Pramāṇa, Vol. 14, No. 3, March 1980, pp. 175–183. © Printed in India.

Electron and plasma stream reflection at a nonadiabatic mirror

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MS received 15 October 1979; revised 22 January 1980

Abstract. Experimental investigations of the phenomena occurring when low density electron and plasma beams are injected into a nonadiabatic magnetic mirror are presented. Effects of nonadiabaticity and mirror ratio on the reflectivity of the magnetic mirror are measured. Transition of the mirror from adiabatic to strongly nonadiabatic results in setting up of a potential barrier which enhances the reflectivity.

Keywords. Magnetic moment; magnetic mirror; nonadiabaticity; reflection coefficient; electron beam; pulsed plasma.

1. Introduction

One of the methods used for confining a plasma in a bounded volume utilises a trap with magnetic barriers. The finite bounds of the motion of a charged particle in such a trap depend on the conservation of the adiabatic invariant μ (magnetic moment). Theoretical estimates of the change of μ (Kulsrud 1957) only show that for $\rho/R \to 0$, the quantity $\Delta\mu/\mu$ tends to zero faster than any power of ρ/R (ρ is the Larmor radius of the particle, R the radius of curvature of the magnetic lines of force). The value of $\Delta\mu/\mu$ at the finite value of the ratio ρ/R remains completely indeterminate. Therefore, it is of importance to investigate the motion of charged particles in adiabatic as well as strongly nonadiabatic magnetic mirror field configurations. Even for a single reflection, the change in the ratio $\Delta\mu/\mu$ of the particles depends on the half width of the mirror, initial Larmor radius of the particles in the midplane of the magnetic mirror and on the magnetic field gradient scale length (Balebanov and Semashko 1967). A theoretical model (Varma 1971), describing the nonadiabatic loss of particles from magnetic mirror traps, shows that there should exist various e-folding times in the decay of the particles; slopes of ln τ_n versus B are integral multiples of the lowest.

However, in the strongly nonadiabatic mirror configurations, the adiabatic theory for the charged particle motion does not hold good. In this present experimental work, the effect of such strongly nonadiabatic magnetic field configurations on the single reflection of electrons as well as of a plasma stream is reported. It is observed that for strong magnetic field gradients near the mirror points, the reflection coefficient becomes density-dependent and increases to a level slightly lower than in the adiabatic case.

2. Experimental set up

The experiment was conducted in a stainless steel chamber (figure 1) of 15 cm diameter and 150 cm in length. The chamber was evacuated to a pressure of $2\text{–}4\times10^{-5}$ torr. The static magnetic field was generated with the help of 12 pancake coils placed at different axial positions to produce mirror field configurations as shown in figure 2. Different field profiles were generated by varying the currents in the coils. The numerically calculated field values at different axial points tally with the actual values with an error $< 5\%$.

A low energy (250 eV) electron beam with currents upto 6 μA and duration of 50μ sec was injected into the system paraxially from one end of the system. The location of the beam was 2 cm off the axis at the point of injection. The electrons were electrostatically focussed and accelerated by a set of three cylindrical electrodes.

The plasma gun used during the experiment was a simple version of the Bostick gun. A surface breakdown between the two electrodes over a nylon rod produced a hydrogen plasma pulse. A 5μF capacitor bank was charged upto 5 kV to initiate the discharge. Duration of the critically damped discharge current pulse of $\sim$ 8K amp was 15 μ sec.

The parallel electron energy was measured with the help of a retarding potential analyser (RPA). It consists of three grids in front of the collector to collect the electron current. The retarding voltage was applied to the middle grid and the two grids on either side were kept at ground potential to reduce the effect of the

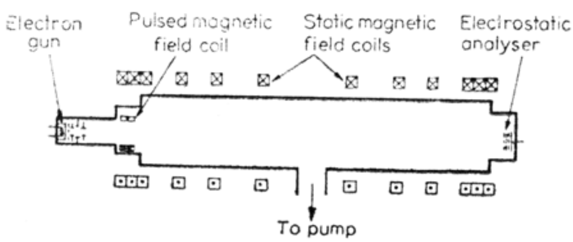

Figure 1. Schematic of the experimental set-up.

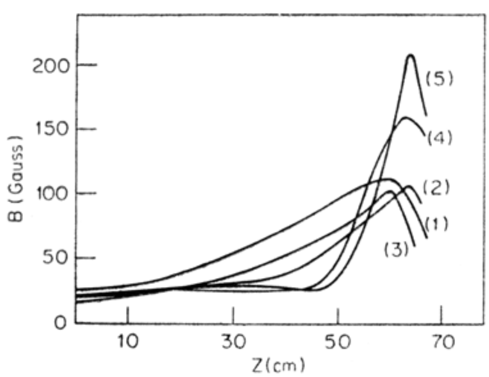

Figure 2. Axial magnetic field distribution from centre of the system to one of the mirrors for five different mirror configurations.

retarding potential on rest of the electrons. While measuring the plasma properties one more grid was used so as to discriminate ions from the electrons. The reflected electron current was measured by directional probe made of stainless steel placed near the midplane of the system.

3. Experimental methods

For reflection from a magnetic mirror, the particles have to possess transverse velocity such that $V_{\perp 0}/V_{\parallel 0} \geqslant 1/\sqrt{R_m}$ at the midplane of the mirror system. Here $V_{\perp 0}$ and $V_{\parallel 0}$ are the perpendicular and the parallel velocity components respectively at the midplane of the mirror and R_m is the mirror ratio, i.e. the ratio of the maximum magnetic field to the minimum magnetic field value. This was achieved by allowing the particles to pass through a region of transverse electric field, besides the initial pitch angle made by the angle of the axis of the electron gun with the magnetic field lines in the injection region.

The transverse electric field extended over a distance of 1·5 cm axially. The static magnetic field gradient scale length (α^{-1}) was more than 7 cm in all the five different field configurations as shown in figure 2. The change in the local value during the experiment at this region was less than 5% and therefore the magnetic field was considered homogeneous over this distance. Let the axial magnetic field be in Z direction. Then the equation of motion can be written simply as

$$m\dot{\mathbf{V}} = e\mathbf{E} + e/c\ \mathbf{V} \times \mathbf{B}. \tag{1}$$

Let the electric field **E** be in the X direction. The two perpendicular components of the velocity can be written in the following manner

$$(\dot{V}_x + i\dot{V}_y) = e/m\ E_x - (e/mc)\ i(V_x + iV_y)\ B. \tag{2}$$

If Ω is the particle (electron) gyrofrequency, then the above equation can be written as

$$\ddot{\rho} = (eE_x/m) - i\,\Omega\,\dot{\rho};\ \text{where}\ \dot{\rho} = (V_x + iV_y). \tag{3}$$

This can also be written in the following way

$$\dot{\rho} = \exp\,(-\,i\,\Omega\,t \int_0^t (eE_x/m) \exp\,(i\,\Omega\,t')\,dt' + \dot{\rho}_0 \exp\,(-\,i\,\Omega\,t). \tag{4}$$

The second term in the equation comes from the fact that the particle had an initial perpendicular velocity before entering the region of transverse electric field. Then

$$\dot{\rho} = (eE_x/i\,\Omega\,m) + \dot{\rho}_0 \exp\,(-\,i\,\Omega\,t), \tag{5}$$

t can be calculated as

$$t = (-\,V_0 \pm [V_0^2 + 2A\,(\Delta Z)]^{1/2})/A;\ \text{where}\ A = E_z\,(e/m).$$

Here, it is assumed that the electric field is inclined to the magnetic field. Therefore

$$|\dot{\rho}|^2 = [(\dot{\rho}_0 \cos \Omega t)^2 + (e E_x/m\Omega + \dot{\rho}_0 \sin \Omega t)^2]. \quad (6)$$

To a first approximation $t = \Delta Z/V_0$, then

$$V_\perp^2 = [V_{\perp 0}^2 + 2V_{\perp 0}(CE_x/B) \sin \Omega (\Delta Z/V_0) + (CE_x/B)^2]. \quad (7)$$

It is seen from the above equation that if $V_{\perp 0}^2$ is zero, then the maximum energy gained is the $\mathbf{E} \times \mathbf{B}$ drift energy. Essentially in the frame of the electron motion, it sees a time-varying electric field.

Thus it is seen that by applying the proper electric and magnetic field, one can give the required pitch angle to the charged particle so as to reflect from the mirror.

4. Experimental results

The parallel energy of the electron beam was measured by applying retarding voltage on the grid of the RPA. When this voltage is equal to the electron parallel energy, the collector current falls to zero, thus determining the parallel energy of the electrons. The slope of these curves shows the dispersion in the beam parallel energy (figure 3).. The dispersion in the energy was 10–12%. The axial variation of electron parallel energy in a slowly varying magnetic field was determined and was found to decrease linearly as the field value increased (figure 4). In a slowly varying magnetic field the parallel component of the energy is converted to the perpendicular component of the energy of the charged particles as it moves towards a stronger magnetic field region. This is simply because the total particle energy has to be conserved.

The effect of mirror ratio (R_m) on the reflection coefficient η ($I_{reflected}/I_{incident}$) is shown in figure 5. Figure 6 depicts the effect of the adiabaticity parameter ξ, on the reflection coefficient. It is observed that as the value of R_m or ξ is increased the reflectivity of the mirror goes down. However, after a certain value of R_m and similarly for ξ the reflectivity of the mirror increases and saturate at a value slightly smaller than the adiabatic values.

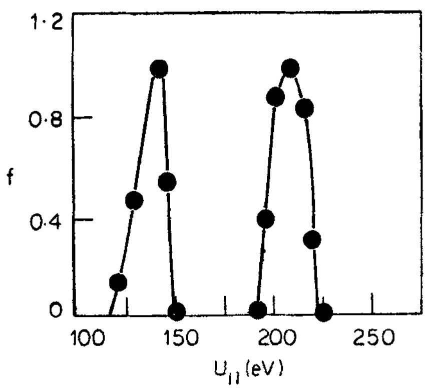

Figure 3. Particle distribution according to the parallel energy.

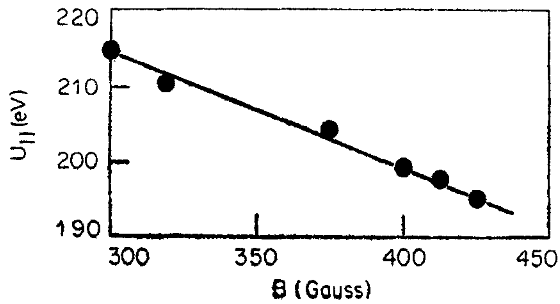

Figure 4. Parallel energy of the electrons as a function of the axial magnetic field.

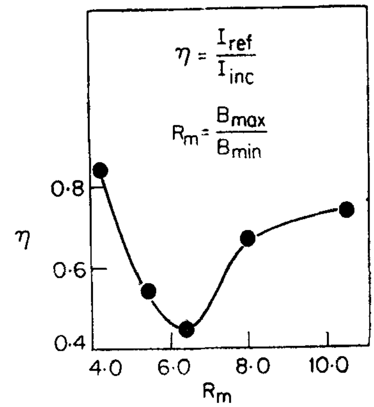

Figure 5. Dependence of the reflection coefficient (η) on the mirror ratio (R_m).

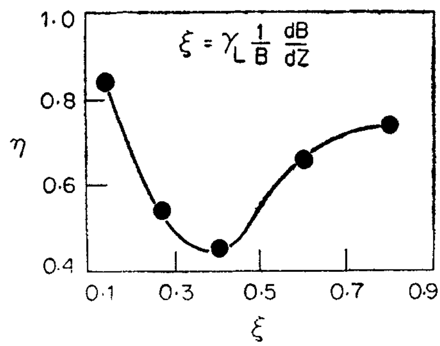

Figure 6. Dependence of the reflection coefficient on the adiabaticity parameter (ξ).

To understand this reflection phenomena, floating potential measurements were conducted near the midplane of the system. For this purpose, a high impedance probe was inserted into the system. Since the transit time of the electron is much smaller than the electron pulse duration, one should expect accumulation of electrons in the system (Sinel'nikov *et al* 1960). Figure 7 shows the floating potential dependence on the mirror ratio. This variation of floating potential also shows a minimum before it saturates. This suggests that the reflection from the mirror becomes more effective for strongly nonadiabatic cases.

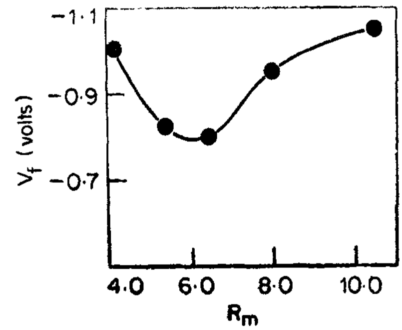

Figure 7. Floating potential at the centre of the system as a function of mirror ratio.

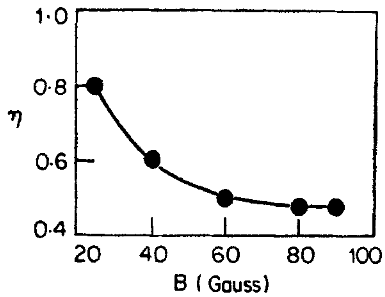

Figure 8. Reflection coefficient as a function of the magnetic field.

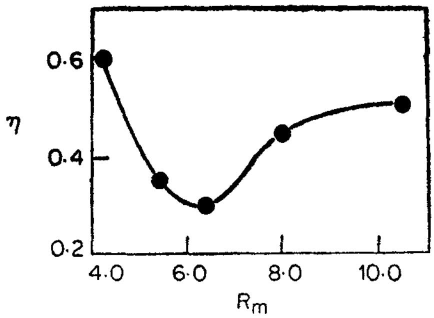

Figure 9. Reflection coefficient as a function of mirror ratio for the plasma case.

Figure 8 shows the effect of magnetic field on the reflection coefficient. It is seen that the reflection coefficient decreases as the base value of the magnetic field is increased, keeping the pitch angle constant. As the base value of the magnetic field increases, the Larmor radius of the particle decreases while the magnetic field gradient remains the same. So the nonadiabaticity in the system decreases to a low value. However, the maximum field value could not be increased further as the current passing through the coils were limited. These observations were made for magnetic field configuration V.

Time of flight measurements was made to determine the directed plasma velocity. The velocity thus found was $\sim 7 \times 10^6$ cm/sec. The directed ion energy was measured with RPA. The energy thus found was $\sim$30–40 eV. The plasma density during the experiment was $n \sim 10^{11}/\text{cm}^3$.

The incident and the transmitted plasma current through the mirror were measured with a collector biased at —50 V. A 33% transparent stainless steel wire mesh was used in front of the collector which was kept at the ground potential. Figure 9 shows

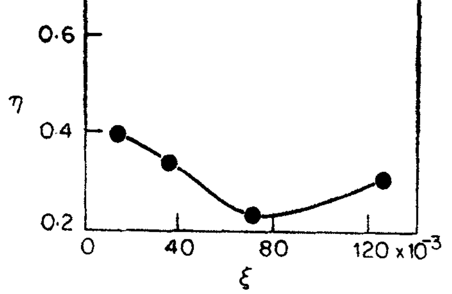

Figure 10. Reflection coefficient as a function of the adiabaticity parameter for the plasma case.

the reflection coefficient as a function of the mirror ratio. It is observed that the functional dependence in this case is similar to that of the electron beam case.

The dependance of the reflection coefficient on the adiabaticity parameter for the field configuration III is shown in figure 10. For these measurements the collector was enclosed in a cylinder, the aperture of which could be varied. Thus by varying the aperture in front of the collector from 3.5 cm to 0.4 cm, selection of ions with different Larmor radii to register the current on the collector was possible. The magnetic field value at the centre of the trap was 50 gauss.

5. Discussion and conclusions

The time for collisional scattering for electrons of the given energy is $\sim 50\mu$ sec, whereas the single transit time for the electrons was never more than $\sim 10\mu$ sec. Therefore, for single reflection, theoretically one would expect total reflection as the energy dispersion was small for the electron beam. The corresponding pitch angle distribution due to the interaction of the particle with the transverse electric field was calculated. But even in the adiabatic case total reflection was not observed. This may be due to the micro-inhomogeneities in the static magnetic field. The electrons, moving in an inhomogeneous magnetic field, encounter the microinhomogeneity which could lead to scattering of the particles. This would change the velocity along the field line thereby changing the perpendicular velocity making the particles fall in the loss cone and escape. As the sytem becomes increasingly nonadiabatic (by decreasing the magnetic field gradient scale length i.e. by decreasing the mirror width), the $\Delta\mu/\mu$ ratio increases and the reflection coefficient decreases and goes through a minimum. The increase in the reflectivity when the system becomes strongly nonadiabatic can be explained in the following way using the results from the plasma experiment. Figure 11 shows the floating potential measured along the axis on the two sides of the mirror point. For the Vth magnetic field configuration, the curve shows a strong negative peak. This must be considered as due to the localised accumulation of the electrons at the turning point. Therefore, a fraction of the electrons, approaching this region, will be electrostatically repelled due to this potential hill. This would add to the usual reflection, thus increasing the effective reflection coefficient. Since this is a collective behaviour of the particles, it should manifest only after a critical density of the particles in the case of the electron beam. Figure 12 shows the dependence

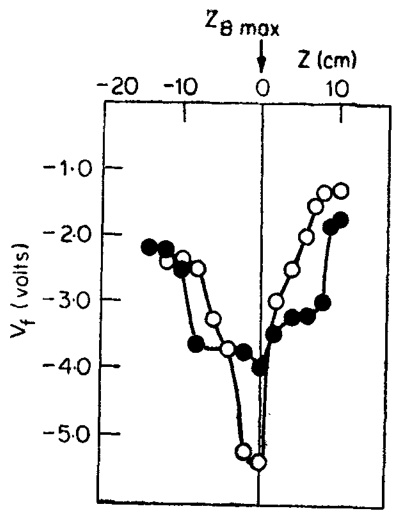

Figure 11. Axial floating potential profile around the mirror point for III and V magnetic field configurations during the plasma experiments.

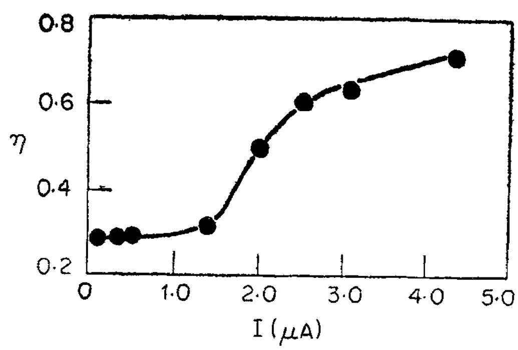

Figure 12. Dependence of the reflection coefficient on the beam current *I* for the electron beam.

of the reflection coefficient on the beam current for the magnetic field configuration *V*. It is clearlv seen that the reflection coefficient incıeases only after a critical current. For large beam current, the value has a tendency to saturate. Therefore, the increase in reflection is due to nonadiabatic effects together with the collective behaviour of the particles.

To conclude, experiments on the effect of nonadiabaticity on the effective reflectivity of magnetic mirror have been performed. Single-particle experiments show that the mirror reflectivity reduces as the nonadiabaticity parameter increases. However, the electrostatic potential hill formation at steep magnetic field gradients when the beam densities go above some critical value causes enhanced reflection; making the nonadiabatic mirror as effective in plasma confinement as the conventional mirror. Additional experiments on long term confinement of plasma pulses will be conducted in a future experiment.

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