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PHYSICS OF MIRROR REACTORS AND DEVICES*

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Abstract

The physics of plasma confinement using the magnetic mirror principle is discussed, and the unique features of the mirror reactor approach to fusion are discussed and compared to the toroidal confinement approach.

Introduction

Since the beginning of controlled thermonuclear research in the early 1950's, several distinct approaches using magnetic fields to confine hot plasmas have been followed. Some of these approaches have been toroidal (Tokamaks, Stellarator, toroidal pinches) mirrors, pinch confinement (θ-pinch, z-pinch), and cusp confinement. (For a general review of the field, see Ref. 1.) The discussion to follow describes aspects of the mirror magnetic confinement approach and makes some comparison to the toroidal (Tokamak) approach to controlled fusion. We should keep in mind that none of these approaches have yet been proven to be scientifically feasible (breakeven power possible) in the sense that the Fermi pile in 1942 proved that fission reactors were feasible. It may turn out that one of the presently conceived approaches may succeed, or several combinations of the ideas, such as mirror-toroidal hybrids. Or the first feasible fusion reactor might be a combined fission and fusion hybrid reactor. All of these approaches depend on understanding plasma physics much better than we do now.

The aspects of plasmas we will discuss are plasma confinement, equilibrium, stability, and thermonuclear power density. We will compare mirrors and toroidal reactors, and finally some new ideas in mirror confinement will be mentioned.

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Confinement, Equilibrium, and Stability

The principle of confinement of charged particles by the magnetic mirror effect can be best understood by viewing the particle's helical motion around a magnetic field line as a moving loop of current, i.e., a dipole sliding along a field line. As this dipole approaches strong field regions, a strong retarding force pushes the dipole back to lower fields; that is, the particle is confined in the direction along the magnetic field. The particle's magnetic moment, defined as

$$\mu = \frac{1/2\ m(\vec{v} \times \vec{B})^2}{|B|^3} = \frac{1/2\ mv_\perp^2}{B} = \frac{W_\perp}{B},$$

is called the first adiabatic invariant, and when the magnetic field seen by a particle in one revolution (cyclotron period) around the field line varies slowly (±5%), then μ is essentially a constant. From the constancy of μ we can derive the idea of a velocity space loss cone as follows. At the low field point (B_{MIN}) along a field line the particles velocity ($\vec{v}$) makes an angle θ with respect to the field line ($v_{||} = v \cos\theta$, $v_\perp = v \sin\theta$). Then $\mu = \frac{1/2\ mv^2 \sin^2\theta}{MIN}$.

As the particle moves into stronger field regions, the angle increases and equals 90° at the reflection point. The particle will reflect at field strengths of $B = B_{MIN}/\sin^2\theta$. The mirror ratio is defined as the ratio of the maximum field to the minimum field along a field line ($R = B_{MAX}/B_{MIN}$). Since the field line is double ended, there are two maxima, and we take the smaller of the two since leakage will occur there. The loss cone angle is then $\mathrm{Sin}^2\theta_{loss\ cone} = 1/R$. Particles having angles less than $\theta_{loss\ cone}$ are lost in one transit, and those having angles greater are confined axially.

Coulomb collisions result in a random walk of the particle's angle as well as its energy. Particles injected at 90° at B_{MIN} will on the average be lost after a time

$$\tau = \frac{3.4 \times 10^{10} \log_{10} R \, \bar{W}^{3/2}}{n}, \qquad (1)$$

where W is the mean energy of the confined deuterium and tritium (in keV) and n is the density (cm^{-3})(2). Radial loss due to collisional cross field diffusion should be smaller than axial loss by the factor $(a/r)^2$, where a is the ion larmor radius and r is the plasma radius. The ratio of a/r is usually about 1/10 in experiments and as small as 1/100 in reactors.

The particles drift from one field line to another due to the gradient of B. If the drift motion closes on itself, then an equilibrium can exist. The condition for existence of drift surfaces is the constancy of the second adiabatic invariant ($J = \oint v_{||} \, ds$) and the third invariant, which is that the flux within a drift surface be conserved ($\Phi = \int B \cdot dA$) (see Ref. 3).

This description applies equally well to the particles confined in the earth's magnetic field, with its north and south magnetic mirror.

Stability

The plasma can satisfy all the above equilibrium conditions but must further satisfy stability conditions for gross magnetohydrodynamic (MHD) motion and also fine grained motion or microscopic motion. It has been well verified that the plasma is unstable to gross displacements if the confining magnetic field decreased in a radial direction, as in the simple mirror shown in Fig. 1. A configuration whose field lines curve inward towards the plasma ("good curvature") has the property that the magnetic field is a minimum in the center. This type of configuration is called magnetic well (or minimum $|B|$ and can be made with several coil configurations, such as Ioffe-bars plus simple mirrors (Fig. 2), the baseball coil (Fig. 3), or the Yin-Yang coil (Fig. 4) (4). Experimentally, minimum $|B|$ configurations have been quite effective in producing stability to MHD motions, but at the expense of rather more complicated coils. A conceptual mirror reactor using the Yin-Yang coil is shown in Fig. 5.

The microinstabilities are a direct result of the loss cone in that low energy particles scatter rapidly in angle into the loss cone and are lost. From energetic arguments, a thermodynamically stable (lowest energy) velocity distribution is Maxwellian. Departure (absence of the low energy part) from a Maxwellian distribution can and does lead to instabilities. The most important goal of the research on mirror machines is to find out if conditions suitable for a reactor can be achieved while suppressing these instabilities to an acceptable level.

Some of the names of these instabilities have become household terms, like drift loss cone mode, Harris mode, Post-Rosenbluth convective mode, Baldwin-Callen theory, and mirror mode (5). These instabilities will not be discussed except to point out that hope for controlling them lies in design of the plasma conditions, such as broadening the ion energy distribution by injecting at widely spread energies with a high mirror ratio (10 or greater), shaping the field to obtain good curvature, shear, fanning of field lines towards the mirrors, warm unconfined plasmas, and control of end boundary conditions. The above list is only intended to give a flavor of a much more complicated picture which is being investigated at Lawrence Livermore Laboratory and elsewhere (6).

Power Balance

In order for a mirror reactor to be of interest it must have the potential for being a reasonably efficient power producer, i.e., making more power than consumed by some margin. This is expressed by Q, where Q is the ratio of thermonuclear power produced (14.06 MeV neutron + 3.56 MeV He^{++} + 4.8 MeV from the n(Li, He) T reaction) to the power that is trapped in the plasma. The mirror reactor can be viewed as a power amplifier where the injected power P_{inj} is multiplied by Q, and the power out of the reactor is $P_{inj} + P_{inj}Q$. If the efficiency of energy recovery η_{TH} and that of injection is η_i, then a breakeven condition is

$$(1 + Q)\, \eta_{TH}\eta_i > 1. \qquad (2)$$

For $\eta_{TH} = 0.45$ and $\eta_i = 0.85$, the required Q is 1.6. The expected Q for a stable D-T plasma with a mirror ratio of 10, assuming injection perpendicular* to $\vec{B}$ at 150 keV, is 1.8. (See Ref. 2.) With this value of Q the overall efficiency would be only 4%. The power balance is considerably improved if we directly convert leaking fuel ions (see Fig. 6 and the discussion in Ref. 7). If we take into account the possibility of direct conversion** with an efficiency $\eta_{DC}(0.6)$ and the fraction $f_c(0.2)$ of energy released as charged particles, and if we assume that the 14 MeV neutrons are converted with an efficiency $\eta_{TH1}(0.45)$, that the direct converter has a thermal bottoming cycle $\eta_{TH2}(0.4)$, and that the blanket multiplication of the 14 MeV neutron energy $M(1.34)$ gives 22.38 MeV per fusion event, then the overall plant efficiency is

$$\eta_{overall} = \frac{f_n M \eta_{TH1} + \left(\frac{1}{Q'} + f_c\right) \eta_{DC} + \left(\frac{1}{Q'} + f_c\right) \left(1 - \eta_{DC}\right) \eta_{TH2} - \frac{1}{Q' \eta_i}}{f_c + f_n M} , \qquad (3)$$

where Q' is the ratio of fusion energy (14 MeV neutron plus 3.56 MeV ^4He) to injection energy.

For the conditions given above, $\eta_{overall}$ is zero (breakeven) for $Q' = 0.656$, and for $Q' = 1.428$, i.e., the expected value, $\eta_{overall} = 27\%$.

Often one looks at the value of $n\tau$ rather than Q, and these are related by the expression

$$n\tau = \frac{4W_0 Q}{(\overline{\sigma v})_{DT} E_F} , \qquad (4)$$

*Assuming a 30% enhancement over the so-called normal mode injection.

**By direct conversion we mean that the energy carried by the leaking plasma in the form of kinetic energy of charged particles is converted directly to electricity without resorting to thermal conversion with its rotating machinery.

where W_0 is the injection energy, $(\overline{\sigma v})_{DT}$ is the reaction rate parameter, and E_F is 22.38 MeV, the fusion energy release. At 150 keV, $(\overline{\sigma v})_{DT}$ is 8.5×10^{-16} cm^3 sec^{-1}, and with a Q of 1.8 the value of $n\tau$ is 6×10^{13} cm^{-3} sec.

Still another measure of confinement is the fraction of fuel ions (D^+ and T^+) which burn (fuse) in one confinement time. The burn fraction BF is related to Q as follows:

$$BF = \frac{2W_0Q}{E_F} .$$

For 150 keV and a Q of 1.8, the burn fraction is 2.4%. This means the average fuel ion will have to be reinjected $\frac{1}{BF}$ times before it burns, or 42 times for a 2.4% burn fraction. The fuel ions leaking out of the reactor will have to be recovered and reinjected. Some of the tritium will inevitably be lost and must be made up by a tritium breeding ratio (ν = tritium bred per tritium consumed in fusion reactions) greater than 1. If the fraction of the tritium leaking out of the reactor which is recovered is f_{rec}, then we require

$$f_{rec} \geq \left(\frac{1}{\nu}\right)^{BF} .$$

For a breeding ratio of 1.2 and a burn fraction of 2.4%, $f_{rec} \geq 0.996$.

The conclusion is that there is a chance for a mirror machine to be a practical power producer if the classical Q values can be achieved, i.e., if the plasma will be essentially stable.

The value of Q is almost energy independent above 150 keV because $(\overline{\sigma v})_{DT}$ is proportional to $W_0^{-1/2}$; thus it is possible to consider mirror reactors operating over a wide energy range from the present example of 150 keV to the 600 keV case discussed by Lee (8).

Densities and confinement times sufficient for a reactor have already been achieved in different mirror experiments — but unfortunately not all of these in one experiment. The parameters for some of the many mirror experiments (9) — past, present, and future — are shown in Fig. 7, along with conceptual design parameters for a mirror FERF (Fusion Engineering Research Facility) (10), a low temperature (150 keV) mirror reactor, a 600 keV reactor (8), and a fusion-fission hybrid (11).

Power Density

The power density in the plasma is related to the fusion energy release E_F as

$$P/V = \frac{n^2}{4} (\sigma v)_{DT} E_F. \tag{5}$$

The ratio of plasma pressure to magnetic pressure is called β and can be quite high (≥0.5) in mirror machines:

$$\beta = \frac{p}{B_{vac}^2/2\mu_0} \approx \frac{nW_0}{B_{vac}^2/\mu_0} \tag{6}$$

The power density then becomes

$$P/V = \frac{1(\overline{\sigma v})_{DT} E_F}{4\mu_0^2} \, \frac{\beta^2 B_{vac}^4}{W_0^2} .$$

Now since

$$(\overline{\sigma v}) \propto W_0^{-1/2},$$

we have

$$P/v \propto \frac{\beta^2 B_{vac}^4}{W_0^{5/2}} .$$

We see that the power density increases rapidly as the energy decreases. Thus, compact reactors should have high β, a high field, and low energy, say 100-200 keV.

Economics

Since mirror reactors will apparently be low gain power amplifiers ($1 \lesssim Q \leq 2$), large circulating powers result. In order for this circulating power, which is about three times the net power in the reference design, not to be economically prohibitive, the power handling equipment must be quite efficient and relatively cheap. In this regard, direct energy conversion is being developed out of necessity to increase the recovery efficiency. (See Ref. 12 for a review of direct energy conversion.) The injection system will also have to be both efficient and cheap. For a discussion of aspects of injection for reactors, see Ref. 13.

Comparison of Mirror and Toroidal Reactors

The $n\tau$ in mirrors scales as $(\log_{10}R)W^{3/2}$; that is scattering into the loss cone does not depend on physical size, and therefore a mirror reactor does not have to be made large, and in fact one of its assets may be that it can be made in small sizes. In toroidal systems $n\tau$ scales up with radius so that large systems are very good for confinement and large enhanced losses can be tolerated. The confinement can be so good that the alpha particles from the fusion burn can heat new fuel so that, in principle, essentially no recirculating power would be required — in contrast to mirrors, where the power gain is so marginal that recirculation of power is a major concern.

The role of impurities should be quite different in the two cases. In mirrors the ions are confined better than electrons, thus leaving the plasma positively charged so that any impurity ion is repelled from the plasma as it tries to enter; consequently, mirror reactors should have essentially no impurity problem. In toroids the electrons are confined better than ions, essentially because loss is by cross field diffusion and the electrons having such small gyro orbits diffuse more slowly than ions. This leaves the plasma negatively charged, and any impurity ion will be attracted to the plasma. Accumulation of impurity ions can be expected, leading to line radiation, enhanced bremsstrahlung radiation, and charge exchange.

In mirror reactors the leaking fuel ions are directed through the open ends into a large direct converter where the energy is recovered and the D_2, T_2, and He gases are pumped. It is a disadvantage to have to have a direct converter, but once we have it, plasma disposal is automatically accomplished. In the toroidal system the plasma must leak across the field into the first wall and the energy flux and particle flux are so great that special precautions such as a diverter must be developed to dispose of the leaking plasma. The diverter and impurities in general are a major concern for toroidal approaches.

With regard to plasma stability, the mirror device is subject to high frequency ($\omega > \omega_{ci}$) instabilities which try to make the velocity distribution more Maxwellian, but MHD (low frequency) modes should be stable by the minimum $|B|$ configuration. In toroids the velocity distribution is very nearly Maxwellian, and thus it has high frequency stability, but low frequency (drift waves) instabilities should occur. The investigation, both experimentally and theoretically, of instabilities of plasmas is the main effort of the fusion research community today.

Advanced Concepts and Applications of Mirror Confinement

Multiple Mirrors

It may be possible to have a series of connected mirrors which could exceed the breakeven $n\tau$ (14). The idea is that a particle escaping from one cell might be trapped in the next cell. Such reactors require very high magnetic fields and are very long; however, the distribution is nearly Maxwellian, so the instabilities in conventional reactors should be avoided. This concept hasn't gained much interest.

Two-Component ("Wet Wood Burner")

The idea here is to inject D^+ at about 200 keV into a tritium plasma target (15). *The D^+ is mirror confined as it slows down, but the T^+ plasma is assumed to be freely* flowing along the magnetic field. This idea is related to the concept of injecting into a relatively cold, sublawson, toroidally confined plasma. The two component concept is receiving a fair amount of attention lately (16).

Hybrid Fusion-Fission Reactors

The idea is to surround a sublawson mirror plasma with a fission blanket to greatly enhance the energy output (17). The unproven speculation is that such a hybrid has advantages over a pure fission reactor. The speculation goes as follows: since the fission assembly can be subcritical, much design freedom exists to make up for the added cost of the fusion 14 MeV neutron source. These concepts are receiving renewed attention lately (11).

Materials Testing Reactor

One would like to develop materials which are compatible with 14 MeV neutron irradiation, as well as for other fusion reactor conditions, before actually building the fusion reactors. To do this will require irradiation facilities, and perhaps a small high power density sublawson mirror reactor could provide just such a facility. It could test first wall materials, tritium handling facilities, and all components of future reactors. Such a facility presently is still in the idea stage and is called FERF (Fusion Engineering Research Facility). A study is now underway at the Lawrence Livermore Laboratory on a Mirror FERF (10)

Conclusion

Mirror Reactors will operate at high energy, probably 150 keV or higher. Impurities are not expected to be a problem as in toroidal systems. However, direct energy conversion must be developed to efficiently recirculate large quantities of power (perhaps three times the net power). A major asset of the mirror concept is its inherent compactness.

References

1. R.F. Post, "Controlled Fusion Research and High-Temperature Plasmas," Annual Review of Nuclear Science 20, 509 (1970).

2. A.H. Futch, J.P. Holdren, J. Killeen, and A.A. Mirin, "Multispecies Fokker-Planck Calculations for D-T and D-^{3}He Mirror Reactors," Plasma Physics 14, 211 (1972). We take the value of the constant to be 2.67 (see p. 228) and enhance this by 30% due to perpendicular injection (p. 240, Table 12).

3. T.G. Northup, The Adiabatic Motion of Charged Particles, John Wiley and Sons, New York (1963).

4. *For a discussion of these configurations see R.W. Moir and C.E.* Taylor, "Magnets for Open-Ended Fusion Reactors," in Energy 70 Conference, 5th IECEC Conference Proceedings, Las Vegas, Nev., Sept. 1970, Sec. 1, p. 80 (Amer. Nucl. Soc., Hinsdale, Ill., 1971).

5. H.L. Berk, L.D. Pearlstein, J.G. Cordey, "Critical Length Criteria for Mirror Machines," Phys. Fluids 15, 891 (1972).
D.E. Baldwin, J.D. Callen, Phys. Rev. Lett. 28, 1686 (1972); also see the references cited in these two articles for further discussion of stability theory.

6. A.L. Hunt, "Surface Requirements of the Mirror Experimental Program," these proceedings.

7. R.W. Moir, "Surface Requirements for Direct Energy Converters," these proceedings.

8. J.D. Lee, "Surface Conditions in a Conceptual D-T Mirror Reactor with Direct Conversion," these proceedings.

9. J.R. Hiskes, private communication and for a list of references of many mirror experiments, see J.R. Hiskes and A.H. Futch, "Some Observations on Mirror Losses," Lawrence Livermore Laboratory Rept. UCRL-75002 (1973) (submitted to Nuclear Fusion).

10. E.B. Hooper, Jr., "Thermonuclear Reactor Test Facility," Lawrence Livermore Laboratory Rept. UCID-16308 (1973); C.E. Taylor, "Conceptual Design of a Mirror Reactor For a Fusion Engineering Research Facility (FERF)," submitted to First Topical meeting on the *Technology of Controlled Nuclear Fusion, American Nuclear* Society, San Diego, April 1973.

11. J.D. Lee, "Neutronics Analysis of a 2500 MW_{th} Fast Fission Natural Uranium Blanket for a DT Fusion Reactor," submitted to First Topical Meeting on the Technology of Controlled Nuclear Fusion, American Nuclear Society, San Diego, April 1973; W.C. Wolkenhauer, B.R. Leonard, Jr., R.W. Moir, R.W. Werner, "Conceptual Design of a Fusion-Fission Hybrid Reactor Based on a Mirror Fusion Reactor with a Subcritical Gas Cooled Fission Blanket," submitted to American Nuclear Society, April 1974 meeting, San Diego.

12. W.L. Barr, M.O. Calderon, T.N. Haratani, J.D. Kinney, R.W. Moir, R.R. Smith, "Apparatus for Testing Direct Energy Conversion of Plasma Energy to Electricity," Proceedings of the Fifth Symposium on Engineering Problems of rusion Research, Princeton, N.J., Nov. 1973.

13. J. Hovingh and R.W. Moir, "Efficiency of Injection of Neutral Beams Into Thermonuclear Reactors," Lawrence Livermore Laboratory Rept. UCRL-74883 (submitted to Nuclear Fusion).

14. R.F. Post, Phys. Rev. Letters, 18, 232 (1967); J.J. Taylor, "Multiple Mirrors and RF Stoppers," Culham Lab. Rept. CLM-R-94, p. 27, UKAEA, England (1969); A. Makhigani, A.J. Lichtenberg, M.A. Lieberman, and B.G. Logan, "Plasma Confinement in Multiple Mirror Systems I: Theory" and B.G. Logan, I.G. Brown, A.J. Lichtenberg, and M.A. Lieberman, "Plasma Confinement in Multiple Mirror Systems II: Experiment and Reactor Calculations," Memoranda Nos. ERL-M 388 and 387, Electronics Research Lab., Univ. of Calif., Berkeley; J.M. Dawson, "On the Possibilities for a Multiple Mirror Fusion Reactor," Bull. Am. Phys. Soc. 18, 1303 (1973).

15. J.M. Dawson, H.P. Furth, and F.H. Tenney, "Stellarator Mirror Machine Target Plasma Reactor," MATT-841 (1971), Princeton University, Plasma Physics Laboratory, Princeton, N.J.; J.M. Dawson, H.P. Furth, F.H. Tenney, Phys. Rev. Lett. 26, 115 (1971); R.F. Post, T.K. Fowler, J. Killeen and A.A. Mirin, "A Concept for a High Power Density Mirror Fusion Reactor," Phys. Rev. Lett., 1973.

16. R.F. Post and T.K. Fowler, "Parameters for a Two-Component Mirror Experiment, Bull. Am. Phys. Soc. 18, 1251 (1973); B. McNamara, J.A. Byers, E.P. Lee, and D. Fuss, "Mirror-Arc Reactor and Target Experiments With Neutral Injection — A Computer Model"; "A Cold Flowing Plasma in Mirror Geometry"; "Mirror Arc Reactor and Target Experiments with Neutral Injection — Numerical Techniques for the Computer Model," Bull Am. Phys. Soc. 18, 1252 (1973).

17. The idea of fission-fusion hybrids is old but some recent works are: L.M. Lidsky, "Fission-Fusion Symbioses: General Considerations and a Specific Example," Proceedings of the British Nuclear Energy Society Conference on Nuclear Fusion Reactors (Culham Laboratory, Culham, England, 1969), UKAEA, (1969) 42; J.D. Lee, "Neutronics of Sub-Critical Fast Fission Blankets for D-T Fusion Reactors," Proceedings of the 7th Intersociety Energy Conversion Engineering Conference (San Diego, California, Sept. 25-29, 1972).

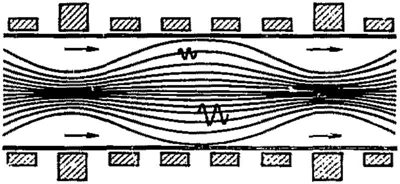

FIG 1

Schematic of the configuration of simple (axially symmetric) mirror fields. Note that field intensity at midplane is saddle-shaped, i.e., while it increases in either direction along the axis, it weakens in the radial direction.

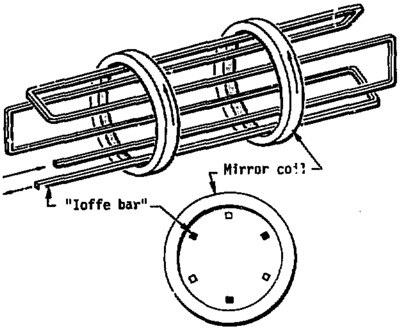

FIG 2

Ioffe bar-mirror coil.

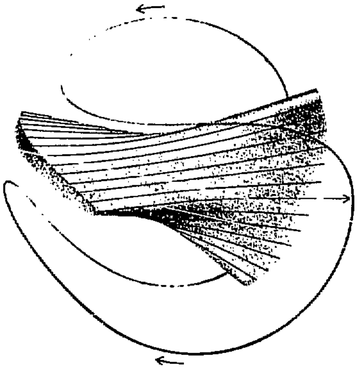

FIG 3

Baseball coil. The field intensity increases from the center in all directions, making a magnetic well.

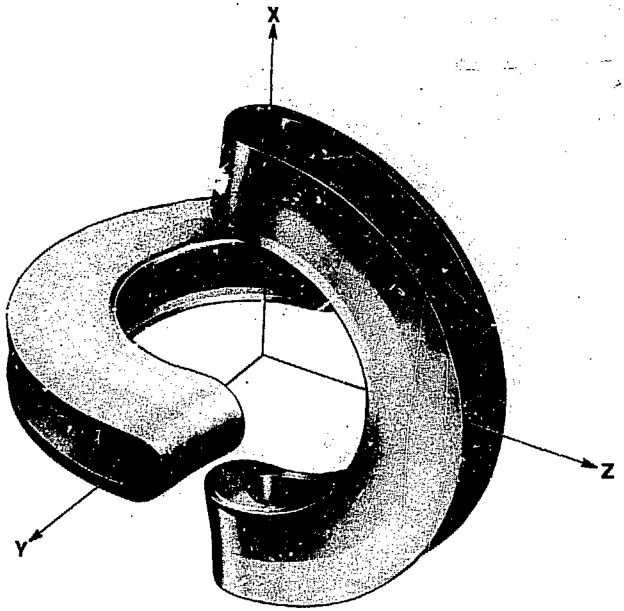

FIG 4

Yin-Yang coil makes a magnetic well with efficient use of conductor material.

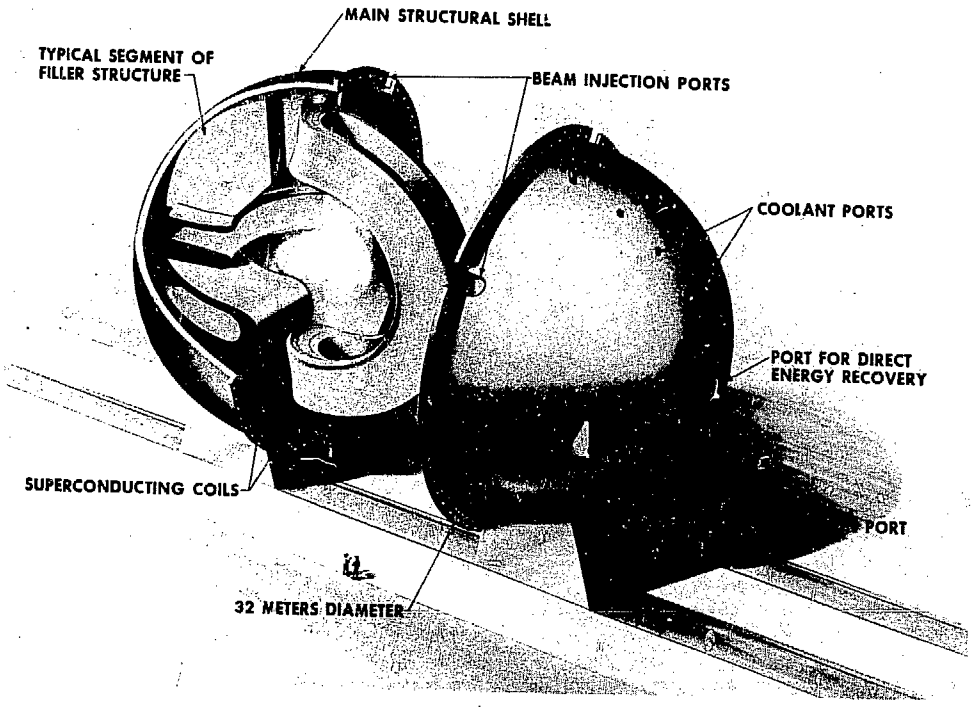

FIG 5

Mirror Reactor based on a Yin-Yang magnet.

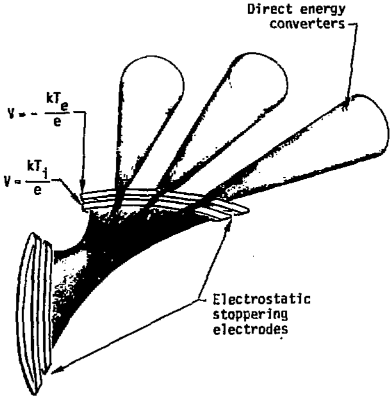

FIG 6

Leaking plasma is directed out individual holes by electrostatic stoppering of all the end regions except the holes. The electrodes are located outside the magnetic mirrors.

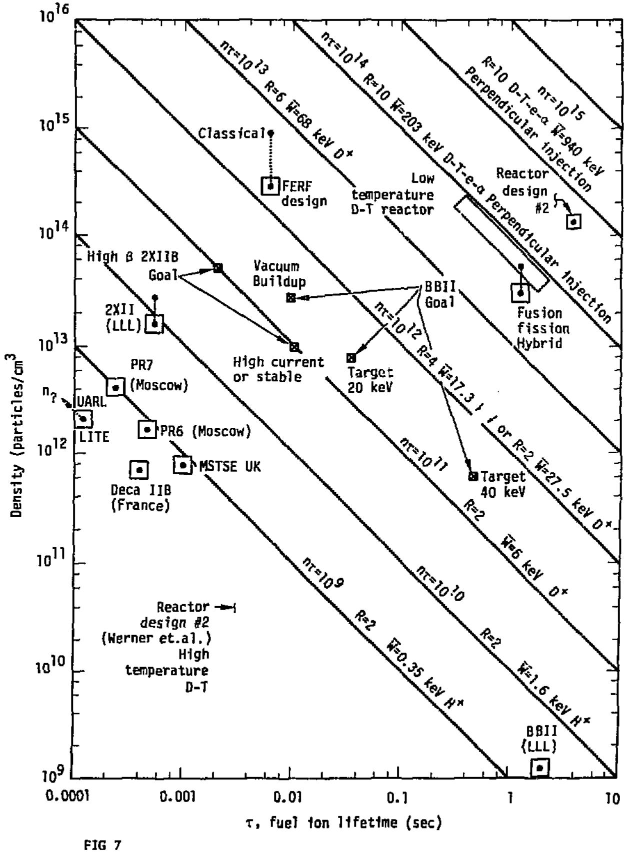

FIG 7

Density vs particle lifetime for mirror experiments and reactors.