Concept for a High-Power-Density Mirror Fusion Reactor*

R. F. Post, T. K. Fowler, J. Killeen, and A. A. Mirin
Lawrence Livermore Laboratory, University of California, Livermore, California 94550
(Received 13 June 1973)

A concept for a mirror-type fusion reactor based on recent advances in neutral-beam technology is shown to have improved plasma stability, a much higher power density, and a somewhat higher factor of energy gain Q, as compared with previous concepts using the magnetic-mirror principle.

We consider a two-ion-component fusion-reactor concept, sketched in Fig. 1, in which deuterium is injected at a high energy (~200 keV) into a dense low-temperature tritium plasma (kT_e ~10 keV). The high-energy component (tritium + electrons) is a plasma column only a few centimeters in diameter. Though contained perpendicular to the magnetic field, it flows freely along the field lines and through the mirrors, since its particle collision rates are high. Thus this plasma component has been assumed to be Maxwellian.

The high-energy deuterium component is injected as energetic neutral atoms derived from an array of neutral-beam sources that surround, and are directed at, the plasma column. Upon entering the plasma column these injected atoms become ionized. Now trapped between the mirrors, a fraction of the deuterons undergo fusion reactions while being slowed down by Coulomb collisions with the electrons and ions of the plasma column. To obtain net energy it is necessary that the rate of slowing down of the deuterons not be excessive; this requirement sets a lower limit of several keV on the electron temperature of the plasma column, and thus determines a minimum value of the power input to the column in order to maintain this temperature in the face of streaming losses. We propose to satisfy this latter requirement by taking advantage of developments in the technology of high-intensity neutral-beam sources.[1] In our proposed system the slowing down of the injected deuterons itself provides the high power level needed to sustain the dense, free-flowing plasma column at keV energies. The approach leads to a high-power-density fusion reactor with improved plasma stability as compared to previous mirror concepts.

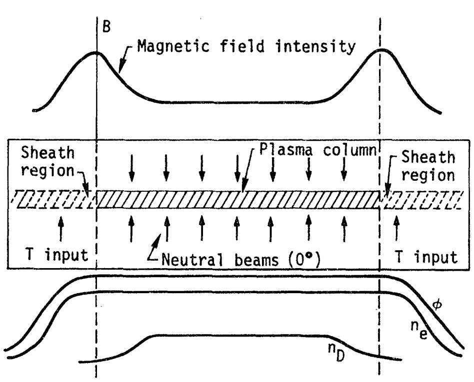

FIG. 1. A two-component mirror-fusion–reactor concept.

The conditions required to obtain net power here are similar to those required for the two-component toroidal system discussed by Dawson, Furth, and Tenney[2] (see also their references to earlier work). We have performed similar calculations for our case, using a Fokker-Planck code modified to take account of mirror losses of the hot deuterium component at high energies and diffusion out the ends at low energies.[3] The quantity calculated is the usual figure of merit for mirror machines, denoted by Q and defined by[4]

$$Q = \frac{\text{Nuclear power out}}{\text{Beam power in}}. \qquad (1)$$

The results of the calculations for a mirror ratio $R_M = 10$, plotted in Fig. 2, differ little from those obtained in Ref. 2 (our Q = their F).

The maximum Q values found here are somewhat higher than those for the "standard" mirror system,[3] in which both deuterium and tritium are injected at high energy and both are required to be contained by the mirrors. Two factors contribute to this improved Q: First, for fusion it is only required that either the deuterium or the tritium ions be energetic. Injecting both at high energy (as required for mirror confinement of both) increases the power input without a corresponding increase in the power output. Selecting deuterium as the hot component, as we have done, gives a somewhat more favorable Q. Second, in the standard mirror, to confine the plasma elec-

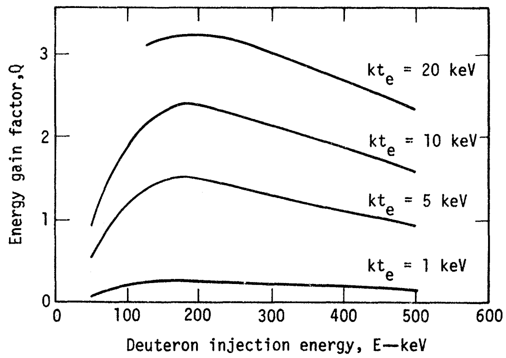

FIG. 2. Energy gain factor Q versus injection energy E and electron temperature T_e for a mirror ratio R_M $=10$ $(kT_i = kT_e)$.

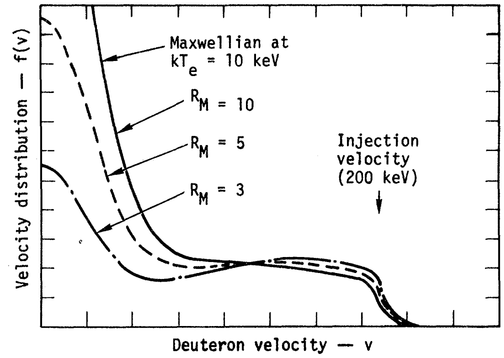

FIG. 3. Steady-state velocity distributions $f(v)$ of deuterons injected at $E = 200$ keV into a tritium plasma $(kT_i = kT_e = 10$ keV) for different mirror ratios R_M.

trons it is necessary that an ambipolar potential, φ, and associated internal electric field, should appear in order to balance the otherwise disparate mirror leakage rates of electrons and ions. Buildup of this potential to its usual equilibrium value of $\approx 4kT_e \approx 0.4kT_i$ leads to enhanced ion loss rates. In the two-component system, in which the ambipolar potential drops occur only in sheath regions *outside* the mirrors (as shown in Fig. 1), this effect should not occur. This circumstance justifies the fact that we have dropped the ambipolar correction in performing the Fokker-Planck calculations presented in Fig. 2. In transferring ambipolar electric fields to regions outside the central mirror region we have accomplished a similar result to that sought by Kelley,[5] except that here the low-temperature ion component is to be dominant both inside and outside the mirror regions.

Note that the improvement in Q for the two-component system is achieved despite the additional drag on the hot ions by the cold ion component. This slowing-down term exceeds mirror losses if $R_M \gtrsim 2$. Having paid this price, the Q of the two-component system, though already higher than that for the standard mirror, is not much improved by higher mirror ratios. For example, at $R_M = 3$, Q is 85% of its value at $R_M = 10$ for $kT_e = 10$ keV and $E = 200$ keV.

Perhaps of greatest importance is the improved plasma stability in the two-component system. Stability of the two-component system can be analyzed by the methods developed for the standard mirror,[6] and appears to be highly favorable. The additional mode that must be examined is that for the interaction of the two ion components at different mean energies. Assuming a Maxwellian tritium distribution, this mode would be stable if the deuteron distribution $f(v)$ were a monotone decreasing function of deuteron velocity v.[7] In Fig. 3 we plot $f(v)$ as calculated by the Fokker-Planck code for typical steady-state cases. It can be seen that $f(v)$ is a monotonic decreasing function of v for sufficiently large mirror ratio R_M. The reason is that, except at low mirror ratios, the mirror losses are small during most of the history of slowing of the deuterium ions down to energies below which deuterium ion losses are by diffusion and their distribution becomes Maxwellian. The monotone decreasing behavior of $f(v)$ also bodes well for avoiding other velocity-space instabilities.[6]

As a model of the dense tritium plasma we assume the configuration of Fig. 1. The plasma electrons ionize tritium gas from sources placed just outside the mirrors. These sources of ionized gas together with heat input from the slowing down of the deuterium ions serve to sustain the plasma column in steady state. Electron energy transport and ion diffusion maintain approximately constant electron temperature and density between the sources. In the model, potential drops with $e\varphi = 4kT_e$ are assumed to appear at the ends to support the electron pressure, as in a classical discharge, and the power required to sustain the plasma is just that dissipated by the outward acceleration of ions escaping through these potential sheaths. A power balance requires

$$IE = 3(A/R_M)n_e(kT_e)^{3/2}(2/m_t)^{1/2} + (\text{mirror losses}). \qquad (2)$$

Here I and E are the neutral beam current and energy, respectively; m_t is the tritium mass; n_e and A are the plasma electron density and cross-sectional area at the center of the column,

TABLE I. Model parameters for a "breakeven" system ($Q=1$) with $R_M=10$.

Injection energy	200 keV
Electron temperature	4 keV
Tritium plasma density	10^{16} cm^{-3}
Plasma column diameter	2 cm
Plasma column length	10 m
Injection current (equivalent amperes)	2000 A
Confinement time of deuterons	1 msec
Fusion power released	400 MW

respectively; and A/R_M is the reduced cross-sectional area at the sheath near the mirror throats. Typically mirror losses amount to 20% of the input power at a mirror ratio $R_M=10$.

To illustrate the model, we list in Table I the parameters for a "breakeven" system ($Q=1$) with $R_M=10$. To achieve these parameters, the availability of highly focused, high-current neutral beams is crucial. Sources with currents, proportional to the emitting area, of 0.2 A/cm^2 with an intrinsic angular divergence of $\pm 0.6°$ have been developed at 20 keV.[1] Scaling up these sources in area and beam energy would meet the requirements.

To achieve $Q>1$ would require higher T_e and thus, with our model, a longer system. Use of multiple mirrors[8] or mirror-torus hybrids[2] could reduce the required length. Moreover, extension to higher currents of direct conversion techniques[9] to recover energy from the sheath-accelerated ions would permit net power production at lower Q. Finally, we note that, in view of the very high power density achievable, transient operation (pulsed beam, static field) may be advantageous.

Potential problem areas are electron heat conduction at the ends (divergent fanning of magnetic lines may help) and the need for a large R_M to reduce beam power by Eq. (2) (helped by high β). Finally we note that, even in a stable plasma, collective enhancement of the drag on hot ions beyond the classical values we have assumed may occur.[10,11] Fortunately it appears that all these issues can be addressed in experiments of moderate size.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]K. W. Ehlers *et al.*, in Proceedings of the Second International Conference on Ion Sources, Vienna, September 1972 (unpublished), p. 259; W. S. Cooper *et al.*, *ibid.*, p. 264.

[2]J. M. Dawson, H. P. Furth, and F. H. Tenney, Phys. Rev. Lett. 26, 1156 (1971).

[3]A. H. Futch, Jr., J. P. Holdren, J. Killeen, and A. A. Mirin, Plasma Phys. 14, 211 (1972). In the notation of this reference, the loss term is modified to choose as the loss coefficient the smaller of C_a/x^2 or $\lambda x^4 v_0^2/4C_a L^2$, where L is the length of the plasma; physically, this chooses between a mirror-loss time constant $\frac{1}{4}\lambda\nu_{\rm coll}$ or a diffusion constant $v^2/L^2\nu_{\rm coll}$. Here we let $L=(4/\lambda)^{1/2}v/\gamma_{\rm coll}$ at $v^2=(2T_e/m_d)^{1/2}$.

[4]R. F. Post, Nucl. Fusion, Suppl. Part 1, 99 (1962).

[5]G. G. Kelly, Plasma Phys. 9, 503 (1967).

[6]H. L. Berk *et al.*, in *Proceedings of the Third International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Novosibirsk, U.S.S.R., 1968* (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. II, p. 151.

[7]L. D. Pearlstein, M. N. Rosenbluth, and D. B. Chang, Phys. Fluids 9, 953 (1966).

[8]R. F. Post, Phys. Rev. Lett. 18, 323 (1967); G. I. Budker, V. V. Mirnov, and D. D. Ryutov, Pis'ma Zh. Eksp. Teor. Fiz. 14, 320 (1971) [JETP Lett. 14, 212 (1971)]; B. G. Logan *et al.*, Phys. Rev. Lett. 28, 144 (1972).

[9]R. W. Moir *et al.*, in *Proceedings of the Fourth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971* (International Atomic Energy Agency, Vienna, Austria, 1971), Vol. III, p. 315.

[10]D. E. Baldwin and J. D. Callen, Phys. Rev. Lett. 28, 1686 (1972).

[11]R. J. Burke, Ph. D. thesis, University of California at Davis, Lawrence Livermore Laboratory Report No. UCRL-51175, 1972 (unpublished).