The diplodok dynamic mirror system for plasma confinement

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The particle and energy lifetime in a mirror system can be increased by using "traveling" mirrors.

1. INTRODUCTION

The particle confinement time of Budker mirror systems is limited to a small value by the ion-ion collision time.[1] This short confinement time is regarded as the primary drawback of such systems and in practice rules out the development of an economically attractive fusion reactor based on this concept. The difficulties stemming from instabilities, on the other hand, can apparently be overcome, as has been shown by M. S. Ioffe and his colleagues, among others.[2]

An important step toward increasing the lifetime of the bulk of the particles was taken by G. I. Dimov and colleagues, who proposed a tandem mirror or "ambipolar confinement system." Switching to a tandem mirror, however, is by no means the only way to weaken the harmful effects of collisions in mirror systems with infrequent collisions. There are two basic approaches here; a combination of the two may make it possible to increase $n\tau_E^{\text{eff}}$ by a factor of 5 to 10.

The first approach is to develop economical injectors and devices (direct conversion systems) for recovering the energy of the particles which escape from the system. We denote by $\mathscr{E}_i$ the energy of the ions entering the confinement system, by η_j the efficiency of the injector, by η_r the efficiency at which the charged-particle energy is recovered (the charge particles here are ions, electrons, and reaction products), and by η_t the efficiency of the heat cycle. The condition for a self-sustaining reaction then takes the form

$$\frac{n}{\tau_E}\left[\frac{\mathscr{E}_i}{\eta_j} - \mathscr{E}_i\eta_r - (\mathscr{E}_i - \mathscr{E}')\eta_t\right] = n^2 \langle \sigma_{\text{nuc}} v \rangle \left[(W_n + W_\gamma)\eta_t + W_c\eta_r\right]. \tag{1}$$

Here W_n, W_γ, and W_c are the energies of the reaction products: neutrons, radiation, and charged particles. It can be seen from (1) that the quantity τ_E^{eff}, given by

$$\mathscr{E}_i / \tau_E^{\text{eff}} = n \langle \sigma_{\text{nuc}} v \rangle W\eta_t; \quad W = W_n + W_\gamma + W_c,$$

is

$$\tau_E^{\text{eff}} = \tau_E \frac{\eta_j}{1 - \eta_j\eta_r}\left(\frac{W_n + W_\gamma}{W} + \frac{W_c}{W}\frac{\eta_r}{\eta_t}\right); \quad \theta = \frac{\mathscr{E}_i'}{\mathscr{E}_i} + \frac{\mathscr{E}_i - \mathscr{E}'}{\mathscr{E}_i}\frac{\eta_t}{\eta_r}. \tag{2}$$

Here $\mathscr{E}_i - \mathscr{E}_i'$ is the energy lost due to radiation and thermal conductivity. If we assume the DT reaction, for which we would have $W_n/W \approx 4/5$ and $W_c/W_{\rm eff} \approx 1/5$, and if we set $\theta = 1$, $\eta_t = 0.3$, and $\eta_j = \eta_r = 0.9$ for a mirror system, we find $\tau_E^{\rm eff} \approx 7\tau_E$. Under "contemporary" conditions, on the other hand, we would have $\eta_r = \eta_t = 0.3$, $\eta_j = 0.6$, and thus $\tau_E^{\rm eff} \approx 0.7\tau_E$. The use of highly efficient injectors and recovery devices would thus make it possible to increase $\tau_E^{\rm eff}$ by nearly an order of magnitude.

Specific recovery systems have been proposed by Post, V. A. Chuyanov, A. V. Timofeev, and others. Although experiments have been carried out on the various schemes, they have been of very small scale, and recovery systems have yet to emerge as a natural component of mirror systems.

The second approach to increasing the reactor efficiency is to increase τ_E by maintaining the ratio $v_\perp/v_\parallel$ at a value which would keep the ions outside the loss cone. To the best of our knowledge, however, the only work in this direction has consisted of a few attempts, not very successful, to increase $v_\perp$ in mirrors by means of an ion cyclotron resonance.

2. OPERATION OF THE FIRST STAGE OF THE DIPLODOK[1)]

Figure 1 shows a diagram of this new confinement system. It consists of two parts: The confinement system proper (the first stage) and a recovery system.[2)] In the first stage, which contains a movable mirror, the value of $v_\parallel$ is reduced through an increase in the distance (l) between the mirrors by virtue of the conservation of the longitudinal adiabatic invariant

$$J_\parallel = \int v_\parallel dl \approx v_\parallel l. \tag{3}$$

In the course of this expansion, $v_\perp$ remains constant if H is conserved. If the length of the confinement system increases by a factor of two over a time $\tau \sim \tau_{i,i}$, then there is a proportional increase in the confinement time per unit initial density. By making the

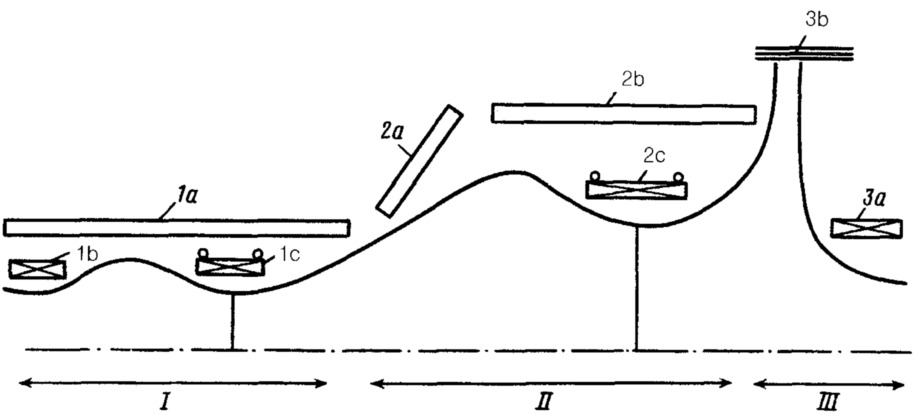

FIG. 1. I: First (working) stage. *1a*—Longitudinal-field coil; *1b*—fixed mirror; *1c*—movable mirror. II: Second (recovery) stage. *2a*—Expander coil; *2b*—longitudinal-field coil; *2c*—movable mirror. III: Receiver stage. *3a*—"Antifield" coil; *3b*—receiver of "spent" plasma and of charged reaction products.

confinement system longer we can evidently deform the phase volume, which is growing by virtue of collisions, without changing the magnitude of this volume—by compressing it along v_z and stretching it out along z. The removal of longitudinal energy from the particles constitutes a direct conversion of this energy into mechanical energy—if the coil is physically movable—or into electrical energy—if the mirror moves by virtue of a redistribution of the current in a fixed magnet system.[3)] The loss of transverse energy of the particles which results from collisions can be offset by a uniform increase in the magnetic field throughout the volume of the first stage, including the mirrors, or through rf heating.

An accurate calculation of the evolution of the ion distribution in a confinement system with moving mirrors is rather complicated and goes beyond the scope of this letter, even in the approximation of a uniform mirror system with a constant magnetic field, which would correspond to a Landau equation [see Eq. (3)]

$$\frac{\partial f_i}{\partial t} + \frac{\partial}{\partial p_z}(\dot{p}_z f_i) = -2\pi e^4 \Lambda \frac{\partial}{\partial p_k} \int d\mathbf{p} [\frac{\partial f_i'}{\partial p_l'} f_i - \frac{\partial f_i}{\partial p_l} f_i'] w_{kl} + Q, \quad \dot{p}_z = -p_z \frac{\dot{l}}{l}. \qquad (4)$$

We find a dimensionless parameter which characterizes the role of the change in l as the ratio of the scale value of the "convection" term on the left side of (4) to the collisional term on the right side:

$$\gamma \equiv \frac{\{\frac{\partial}{\partial p_z}(\dot{p}_z f_i)\}}{\{St\}} = \frac{\dot{l}\sqrt{m}(kT)^{3/2}}{2\pi N l^4 \Lambda} \sim \frac{\dot{l}}{l}\tau_{ii}. \qquad (5)$$

Here $N = nl$. Substituting the values $n = 10^{14}$ cm^{-3}, $l = 5$ m, $T = 10^4$ eV, $m = 3.5\times 10^{-24}$ g, and $\Lambda = 15$ into (5), we find $\dot{l} \equiv v = 300$ m/s to the piston velocity which corresponds to the value $\gamma = 1$. We also find that the distribution function is determined to a large extent by the expansion of the confinement system.[4)] We would apparently want to expand the confinement system by a small factor, 2 to 4. We would then need to recover all the particle energy. The reason is that the expansion of the confinement system results in a removal of energy from the particles and a substantial decrease in the particle density. If the decrease in $\mathscr{E}_i$ and n is not offset by the increase in the magnetic field in the first stage, the confinement system will quickly deviate from normal operation. The increase in H, however, is limited to ~ 100 kOe. Furthermore, overly long confinement times ($\tau \gg \tau_{ii}$) would be prevented by "close" Coulomb collisions, which would scatter particles directly into the loss cone. The choice of the actual expansion factor will of course have to await corresponding calculation based on the Landau equation.

3. SECOND STAGE OF THE DIPLODOK (THE RECOVERY SYSTEM)

Efficient recovery can be carried out by means of a second mirror system, substantially larger in diameter, connected through the movable mirror discussed above to the first (working) mirror system (Fig. 1). The expansion of the magnetic field leads to the pumping that we need. The second mirror (that on the right in Fig. 1) of the recovery system is also movable, but the field at its axis is generally stronger than that at the mirror of the working section.

The recovery mirror system can be filled either by drawing particles from the working mirror system through the mirror or—if it proves to be a better idea—by discharging the bulk of the particles at a certain time, by quickly weakening the field of the movable "intermediate" mirror.

When the recovery system is filled with plasma to the optimum extent, the right-hand mirror (or piston) (Fig. 1) begins to move, the longitudinal energy of the particles is transferred to the piston and is converted into electrical energy. The efficiency of this recovery system can be estimated quite simply. If the radius of the working mirror system is a_1, and that of the recovery system a_2, the transverse energy decreases by a factor $N_\perp \approx a_2^2/a_1^2$ in the course of adiabatic expansion. When the secondary volume is subsequently lengthened from L_1 to L_2, the longitudinal energy decreases by a factor $N_\parallel \sim L_2^2/L_1^2$. The efficiency of the recovery system is thus

$$\eta_r \approx 1 - \frac{1}{N_\perp} - \frac{1}{N_\parallel}.$$

Assuming $a_2/a_1 = 5$ and $L_2/L_1 = 5$, we find $\eta_r = 90\%$.

We wish to stress that the dynamic recovery system which we have been discussing would have the same efficiency for the "working medium" and for charged reaction products, in contrast with the static recovery systems proposed by Post *et al.*

In Ref. 1, Budker devoted much effort to the periodic operation of a mirror system, including the energy recovery problem, but his schemes and emphasis were different from our own. In principle, the recovery system proposed in the present letter might turn out to be fairly versatile. It might be used, for example, in the divertor sections of tokamaks and stellarators.

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[1] Acronym formed from the Russian words *dinamicheskaya plazmennaya lovushka dvukhkamernaya* ("dynamic plasma confinement system, two-chamber").

[2] We will not take up the problem of maintaining plasma stability in the diplodok in this letter.

[3] We are of course assuming that the magnet system is a superconducting system and that the manipulations with the field do not involve a dissipation of energy.

[4] G. I. Budker's theory for the escape of particles was derived for the steady state. An estimate of the confinement time in that theory, even for a confinement system with fixed mirrors, may differ significantly from the confinement time under dynamic conditions, in a system which is being filled in pulses.

[1] G. I. Budker, in *Plasma Physics and Problems of Controlled Fusion, Vol. 3*, Pergamon, New York, 1959.
[2] D. A. Panov, in *Scientific and Technological Progress, Vol. 8*, Izd. VINITI, Moscow, 1988, p. 5.

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