignited DT plasmas in a K-S T-M.

In addition to the code updating, some studies are being made of the application of LLNL-developed liquid-wall concepts [21] to the KS/TM. Because of its axisymmetry the KS/TM seems well suited to introducing liquid walls whose purpose is to absorb the power generated in the fusing plasma and transport this resulting heat to the conventional part of the power plant where the heat is converted into electricity. The liquid is kept from falling into the plasma by centrifugal force of azimuthal motion. If the liquid is the molten salt, “flibe” (Li2BeF4) about 0.5 m thick (7 mean free paths for 14 MeV neutrons), the structures are predicted to last the life of the power plant, being limited by neutron radiation damage. The use of liquid walls solves the "first wall" problem. The economic benefits of successful liquid walls to a fusion plant are multiple: higher power density, less down time due to not changing out structures, less building space from avoiding these change-outs and less radioactive structures to handle. The open-ended nature of the KS/TM facilitates introducing and extracting the flowing liquid. The edge plasma will (and must) sufficiently protect the core plasma from too much contamination by the evaporating liquid. The feasibility of using liquid walls will rest on the contamination being kept to under about 1% fluorine contaminant in the core plasma. If analysis and experiments prove contamination is acceptably low, liquid walls could significantly improve the power plant competitiveness of the KS/TM relative to other power plants.

8. SUMMARY AND CONCLUSIONS

The history of magnetic fusion research has shown us that open systems with axisymmetric fields have the potential to confine plasma in near-quiescent states, with cross-field transport rates approaching classical values. Undergirded by theory, experiments performed on the Gas Dynamic Trap at Novosibirsk show the way to stabilizing axisymmetric mirror systems against MHD interchange modes. The Kinetic Stabilizer concept and its variations represent a way to implement the same stabilization concept in a tandem-mirror system based on the original Dimov/Fowler-Logan concept. Following this path may lead to “simpler, smaller” magnetic fusion power systems the development of which might be much faster and less costly than the path represented by the tokamak or other closed-field approaches.

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REFERENCES

1. R. F. Post, Trans. of Fusion Technology, **39**, 25 (2001)
2. R. F. Post, R. E. Ellis, F. C. Ford, M. N. Rosenbluth, Phys. Rev. Ltrs., **4**, 166 (1964)
3. P. A. Bagryansky, et. al., Trans. of Fusion Technology, **35**, 79 (1999)
4. T. D. Akhmetov, V.S. Belkin, V. I Davydenko, G. I. Dimov, et. al., “Creation and Studies of Hot Startup Plasma in the Central Solenoid of AMBAL-M,” paper at: 28th EPS Conference on Controlled Fusion and Plasma Physics, Portugal, June 2001

5. D. D. Ryutov, "Axisymmetric MHD-Stable Mirrors," Proc. of Course and Workshop, Varenna, Italy, Vol. II, 791 (1987)
6. A. Ivanov, A. V. Anakeev, et. al., Trans. of Fusion Technology, **39**, 127 (2001)
7. L. Spitzer, *Physics of Fully Ionized Gases,* 2nd Ed., Interscience Publishers (1962)
8. M. N. Rosenbluth, C. L. Longmire, Ann. Phys. **1**, 120, (1957)
9. R. W. Moir, R. F. Post, Nuclear Fusion, **9**, 253, (1969)
10. Yu V. Gott, M. S. Ioffe, V.G. Tel'Kovskii, Nuclear Fusion Supplement, Part 3, 1045 (1962)
11. D. D. Ryutov, G. V. Stupakov, JETP Letters **26**, 174 (1977)
12. R. F. Post, Transactions of Fusion Technology, **43**, 198 (2003)
13. R. F. Post, Transactions of Fusion Technology, **35**, 40 (1999)
14. L. J. Perkins, B. G. Logan, R. B. Campbell, et. Al., Fusion Technology, **8**, 685 (1985)
15. G. R. Smith, Phys Fluids, **27**, 1499 (1984)
16. T. Orzecchowski, S. L. Allen, J. H. Foote, et. Al., Phys Fluids, **26**, 2335 (1983)
17. T. Cho M, Ichimura, M. Inutake, et. Al., in *Plasma Physics and Controlled Nuclear Fusion Research 1984* (Proceedings 10th Int. Conf. London, 1984), Vol. 2, IAEA Vienna, 275 (1985)
18. R. F. Post, "Sixteen Lectures on Controlled Thermonuclear Reactions," Report UCRL-4231, 2 February 1954 (unpublished)
19. V. V. Mirnov, D. D. Ryutov, "Gas Dynamic Trap," pp. 77-130, In *Plasma Physics*, Vol. 8 (Summaries in Science and Technology, V. D. Shafranov, ed., State Institute for Scientific Information, Moscow, 1988 (in Russian)
20. H. L. Berk, B. G. Lane, Phys Fluids, **29**, 3749 (1986)
21. R. W. Moir (Private communication)