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MAGNETIC MIRROR FUSION SYSTEMS; CHARACTERISTICS AND DISTINCTIVE FEATURES

R. F. Post

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R. F. Post

Lawrence Livermore National Laboratory, University of California
P.O. Box 808, Livermore, CA 94550

ABSTRACT

A tutorial account is given of the main characteristics and distinctive features of conceptual magnetic fusion systems employing the magnetic mirror principle. These features are related to the potential advantages that mirror-based fusion systems may exhibit for the generation of economic fusion power.

I. INTRODUCTION

The magnetic mirror approach to fusion represents one of the earliest of the distinct lines of endeavor in magnetic fusion research. Over the years mirror fusion concepts have undergone many evolutionary changes, in response to theoretical predictions and laboratory results, and to perceived requirements of economic origin. At this point in time it is not possible to foresee what roles the magnetic mirror principle, and approaches to fusion based on

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this principle, will play in the future of fusion power. It is, however, possible to set down a list of those characteristics of mirror confinement systems that distinguish them from other approaches (e.g., the tokamak and the reversed-field pinch), together with the advantages and/or disadvantages that these distinctive features represent. This paper presents a brief tutorial account of these characteristics and distinctive features, together with comments on their implications in the broader perspective of the fusion goal.

II. REVIEW OF BASIC MIRROR CONFINEMENT PRINCIPLES

In its simplest form a mirror plasma confinement system consists of a solenoidal field that is intensified at its ends (the mirrors), beyond which the field lines expand and leave the system. This elementary topological feature--the "open-ended" nature of the field--has consequences that set mirror plasma confinement apart from confinement in the whole genre of "closed" magnetic field systems, i.e., from those with the topology of a torus. For example, in closed field systems confinement need only be effective relative to transport across the field lines--confinement along the field lines is largely irrelevant. Open-ended systems, however, must provide for confinement--i.e., for restraint of particle and energy transport--both across and along the field lines, the latter referring specifically to the region where the field lines leave the system, typically at its open ends. This requirement in turn implies important constraints on the nature of the ion and electron particle distribution functions that will be typically encountered in mirror systems. For example, in order for there to be a negative gradient in particle density along the field lines (i.e., to provide confinement in this direction) the plasma pressure cannot be everywhere isotropic (as it typically is in closed systems). This difference is made apparent by writing down the expression for the magnetostatic equilibrium of a plasma (parallel to $\vec{B}$; in the "one-fluid," MHD, limit):

$$(\nabla p_{\parallel}) \cdot \vec{b} = -(p_{\perp} - p_{\parallel}) \frac{\nabla B}{B} \cdot \vec{b} \quad , \qquad (1)$$

where $\vec{b}$ is a unit vector parallel to $\vec{B}$. Only if $p_{\perp} > p_{\parallel}$ is it possible to sustain a negative gradient of the parallel pressure, supported by a positive gradient in B, i.e., by mirror action. It follows that in open-ended mirror systems there must always be regions of the confinement system where the plasma pressure is anisotropic, in particular where $p_\perp > p_\parallel$. There may be inner regions (such as in the central cell of a tandem mirror; see below) where the plasma pressure is isotropic ($p_\perp = p_\parallel$), but within these regions, as seen from Eq. (1), there can be no gradient in plasma pressure along the field lines, whether or not there are local mirrors present.

The origin of the particle-containing ability of a magnetic mirror is based on the existence of an adiabatic invariant of the particles' motion--the magnetic moment, $\mu = W_\perp/B$, where $W_\perp = \frac{1}{2} Mv^2$ is the kinetic energy of rotation of the particle around a field line. This invariant is associated with the quasi-periodic cyclotronic motion of the particle as it gyrates in the magnetic field while drifting along the field lines.

As is apparent from its definition, if μ remains constant as a particle moves into a region of increased B, its rotational energy must increase, necessarily at the expense of its parallel energy, i.e., its parallel velocity is decreased. Ignoring for the moment the possible effects of internal electrical potentials, mirror confinement then requires that the particle's kinetic energy should be less than a critical energy, i.e.,

$$W < \mu B_{max} \quad , \qquad (2)$$

where B_{max} is the magnetic field at the peak of the mirror. From the definition of μ this condition is seen to be equivalent to the requirement that

$$\theta < \sin^{-1} (1/R_m)^{1/2} \quad , \qquad (3)$$

where $R_m = B_{max}/B_{min}$, is the "mirror ratio," and θ is the "loss-cone" pitch angle defined by the particle orbit as it passes through the place where $B = B_{min}$. Only those particles whose "midplane" pitch angles are greater than the loss-cone angle will be mirror-confined; those moving at smaller pitch angles (more nearly parallel to $\vec{B}$) will be lost. The loss-cone condition, Eq. (3), is thus the particle-kinetic equivalent of the pressure anisotropy condition implied by Eq. (1).

Being dependent on the magnetic moment, mirror confinement is sensitive to processes that may perturb this quantity. There are two such processes, inherent to any mirror-based system, that can perturb μ. The first of these is the effect of spatial non-uniformity of the field. If the gradients of the magnetic field along the field have too short a magnetic scale length L_m (as measured in units of the locally evaluated gyroradius of the particle orbit, a, then as it gyrates along the spatially varying field the particle will be subjected to a time-varying magnetic field with frequency components in the vicinity of its cyclotron frequency or its harmonics. This circumstance will lead to "jumps" in μ as the particle experiences these resonances in transit between the mirrors. All practical mirror systems are therefore designed so that the condition $a \ll L_m$ (typically $a < 0.1\ L_m$) is satisfied up to the highest particle energy that is to be confined. This condition is obviously most restrictive on energetic ions; electrons have much smaller orbit radii at comparable energies.

The second μ-perturbing process intrinsic to mirror confinement is of course particle-particle collisions. Collisions lead directly to particle losses through the mirrors whenever they result in a particle being scattered into the loss cone in velocity space. In the absence of other confining effects, therefore, the lifetime of a mirror-trapped particle is approximately equal to its collisional "relaxation" time, as given by Spitzer [1]. For deuterons this time is given approximately by the expression

$$\tau_r = 2.2 \times 10^{10}\ E^{3/2}/n_i \qquad (4)$$

where E is the mean particle energy in keV, and n_i cm^{-3} is the ion density. The equivalent scattering rate for e-e (or e-i) collisions is a factor $(M/m)^{1/2} \approx 60$ faster. When the effect of the mirror ratio is taken into account (by calculations with the Fokker-Planck equation) the above expression is modified to become:

$$n_i\tau = k_i \times 10^{10}\ E^{3/2}\ \log_{10}(R_m), \qquad (5)$$

where k_i values are typically approximately equal to 2.5, for mirror plasmas maintained by neutral beam injection.

Two important facts about mirror systems can be deduced immediately from Eqs. (4) and (5). These are

1. Lawson "$n\tau$" values of order 10^{14} cm^{-3} s. are only approached in conventional mirror systems at very high ion energies [$E > 250$ keV in Eq. (5) for realistic mirror ratios]. Simple mirror systems are

therefore at most marginal for fusion power purposes, requiring "backup" means to enhance their "Q" (power gain). The tandem mirror idea represents one such means.

2. The intrinsically disparate scattering rates of electrons and ions leads automatically to the generation of an ambipolar potential that electrostatically confines the electrons. The distribution function of the electrons is therefore Maxwellian, truncated at the value of the ambipolar potential (typically 4.0 to 5.0 kT_e).

Because the electrons are electrostatically confined and therefore have an isotropic Maxwellian velocity distribution their confinement is governed by a Boltzmann-like behavior, as constrained by quasi-neutrality. That is, the local value of the ambipolar potential is related to the local value of the electron density by the equation

$$\frac{n_e}{n_0} = \exp\left[-e(\phi - \phi_0)/kT_e\right] \quad . \tag{6}$$

Because the density of the mirror-confined ions decreases to near-zero at the mirrors, the ambipolar potential (positive and a maximum at the midplane) will also decrease as the mirror is approached. As a result there will appear within the plasma a steady-state dc electric field with a component parallel to $\vec{B}$. In plasmas with isotropic pressures, such as those typically encountered in closed systems, no such parallel electric fields can exist in steady-state.

As described briefly later, the existence of internal ambipolar potentials, and the ability to localize and control them, forms the basis for the operation of the tandem mirror in its various forms.

While axial confinement in mirror systems derives from the constancy of the magnetic moment, radial confinement in mirror systems is governed by a different invariant, J, the longitudinal action integral, $\int v_{\parallel} ds$. The adiabatic invariance of the magnetic moment arises from the cyclotronic gyration of the particle in the magnetic field, where the period of this gyration varies slowly as the particle moves along field lines. The adiabatic invariance of J arises from another quasi-periodic motion of the particles: the periodic "bouncing" motion that they undergo as they are reflected back and forth between the mirrors, meanwhile slowly drifting in the azimuthal direction. As shown in early work by Northrop and Teller [2], the invariance of J guarantees that particles, while they are bouncing axially, will continue to drift azimuthally on <u>closed</u> drift surfaces, that is they will be confined radially.

Similar to the case of the magnetic moment, there are two processes that can operate to perturb J, thus can lead to radial transport. The first of these is departure from axial symmetry of the confining field. In a non-axisymmetric field the azimuthal drift velocity is not a constant, giving rise to higher frequency components in the slow azimuthal drift rate. These can couple to the bounce motion, thus perturbing J and thereby leading to radial transport [3]. Again, as was the case with the magnetic moment, attention to detail in the design of the fields can minimize the field-related perturbations of J, thus minimizing the associated radial transport.

The second intrinsic source of J perturbations and associated radial transport is of course particle-particle collisions. Here the situation is much more favorable than was the case for mirror losses. Under most circumstances the "classical" radial transport rates involved can be expected to be small enough to be of no serious concern in fusion-scale devices.

As dictated by μ and J conservation, mirror plasma equilibria are of a rugged nature, and are not sensitively dependent on the geometry of the confining field. This ruggedness is particularly evident when it comes to MHD stability. By contrast with toroidal systems, where maintaining stability against MHD modes is difficult, even at quite low values of the plasma "beta" parameter $[p_\perp/(B^2/8\pi + p_\perp)]$, mirror-type fields can be arranged to provide MHD stabilization up to beta values that approach unity, theoretically predicted and experimentally confirmed.

Absolute stabilization of MHD modes in mirror-confined plasmas can be provided by the use of so-called "minimum-B" or "magnetic well"-type fields, that is, mirror fields in which the curvature of the field lines of the externally applied ("vacuum") magnetic field is convex toward the plasma (i.e., the vacuum field has a positive outward gradient) everywhere in the confinement region. Such fields are possible only with open systems. In closed toroidal systems the vacuum field lines must obviously be concave toward the plasma over at least some regions of the field.

An example of a magnetic-well field is shown in Fig. 1, which depicts a "quadrupole" magnetic-well as produced by a so-called "baseball" coil.

Fig. 1 Schematic drawing of Magnetic-Well field produced by a "baseball" coil

In mirror systems where more than one mirror cell is linked together the magnetic well property cannot be maintained throughout the confinement region: There must be regions (between the cells, for example) where the field lines are concave toward the confinement zone. MHD stability may still be mainmaintained in such systems, however, if the fields possess an "average minimum-B" character [4], or if the plasma beta in cells with "good" curvature is increased, so as to overcome the destabilizing effects of the plasma in those regions with "bad" curvature. The appropriate theoretical condition to be satisfied in order to insure MHD stability of the plasmas is given by the expression

$$\int_{s_1}^{s_2} \frac{\beta}{Rr}\, d\ell > 0 \quad , \quad \text{stable.} \qquad (7)$$

Here the integral is to be taken over the length of the field lines in the confinement zone; R is the local curvature of the field line (positive in regions of "good" curvature and vice-versa), and β is the local value of the plasma pressure parameters as earlier defined. The validity of this relationship has been tested experimentally [5]. Provided resonable precautions are taken to avoid localized modes (such as the so-called "ballooning" modes), maintaining MHD stability even in complex mirror systems has not been a major issue.

To recap, mirror systems, having an open-ended field line topology, require anisotropic pressure distributions in order for the mirrors to provide confinement at the open ends. Leakage of particles through the mirrors occurs as particles are scattered into the loss cone. The disparate scattering rates of electrons and ions leads to the development of an ambipolar potential that electrostatically confines the electrons and that results in steady-state electric fields parallel to B within the plasma.

Finally, magnetostatic equilibria in mirror systems can be said to have a "rugged" character, as established by the action of two adiabatic invariants of the particle motion, the magnetic moment (provides axial equilibrium) and the longitudinal action integral (establishes radial equilibrium). Furthermore, the MHD stability of mirror equilibria can be assured in mirror cells up to beta values approaching unity by the use of magnetic well-type fields. MHD stability may also be maintained at high beta values in linked mirror cells by the design of the magnetic field (average min-B fields) and/or by controlling the spatial distribution of plasma beta along the field lines.

III. CONCEPTUAL FUSION POWER SYSTEMS EMPLOYING MAGNETIC MIRRORS

Since the earliest days of mirror fusion research the question of how mirror-based ideas might best be incorporated into future fusion power systems has exerted an important influence on the research. It was appreciated from the start that the simplest form of a mirror machine--that is a single cell bounded by simple mirrors at its ends--would, because of particle leakage through the mirror, have a marginal Q value. The mirror-based fusion concepts that have emerged over the years have therefore in every case represented proposals for dealing with the issue of mirror end losses. We will here list and briefly describe some of these concepts, starting with the earliest ones. Some concepts have had only limited study. Others, such as the tandem mirror, represent mainline efforts today.

A. The Simple Mirror plus Direct Conversion

There are two conceptually different ways of dealing with the problem of end losses. The most obvious one is to look for ways to plug the leak. An alternative, seriously studied at Livermore in the 1970's, would be to directly convert, at high efficiency, the kinetic energy of the escaping charged particles (reaction products and unburned fuel ions) into electrical energy [6]. If coupled with a high efficiency plasma heating scheme, high efficiency direct conversion would in effect convert a low Q system into a high Q one. In the Livermore studies an electrostatic direct conversion system was developed that demonstrated conversion efficiencies approaching 90 percent [7].

Although high efficiency direct conversion offered (and still offers) an in-principle solution to mirror losses, the projected cost of such systems, together with the emergence of the tandem mirror idea, led to the termination of the Livermore direct conversion studies. What survived was simpler, lower cost versions of the direct converter, proposed for use as auxiliary devices on a tandem mirror systems to provide power for plasma heating.

B. Rotating Plasmas

One of the earliest-proposed ideas for reducing mirror leakage was to spin the plasma. In a simple axially symmetric mirror field the centrifugal forces in a rapidly rotating plasma should have the effect of stopping the end leakage. Rotation can be induced by producing a radial electric field with the plasma, coupled in by electrodes outside the mirrors at the ends.

Early work on this idea--then called the "Omnitron"--was carried out by Baker and coworkers [8] at the Lawrence Berkeley Laboratory. In recent years the idea has been pursued and extended by Volosor and coworkers at Novosibirsk [9]. In that work two important related issues are being addressed: How to maintain electrical contact with the plasma without excessive power losses, and, how to control MHD-like instabilities driven by the rotation and by the "bad" curvature of the field lines in the simple mirror.

C. R. F. Plugging

The fact that mirror action derives from the rotational energy of the particles lead early-on to the idea of using r. f. fields to enhance mirror action by spinning up the ions (or electrons) as they approached the mirrors. Among others, Watson and co-workers [10] investigated the concept theoretically, and r. f. plugging has been studied intensively, both theoretically and experimentally, at Nagoya in Japan [11]. Though an attractive idea, there are both physics and technology issues that have presented difficulties in implementing r. f. plugging in plasmas of fusion interest.

D. Multiple Mirrors

One of the forerunners of the tandem mirror concept was the multi-mirror idea [12]. If a central mirror cell is flanked at both ends by many additional cells and if certain plasma conditions can be met, the $n\tau$ confinement factor for ions in the system can be substantially enhanced over that for a single cell. In a multi-mirror system ions that are scattered into the loss cone in one cell may be retrapped in an adjacent cell, so that they in effect execute a random walk from cell to cell. If the left-right trapping/detrapping probabilities are equal, the resultant confinement time will scale up with the square of the number of cells exterior to the central cell [13]. If the left-right probabilities can be skewed toward the central cell (by r. f. fields and/or asymmetric mirrors, for example, then the confinement time is predicted to increase exponentially with the number of cells [14].

If the trapping/detrapping arises solely from particle-particle collisions, for multi-mirror action to be effective under fusion conditions the plasma density must be very high, this in order to satisfy the requirement that the mean free path for such events should be of order L/R_m (cell length divided by mirror ratio). One example of such a high density multi-mirror system was studied by Budker [15], who proposed a system where the multi-mirror fields served to inhibit plasma flow along the field lines, but were not required to sustain the plasma pressure transversely; this was to be accomplished by adjusting the distribution of plasma temperature and density so as to maintain constant pressure out to the plasma boundary.

E. The Field-Reversed Mirror

One of the early, and still very attractive, ideas for improving the confinement time of mirror systems is what will be here called the Field-Reversed Mirror, or FRM for short. An artists concept of the plasma and magnetic field configuration in an FRM is shown in Fig. (2). In an FRM the mirrors act to constrain, not individual ions, but a field-reversed entity produced by the diamagnetic effect of self-trapped ions. Except that ions rather than electrons are to provide the dominant diamagnetic effect, the FRM resembles the ASTRON of Christafilos [16], or the more familiar field-reversed theta pinch (now usually called an FRC, for "Field-Reversed Configuration").

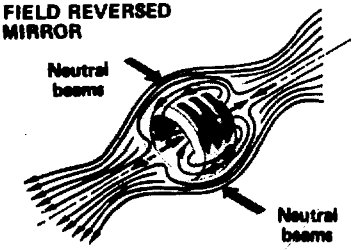

Fig. 2 Schematic drawing of the plasma and field configuration in a Field-Reversed Mirror

The FRM idea combines the advantages of high beta and linear geometry of the simple mirror with the (expected) improved confinement of a closed-line system. However, except as an FRC, this configuration has not been implemented, so that substantial physics issues, both as to MHD stability and as to cross-field particle and energy transport, remain to be resolved.

F. The Tandem Mirror

Presently the most actively pursued of all of the mirror variants, the tandem mirror (TM) [17], [18] takes advantage of some well-understood mirror physics, namely the generation of ambipolar potentials, to solve the end-leakage problem. In its simplest form, the TM consists of a central cell, within which the fusion plasma is contained, flanked by two smaller-volume "plug" cells where electrostatic potentials are generated that electrostatically plug the mirror leaks from the central cell. Fig. (3) shows in schematic form the configuration of the TM in its simplest form. The plasma density in the plugs is maintained (by neutral beam injection) at a higher value than the central cell density, and the ion temperature is also higher. Solving equation (6) for the potential we find for the potential difference between the plug and the chamber cell:

$$|e|\ (\phi_p - \phi_c) = kT_e \log_e (n_p/n_c) \tag{7}$$

where n_p and n_c are the electron densities in the plug and central cell,

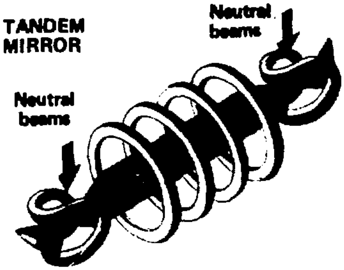

Fig. 3 Schematic illustration of a simple tandem mirror, showing the configuration of the coils, plasma, and neutral beam injector

respectively. As shown first by Pastukhov [19], the effect of an electrostatic potential on the $n\tau$ confinement factor in a mirror is (approximately) to multiply equation (5) by a factor

$$k_p = \frac{|e|\Delta\phi}{kT_i} \log_e \left(\frac{e\Delta\phi}{kT_i}\right) \qquad (8)$$

so that the confinement $n\tau$ factor is exponentially increased over its value for the simple mirror. A later version of the TM, the TM with "thermal barriers" employs a magnetically trapped hot electron component in the plug to generate a negative-going potential peak (the thermal barrier) that isolates the positive-peak region from the central cell [20]. This in turn allows electrons in the positive region to be heated without thermal contact with the central cell electrons. The resultant higher electron temperature in the plugs enhances the ambipolar potential and the plugging, even when the plug plasma density is comparable to or even lower than that in the central cell. This trick could greatly improve the economic prospects of the TM in fusion power applications.

IV. PRECAUTIONS, DIFFICULTIES, AND UNCERTAINTIES

While three decades plus of mirror research has resulted in impressive progress toward the fusion goal, this research has at the same revealed physics issues that must be further investigated, and pointed out areas where particular precautions must be taken.

An example of the latter is the issue of microinstabilities--that is, unstable high frequency particle-wave interactions--that have plagued mirror systems from the earliest days. Owing to the necessary existence of non-maxwellian ion distributions in at least some regions of a mirror system, (in the plugs of a TM, for example), certain plasma waves, usually at the ion cyclotron frequency or its harmonics, may grow up and perturb the confinement. Over the years, with the growth of understanding of these waves gained from theory and experiment, ways have been found to suppress these instabilities, through tailoring of the distribution functions and/or geometrical constraints. As a result the fluctuation levels associated with these instabilities have been driven to such low levels that it is believed they will not represent a problem. This conclusion is, however, yet to be tested under realistic fusion conditions as to ion temperature and plasma size.

While MHD stability at high beta has been demonstrated in small-scale mirror experiments, the extrapolation of these results to fusion-scale plasmas and long confinement times is yet to be done. Also, the MHD stability of the FRM is still an unresolved physics issue.

Finally, while TM experimental results, particularly those from the Gamma-10 facility at Tsukuba University [21], are very encouraging with respect to the control of radial transport in a TM, it will take a larger-scale, higher ion temperature, experiment to demonstrate this result conclusively.

What is remarkable about mirror research, as contrasted with some aspects of toroidal research, is that theory and experiment have been closely linked throughout the history of mirror research. As a result it appears that in mirror research one is much closer to having theoretical models that have quantitative predictive power, thus lessening the need for purely empirical approaches in order to project to fusion scale.

V. Distinctive Features of Mirror Systems and their Significance to the Fusion Goal

At this point in time it appears to me that fusion research is "in the home stretch". That is not to say that all critical physics/technology issues have been resolved for any approach to fusion, but only that there now exists a sufficient basis of understanding of critical plasma physics issues and of fusion technology to begin to make educated speculations about fusion power systems.

In my opinion, however, despite the many accomplishments in fusion, it is still premature to single out "the approach" to fusion, and thereby to shut out alternatives that may prove to be superior in the long run. Especially is this the case for those alternative approaches, such as the mirror, that differ markedly from the present "mainline" approach--the tokamak. This assertion is made partly because unforeseen physics or technological/economic difficulties of one approach, meaning specifically here the tokamak, are less likely to be shared by a radically different approach. Another basis for this assertion is that the scaling laws for the tokamak seem to be sufficiently well understood empirically to preclude its adaptation to other than large-scale fusion power systems. By contrast, high beta mirror systems, particularly the FRM, appear to offer the possibility of much smaller scale fusion power plants.

Calling on what has gone before, I will conclude, therefore, with an enumeration of those distinctive features of conceptual fusion systems based on the mirror principle that could represent major advantages in future fusion power applications. They are:

1. The demonstrated possibility of MHD-stable operation at high plasma beta, and the wide variety of mirror field configurations for which this is possible.
2. The ability, through external manipulation of electrode potentials or of the magnetic field, to control the plasma rotation or to translate it from one region to another, if need be.
3. The ability to generate internal electric potentials and to employ these potentials to enhance confinement or to selectively direct the plasma flow.
4. Associated with items (1) and (3), the natural adaptability of open-ended systems to the use of high efficiency electrostatic direct converters, particularly in the context of alternative fuel cycles, such as D-^{3}He.
5. The ability (in the FRM) to contain high beta field-reversed entities having purely poloidal fields (i.e., no currents parallel to B).

6. The engineering/economic attractiveness of a linear system in terms of its modularity and of the superior access for maintenance or for plasma heating that it offers.
7. The possibility of steady-state operation, sustained by neutral beams and/or r. f. heating.

There is an additional attribute of mirror systems, one that is difficult to quantify, that may be of great importance for the future role of mirrors in fusion applications. That attribute is flexibility, i.e., width of scope for variation and innovation. The open-ended geometry of the mirror seems to lend itself particularly well to the introduction of innovative variations--the TM being a prime example. With flexibility and with the possibility of innovation comes the opportunity for optimization and for the circumvention of difficulties that may have arisen for another approach. That is to say, another approach, say the tokamak, might encounter physics difficulties or economic or technological problems which could be difficult to surmount because of the relative inflexibility of that concept. In that event, a different approach, here the mirror, operating with different physics constraints, with greater flexibility, and allowing therefore more opportunities for optimization and innovation, could become the preferred path to fusion power.

VI. Conclusion

A tutorial review of the main characteristics, and the advantages and disadvantages of fusion systems based on the use of magnetic mirrors has been presented. The case is made that mirror-based systems have attributes that may become decisive advantages when viewed in the light of the eventual goal of all fusion research, i.e., the practical and economic generation of fusion power.

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