COMMENTS ON PLASMA PHYSICS AND CONTROLLED FUSION

A Journal of Critical Discussion of the Current Literature

BURTON D. FRIED, *Co-ordinator*

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The Tandem Mirror Reactor

A new plasma confinement scheme is described which employs magnetic mirror plasmas to stopper the ends of a long solenoid. The overall system Q, defined as the ratio of fusion power to total plasma injection power, can exceed that of a conventional mirror by an arbitrary factor, depending on the size and power of the system.

The Tandem Mirror Reactor

This Comment describes a new idea for a mirror fusion reactor that can achieve a high value of Q, defined as the ratio of the fusion power produced to the input power necessary to sustain the reaction. Present mirror concepts yield $Q \sim 1$ and require very efficient direct conversion of energy in the escaping plasma in order to obtain a net electrical output.[1] For the new idea, Q can be 5 or more, depending on the size of the machine. Moreover, in many respects the new system is simpler from an engineering standpoint than either tokamaks or ordinary mirror machines, and the physics principles are for the most part well-established elements of the mirror art.

The concept utilizes to advantage one of the features that has contributed to the low Q of mirror systems. This is the strong, positive "ambipolar" potential that confines the electrons but ejects low energy ions. Because electrons have higher velocities than the ions, they scatter more rapidly and would be more poorly confined by the magnetic mirrors except for a net positive charge that develops to hold them back. In other words, the magnetic mirrors confine the ions but the ions confine the electrons, electrostatically. In this way a positive potential barrier equal to several times T_e develops between the peak of the density and the end walls. (Here T_e is the electron temperature in kilovolts.) Usually T_e is only 10% of the ion energy because the confinement time is much less than the time for temperature equilibration between ions and electrons. Nonetheless, if the ion energy were several 100s of keV, the ambipolar potential barrier would be many 10s of keV.[2]

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In the new scheme, the idea is to plug up the ends of a solenoid electrostatically by means of ambipolar potential barriers created in two mirror machines, one at each end of the solenoid. We call it the Tandem Mirror, or sometimes the Triple Mirror. Most of the fusion power is produced by thermal burning in the solenoid, which may actually ignite. Despite the fact that input power is required to sustain the plasma in the end cells, the overall Q can be high if the plasma volume in the solenoid greatly exceeds that in the end cells. We find that a modest $Q \sim 2$ to 3 can be obtained in units of modest power output – a few hundred megawatts or so. The Q progressively improves in larger machines at higher power output.

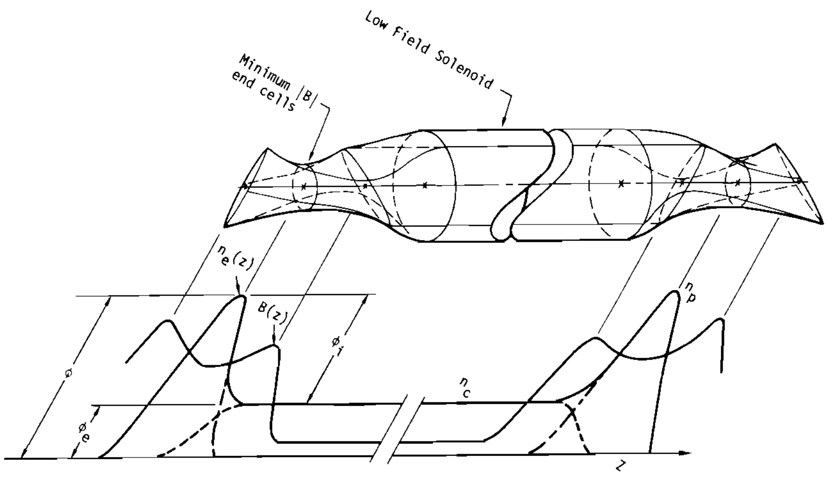

FIGURE 1. Tandem mirrors with ambipolar barriers at the ends.

Imagine, then, two mirror machines in tandem connected by a solenoid such that the magnetic flux flows out of one mirror machine through the solenoid and into the next, as shown in Figure 1. We suppose that very energetic neutral beams (several 100 keV or more) deposit hot ions in the end cells and only cold fuel (possibly as low energy neutral beams) enters the solenoid. For simplicity, we shall neglect supplemental heating in the solenoid and recapture in the solenoid of hot ions escaping from the end cells (a design option, if the outer mirrors are made stronger). Then, with neutral injection in the two end cells,

hot plasma will accumulate in each end cell in the usual manner and also a strong net positive charge develops in each cell as described above. This positive charge in each of the end cells establishes potential barriers that would prevent the escape of ions created in the solenoid, while electrons would be confined by the overall positive potential end-to-end. Once established, a steady-state could be sustained in which neutral injection at an energy E_0 maintains the hot ions in the end cells; the hot ions heat the electrons to a temperature $T_e \ll E_0$; and the electrons (which communicate throughout the system) ionize and heat cold fuel continuously injected to the solenoidal region. The end result is that T_e is approximately constant throughout the system while the ions, having little thermal contact between regions, are much hotter in the end cells.

The ions in the solenoid are confined in a relative potential minimum as indicated in Figure 1. The effective barrier, labelled Φ_i in the figure, is uniquely determined by T_e and by the injection rates that fix the density in the end cell and the density in the solenoid. This follows from the fact that the electric potential $\Phi(z)$ distributes itself along field lines just so as to make the electron and ion densities nearly equal everywhere. Assuming a Maxwellian distribution, the electron density varies as $\exp[\Phi(z)/T_e]$ along the lines, or equivalently $\Phi \sim T_e \ln(n)$, and hence

$$\Phi_i = T_e \ln(n_p/n_c), \quad (1)$$

where n_p is the peak density in the end "plug" and n_c is that in the central solenoid. Given a rate of injecting hot ions that fixes n_p, Φ_i is then greater or smaller depending on the rate of injecting cold fuel into the solenoid, which fixes n_c. If nothing were injected into the solenoid, the density would be very low there and Φ_i would approximately be the same as the potential drop from the end cells to the walls. On the other hand excessive injection of cold fuel into the solenoid could eliminate Φ_i and stop the fusion reaction. It is this choice of how best to inject the center cell which is the main difference between our new concept and an earlier proposal by Kelley that, in fact, inspired our idea.[3] Kelley's objective was to make $\Phi(z)$ constant in the center cell and hence eliminate deleterious effects of the ambipolar potential on mirror confinement in the center cell. We propose to go one step further by creating a potential minimum that confines the plasma.

In order to escape out of the ends of the solenoid, the ions must diffuse upward in energy until they reach an energy exceeding the effective barrier Φ_i. We suppose that $\Phi_i > T_i$ (with Φ_i in energy units). Then the ions would establish a Maxwellian energy distribution and intuitively one expects a confinement time $\sim \tau_{ii} \exp(\Phi_i/T_i)$, where T_i is the temperature of ions in the solenoid and τ_{ii} is the Spitzer collision time for self-collisions among the ions. This is indeed roughly the energy confinement time τ_E, as has been shown by Pastukhov.[4] The particle confinement time τ is larger by a factor of Φ_i/T_i.

Mirror action further improves the confinement since, in order to escape, an ion must both attain an energy $> \Phi_i$ and also lie in the magnetic loss cone ($v_\parallel/v_\perp$ sufficiently large). This is important in the present case, as it turns out that we will want a relatively low field in the solenoid. Typically the mirror ratio between the solenoid and the end cells is $R = 10$. For $R = 10$, Pastukhov's formula applied to the escaping ions gives (for $\Phi_i \gg T_i$).

$$n\tau \simeq 10^{11}\, T_i^{3/2} \left(\frac{\Phi_i}{T_i}\right) \exp\left(\frac{\Phi_i}{T_i}\right) , \tag{2}$$

in units of cm^{-3} sec with T_i in keV. For example, at $T_i \simeq T_e = 35$ keV, $\Phi_i = 2.4\, T_i$, $n\tau \simeq 5 \times 10^{14} cm^{-3}$ sec (particle lifetime) and ignition occurs in a mixture of equal parts of deuterium and tritium. We have verified this conclusion by numerical solution of appropriate Fokker-Planck equations including energy deposition by alpha particles. For D-D, burning the H_e^3 and T reaction products, we find ignition at more stringent conditions: $T_i \simeq T_e \simeq 150$ keV, $\Phi_i = 3.4 T_i$, and $n\tau \cong 3 \times 10^{15} cm^{-3}$. Since 60% of the energy appears as charged particles which can be directly converted to electrical energy at high efficiency, a DD Tandem Mirror reactor may prove to be economic despite the low power density forced by the large density ratio($n_p/n_c \simeq 30$). The possibility of operating on the direct converter alone, disposing of the neutrons in a cold blanket of low cost, low activation materials, would be of great advantage in environmental concerns of fusion.

In the course of our work we have learned that Dimov and coworkers at Novosibirsk have independently considered the Tandem Mirror idea with very similar conclusions.[5] However, with results from the 2XIIB mirror experiment at Livermore as our guide, we have reached somewhat more optimistic conclusions as to the magnetic field strengths and overall system dimensions necessary to realize the concept in practice.

The principal limitation is the density n_p that can be achieved in the end cell. According to Equation (1), the density n_c in the solenoid must be several times less than n_p in order to obtain a large potential barrier. On the other hand, n_c must not be too small ($> 10^{14} cm^{-3}$) in order to achieve an interesting fusion power density in the solenoid. Thus n_p in the end cells must be $10^{14} - 10^{15}$ cm^{-3} and, as noted above, the ion energy there must be several times 100 keV in order that T_e reach interesting values. This simultaneous demand for both high density and high ion energy requires both a high value of the magnetic field in the end cell (100 - 150 kilogauss) and a plasma β around unity.

Two aspects of the experimental results in 2XIIB lead us to believe that these stringent demands can be met.[6] First, $\beta \sim 1$ has indeed been obtained by neutral injection in 2XIIB (at an ion energy of 13 keV). Secondly, by virtue of the strong diamagnetic currents circulating in this high-beta plasma, the plasma has "dug its own well' and is, in fact, almost totally confining itself in the axial direction (along the field) without the benefit of the external mirrors. Consequently, we believe that it would be possible to design suitable end cells with small vacuum mirror ratio and high field strength, within the capability of superconducting magnet technology.

One possible magnetic flux tube is sketched in Figure 1. The end cells could be of the Yin-Yang (minimum-B) design in order to insure MHD stability of the hot plasma. (Alternatively, because the mirror ratio is small, a combination of circular coils and quadrupole windings might be used.) An additional Yin-Yang coil would be needed to join the circular solenoid to the flattened flux bundle emerging from the end cell. Despite unfavorable line curvature in this joining region, MHD stability can be obtained by careful design taking account of the stabilizing influence of the end cell. Previous calculations for a similar geometry indicate that the "ballooning" mode that could effectively disconnect the end cells from the solenoid should occur at beta values near unity in the solenoid.[7] Of course, precise requirements will depend on details of the design.

A major design issue is the neutral injection system required to maintain the density n_p in the end cell. If the confinement time in the end mirrors were "classical", determined only by Coulomb collisions, the power requirement is reasonable. In the 2XIIB experiment,[8] the confinement time is less than classical, by about a factor of 3, as a consequence of extra cooling on a stream of cold plasma that must be supplied to suppress fluctuations at the ion gyro-frequency attributed to the drift-cyclotron loss cone instability. According to the theory of this instability, the requirements for external cold plasma will diminish toward zero as the plasma radius is increased until finally classical confinement is achieved.[9] Also, for the present concept the fact that the Maxwellian plasma from the solenoid penetrates part way into the end cells may be a mitigating influence. How these stability requirements sort out in future experiments and theoretical studies will determine how large the Tandem Mirror system must be to produce more power than that consumed by the end cells.

Another important consideration is the containment of high Z ions. Since the potential barrier confines high Z ions very well, alpha particles tend to accumulate and so would impurities if they could get inside. With regard to the penetration of impurities, the potential barrier itself shields the interior from an any high Z ions released by plasma bombardment of the end walls. The strong radial electric field also helps to prevent high Z ion penetration radially and field lines lying just outside the shadow of the hot plasma "end plug" constitute a natural "divertor" around the plug and out to the ends of the machine. As to the alphas, they do appear to accumulate and quench the reaction for high Q systems. If so, this may require periodic purging of the system. For the present scheme, this can be done simply by turning off the neutral beams in the end cells for about one second out of a total burn cycle of tens of seconds.

Perhaps the most important aspect of the Tandem Mirror, from the viewpoint of reactor design and development, is the distinct separation of the end cells from the simple solenoid, where most of the fusion reactions occur. Thus, the nuclear processes and heat recovery can be isolated from the more sophisticated plasma technology in the end cells. For example, in the end cells, one might choose to inject ordinary hydrogen beams in order to reduce neutron bombardment of the injector hardware and also to reduce magnetic shielding requirements. Moreover, developments to improve the end cells – to reduce the power input and simplify the design – could proceed quite independently of the main reactor components. As better "end plugs" come along, they could be put into service without perturbing the design of the solenoidal magnet, heat exchanger, first wall and the like. As to the reactor core itself, the straight solenoid is the epitome of simple and potentially economical magnetic fusion ideas. In old books on fusion, that is what the mirror machine was said to be. Perhaps, in the Tandem Mirror, this ideal can indeed be realized.

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Energy Confinement in Mirror Plasmas

The theoretical status of confinement in mirror machines is summarized as a basis for a program aimed at improving the energy multiplication of mirror reactors. Several methods which have been advanced are briefly reviewed.

The past year has seen a number of significant advances in the mirror confinement program.[1-4]

i) Ion cyclotron noise identified as the drift-cyclotron-loss-cone mode (DCLC) has been reduced to low amplitude by the axial injection of cold plasma or controlled injection of neutral gas.

ii) The $n\tau$ product consequently increases by an order of magnitude to the point that it is determined by classical ion energy degradation by the electrons.

iii) With gas stabilization, plasma buildup with neutral injection proceeds to β greater than unity and (at the time of writing) limited only by available beam current (β defined as the ratio of peak plasma pressure to midplane vacuum magnetic energy density).

iv) Hot plasma buildup by neutral injection into a cold target has demonstrated a method of startup, long thought a potentially difficult problem for mirrors.

The 2XIIB plasma behavior is in quantitative agreement with theory ascribing saturation of DCLC fluctuations to a partial filling of the loss-cone by low energy unconfined plasma whose lifetime is an axial transit time.[5,6] In the absence of an external source of cold plasma, the flux of the stabilizing unconfined component must be supplied from the confined component by enhanced diffusion in velocity space, implying a short lifetime for the latter. In the presence of an external source of cold plasma, the fluctuation level is reduced to the point that the ion lifetime is determined by energy drag on the electrons whose

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