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A B S T R A C T

A mirror confinement principle is described in which particles escaping through the mirrors are neutralised and reinjected directly, without the use of an external energy recovery system. This method could, in principle, lead to a thermonuclear reactor with an order of magnitude increase in the effective 'Q' of the reacting plasma and a corresponding decrease in the injected current. The low operating energy (~ 100 keV D-T) relaxes the β constraint.

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The first extensive assessment of the thermonuclear reactor potential of open-ended mirror systems was made by Post in 1961[1]. Since that time the subject lay fallow for a number of years until the calculations of Fowler and Rankin[2] suggested that the effect of electron cooling and high plasma potential substantially reduced the $n\tau$ and hence made the energy gain of such systems uncomfortably small. Since then a series of papers have dealt with the problem and have pointed out the difficulty of generating power economically with such a small energy margin and the consequent high recirculating power[3].

Post[4] has suggested a way of converting the energy emerging through the mirrors into electrical power which may be used to reinject neutral atoms. The power handling capacity of such a recovery system is however limited by space charge considerations to a value which scales as $E_i^{5/2}$ (where E_i is the injection energy). Thus the injection energy may have to be greater than 500 keV if station outputs in the 1000 Megawatt region are to be achieved and the consequent high plasma pressure results in a severe constraint on the power density.

In this letter we suggest an alternative scheme in which the particles emerging through the mirrors are neutralised and reinjected directly with high efficiency. The system is not subject to space charge limitations of the kind mentioned above, so that a relatively low operating energy may be used (~ 100 keV D-T system). The system is capable of approaching the self-sustaining condition if fairly modest criteria on recirculation efficiency are met.

The scheme depends on the fact that the particles emerging through the mirror have their energy mostly in the perpendicular direction. As the magnetic field beyond the mirror falls, so some of this energy is converted to energy parallel to the field lines, but by arranging for the particles to adiabatically enter a second mirror with field of similar value to that of the first, the energy may be converted back into perpendicular energy again. If this second mirror is made into a particle neutralisation region, neutral atoms emerge with a rather narrow angular spread on either side of the plane perpendicular to the magnetic field lines.

In the present scheme these fast atoms are reinjected into the original reacting volume by arranging for the field lines to be re-entrant. Figure 1 show a schematic arrangement to achieve this for simple mirror geometry. The system is essentially axisymmetric about the centre line and ions are normally confined and react in the annular region A. The top mirror (at B) of this reacting region is made slightly weaker than the bottom (at D) so that essentially all the escaping ion flux emerges from the top. Those escaping through the mirror (at B) are conveyed to the region C where the field along each flux tube is arranged to be the same as at B. A high gas pressure is maintained in region C such that the probability of neutralisation is of order unity. Those particles that are neutralised emerge at a small angle to the normal to the field and are recaptured in the reacting region with high probability.

The magnetic field geometry required for the system may be generated by a system of windings similar to those shown in the Figure. A particularly simple version which has very nearly the required field configuration is provided by a double Helmholtz coil arrangement with opposing currents, the outer pair being at approximately twice the radius of the inner pair. Access to the top inner coil for supports, current leads, cooling etc. is made through the magnetic field as shown. Particle bombardment of the supports is avoided by arranging for the mirror magnetic field to be slightly non-uniform around the toroidal azimuth so that particles escape through the mirrors only in regions free of supports. The bottom inner winding supports may be brought in from below where there is free access. The inner windings are surrounded by blanket sufficient to absorb neutrons and reduce the radiation level at the windings to an acceptable value.

The angular range about the plane perpendicular to the field lines, $\bar{\theta}_c$ is decided by the following considerations:

(i) The natural spread of the angular distributions emerging through the mirrors is important. Analytic solutions of the Fokker-Planck equation show the mean angle at the mirror $\hat{\theta}_B$, to be given approximately by

$$\hat{\theta}_B \approx \left(\frac{\tau_b}{\tau_c} \right)^{\frac{1}{4}} , \tag{1}$$

where τ_b = 2 x the transit time between the mirrors, and τ_c = the classical 90^0 scattering time.

For $\tau_b = 3 \times 10^{-6}$ sec and $\tau_c = 1$ sec then

$$\hat{\theta} \approx 0{\cdot}04 \quad (\text{i.e.} \quad 2{\cdot}4^0) \ .$$

(ii) The magnetic field at C and B must be matched closely. Simple adiabatic mirror theory gives

$$\frac{B_B}{B_C} - 1 \approx \theta_C^2 - \theta_B^2 \ . \tag{2}$$

To make $\theta_C < 0{\cdot}1$ then

$$\frac{B_B}{B_C} - 1 < 0{\cdot}01 \ . \tag{3}$$

This condition may be relaxed somewhat if a small mean angle of reinjection at C may be tolerated.

(iii) The potential at C and B must be matched. Since particles at B have a spread in their absolute energy, the addition of energy parallel to the field lines due to a potential difference between B and C results in dispersion in angle at C. The maximum angle at C due to a potential difference $\Delta\varphi$ is approximately given by

$$\theta_C^2 = \frac{\Delta\varphi}{E_\perp} , \tag{4}$$

i.e. for θ_C not to exceed $0{\cdot}1$ rad then

$$\frac{\Delta\varphi}{E_\perp} < 0{\cdot}01 \ .$$

For the purpose of further discussion we assume that particles reaching the neutraliser region have a mean value of θ_C of $\sim 0{\cdot}1$ radians.

The neutraliser region is critical to the concept. In the region of high gas pressure neutralisation can occur with high efficiency since those ions that become neutralised may escape from the high pressure region and not become recharged. In practice there is a finite probability of reionization before escape and the particles execute a two-dimensional random walk across the neutraliser preserving their velocity along the field lines. The efficiency of neutralisation in a neutraliser of depth d and the radius r is given by

$$\eta_n = 1 - \exp(-\, d/\ell) \ , \tag{5}$$

where the mean free path along the field lines (ℓ) is given, on a somewhat simplified model, by

$$\ell \sim \frac{\theta_C}{n_o\, \sigma_{10}\, \exp(-\, n_o\, \sigma_{01}\, r)} , \tag{6}$$

where n_o is the gas density and σ_{10} and σ_{01} are the respective neutralisation and ionization cross sections. For typical reactor parameters $d = 200$ cm, $r = 250$ cm; at the energy at which $\sigma_{10} \sim \sigma_{01}$ (i.e. for D's on most gases at between 60 and 100 keV), η_n has a maximum value of 0·95. The need to work at low energy is emphasized by equations (5) and (6) since a large ratio of σ_{01}/σ_{10} rapidly decreases η_n. By arranging for the particles to enter a higher field region beyond the neutraliser a multiple pass system is possible which might have some advantage in reducing the gas density requirement.

The neutraliser gas, if allowed to impinge on the reactor plasma, could provide an energy drain problem. For typical reactor conditions, with a single pass system and uncollimated neutraliser gas, the flux of neutraliser atoms entering the reactor volume is comparable with the flux of fast ions leaving through the mirrors. Thus the situation is similar to certain toroidal reactors (e.g. Tokamak) where the plasma ions deposit on the wall and in equilibrium release an equivalent amount of gas. A boundary layer of relatively cold plasma is likely to form on the inside surface of the reacting volume and it is not clear without detailed calculations whether this would lead to an unacceptable heat drain. The problem would be avoided completely however, by a modest degree of collimation of the neutraliser gas to prevent direct streaming into the reacting volume or an annular arc screen around the neutraliser.

The production of cold ions and electrons in the neutraliser region provides one of the major problems.

Cold ions and electrons are created by collision of the fast primary ions and electrons with the neutraliser gas. In addition, the secondary electrons produce further ionization. This latter effect is more difficult to estimate quantitatively since there may be appreciable energy given to the secondary electrons by Coulomb collisions with the primary flux. However, much of this energy is radiated as line radiation, so for the present purpose it will be assumed that each secondary electron results in less than one further ionizing event, i.e. there is no exponential growth of plasma density feeding on energy drained from the fast primaries. Thus we take there to be ξ cold ions produced in the neutraliser for each primary ion. Then, assuming one-dimensional flow along the field lines at the ions sound speed

$$n_c \approx \frac{I_p}{10\ e}\left(\frac{m_i}{kT_e}\right)^{1/2} , \qquad (7)$$

where I_p is the current of cold ions generated (amps/cm^2), m_i is the mass of the ions produced in the neutraliser gas and T_e is the electron temperature in the neutraliser. A more accurate treatment with the correct spatial dependence of the ion production rate would modify this somewhat.

I_p we take as ξI_M, where I_M is the current density emerging through the mirrors

$$I_M = \frac{P_M}{S\ E_o} \text{ amps/cm}^2 , \qquad (8)$$

where P_M is the power emerging through the mirrors (watts). S is the mirror throat area (cm^2) and E_o is the mean energy of the particles emerging from the mirror (eV).

In a typical reactor regime[3] $P_M \simeq 1{\cdot}7\ P_o$, where for typical dimensions the net electrical power output of the reactor (P_o) is the of the order of 1000 MW(e).

Taking $P_o = 10^9$ watts, $S = 2 \times 10^5$ cm^2, $E_o = 10^5$ eV, $T_e = 10$ eV, thus

$$I_M \simeq {\cdot}035 \text{ amps/cm}^2$$

and

$$n_c \approx 1{\cdot}6 \times 10^{11} A^{\frac{1}{2}} \xi \text{ cm}^{-3} ,$$

where A is the mass of the neutraliser gas (AMU).

In the absence of loss processes this order of plasma density would be expected to extend along the field lines as far as the main reactor where the positive plasma potential necessary to hold in the reactor electrons acts as a reflecting wall to cold ions.

The presence of this cold plasma carries with it problems of energy drain from the hot ions due to Coulomb collisions and undesirable neutralisation of the primary ions before they reach the gas region.

On the assumption that T_e in the cold plasma is kept much less than 25 eV by line radiation then the energy drain from the hot ions is given by

$$\frac{dE_o}{dt} = -\,3{\cdot}6 \times 10^{-4} \frac{A_p^{\frac{1}{2}} \ell n \Lambda\, n_e}{E_o^{\frac{1}{2}}} \text{ eV/sec} , \tag{9}$$

where A_p is the average atomic mass of the fast primaries (AMU) and $n_e \simeq n_c$ if the neutraliser gas is singly ionized.

The time for the fast primary to travel from the reactor to the neutraliser is $\tau \approx L/v\,\bar{\theta}$ where L is the distance involved, v is the primary velocity and $\bar{\theta}$ is some average angle to the normal to the field lines. If we take $L = 10^3$ cm, $v = 3 \times 10^8$ cm/sec, $\bar{\theta} = 0{\cdot}2$, $A_p = 2{\cdot}5$, $\ell n \Lambda = 10$, $n_e = n_c = 1{\cdot}6 \times 10^{11} A^{\frac{1}{2}} \xi \text{ cm}^{-3}$, and $E_o = 10^5$ eV then $\tau \approx 1{\cdot}7 \times 10^{-5}$ sec and the energy loss $\Delta E_o \simeq 46\, A^{\frac{1}{2}} \xi$ eV. Thus provided ξ is not too large, the energy drain per transit is not a serious problem.

The probability of a primary ion neutralising on a cold ion before reaching the gas region is given approximately by

$$P = \frac{L\, n_c\, \sigma^i_{10}}{\bar{\theta}} , \tag{10}$$

where σ^i_{10} is the cross section for neutralising on an ion.

If $L = 10^3$ cm, $n_c = 1{\cdot}6 \times 10^{11} A^{\frac{1}{2}} \xi \text{ cm}^{-3}$, $\bar{\theta} = 0{\cdot}2$ then

$$P \approx 0{\cdot}8 \times 10^{15} \sigma^i_{01} A^{\frac{1}{2}} \xi .$$

The value of $\sigma^i_{10} A^{\frac{1}{2}} \xi$ depends critically on the neutraliser gas used. The choice of gas is wide. As examples: lithium vapour which is desirable from the vacuum point of view, since it may be arranged to condense on the walls and run off as liquid, has $\sigma^i_{10} \sim 5 \times 10^{-18}$ cm^2, $A = 7$, $\xi \sim 20$, therefore $\Delta E \simeq 2{\cdot}5$ keV and $P \sim 0{\cdot}2$; deuterium on the other hand, has $A = 2$, $\xi \sim 2$, therefore $\Delta E \simeq 130$ eV and the neutralisation problem is essentially non-existent since the plasma extending towards the reactor will have dissociated to D^+.

The effect of the cold plasma on the reactor is difficult to assess without a complete self-consistent solution of the particle and potential distributions for the reactor and external plasma. These distributions may be significantly affected by non-classical momentum and energy transfer processes such as two stream instabilities in region BC. The cold plasma could play a vital role in stabilising the reactor plasma against interchange modes. However, the presence of cold plasma may prove to be undesirable because of electron thermal conduction from the hot reacting plasma. Various possibilities exist for removing cold plasma preferentially. One possibility is to arrange for different flux tubes to be at different potentials so as to create a radial electric field. In the region between the neutraliser and the reactor the consequent $E \times B$ drift of the cold ions could be made to carry them on to the upper coil supports. The fast ions experience the $E \times B$ drift for too short a time to be affected.

As described here the reactor is a simple mirror and stabilisation against flute modes depends on line tying to the ends. A minimum-B version of the system can be produced in principle, however, by superposition of a high order multipole field on to the outside of the reactor volume. By suitable adjustment of the simple mirror field the inside of the reactor volume can be arranged to be stable. As an alternative it may be possible to combine this injection idea with a minimum-B system of the Andreoletti/Furth type[5,6]. It is expected that the escaping ions will be stable against flute modes in region BC since the transit time through the region is shorter than the growth time, and since this region is electrically connected to the main reactor the stability of the region should be determined by the reactor stability.

We consider now the overall energy and particle balance in the reactor system. We may express the power gain introduced as a result of the reinjection as the ratio of the injected power requirements in the absence of the reinjection loop (P_0) to the power required with the loop functioning (P_I)

$$\frac{P_0}{P_I} = \frac{1}{1 - \eta(1 + \varepsilon Q)} , \qquad (11)$$

where ε is the ratio of the thermonuclear reaction output appearing in the ions emerging through the mirrors to the total thermonuclear reaction output and Q has the usual definition

$$Q = \frac{\text{total thermonuclear reaction output}}{\text{rate of energy input to plasma}} .$$

Thus the effective Q of the system is amplified by the ratio $1/\{1 - \eta(1 + \varepsilon Q)\}$ and, as the loop efficiency approaches $\eta_c = 1/(1 + \varepsilon Q)$, the system approaches the self-sustaining condition.

Typically, for a D-T system with a total energy release including capture energy of 22·4 MeV, the maximum value of ε is 0·16. Fokker-Planck calculations however, show that some fraction of the thermonuclear energy release appears in the electrons emerging through the mirrors[7] which is recovered in the thermal cycle; ε is therefore closer to 0. Thus for a typical system ε probably lies between 0·16 and 0. Q with-out recirculation[7] may be 1·0 which leads to a value for η_c between 0·86 and 1·0. It should be noted that if $\eta_c < 1$ then the recirculation loop becomes energetically self-sustaining before 100% particle recirculation is achieved. This implies that to maintain equilibrium the external injection of particles must take place at an energy below the recirculation loop energy, the injection energy going to zero as $\eta \to \eta_c$.

In practice it would seem to be feasible to make $\eta \sim 0{\cdot}8$–$0{\cdot}9$ and thus run close to the self-sustaining condition.

External injection is required to make up particle losses and this could be provided as injection of high energy neutrals directly into the reactor volume. There might be some advantage however in a running reactor in using the built-in highly efficient neutralisation system by injecting charged particles at the appropriate angle down the central flux tube, to which there is free access.

The radial density and energy distributions in the reacting plasma will be determined by the penetration depth of fast atoms. Some control over the distributions can be provided by the external injection method. At a density of 10^{14} ions/cm^3, the penetration depth of a 100 keV deuterium atom is ~ 30 cm and is inversely proportional to density[8]. This depth can be self-consistent with the assumed reactor plasma width.

The neutralisation efficiency considerations discussed above together with the nuclear cross section behaviour results in an optimum operating energy for a D-T system of the order of 100 keV. Thus the β restrictions are much less severe than for schemes using external direct recovery where the operating energy is likely to be greater than 500 keV. This, together with the possibility of an order of magnitude of more effective gain in Q and a corresponding reduction in injected current, make this "auto-injection" system attractive. It should be pointed out that it might be possible to dispense entirely with the mirror at B and arrange for neutralisation to occur just prior to the mirror at C. In this case however, it is difficult to see how it could be made minimum-B to stablise against interchange instabilities.

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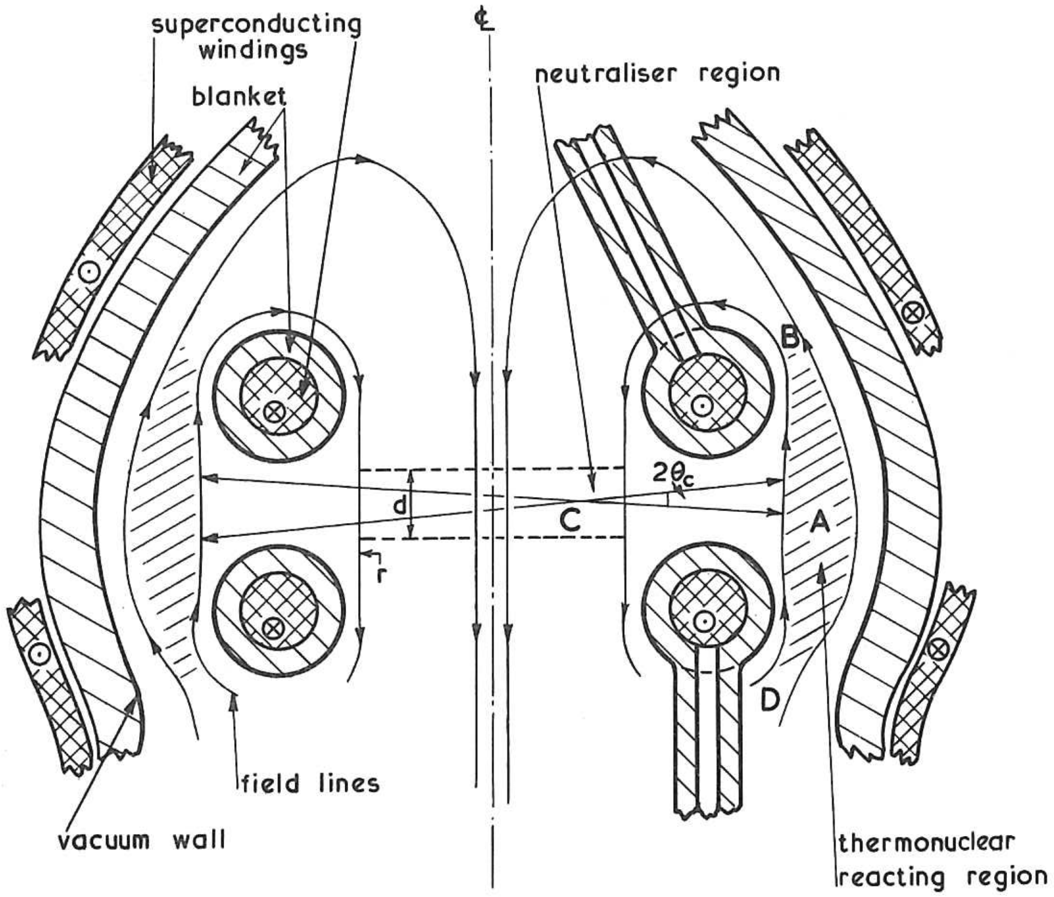

Fig. 1 Schematic diagram of auto-injection mirror. The radial thickness of the reacting plasma is somewhat exaggerated in this drawing.

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