TRAP WITH MAGNETIC MIRRORS, DESIGNED FOR PROLONGED ELECTRON CONFINEMENT

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Submitted to JETP editor January 16, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) **49**, 373-378 (August, 1965)

A trap is described with magnetic mirrors and with a simple system of external injection from an electron gun, with a vacuum $\sim 8 \times 10^{-10}$ mm Hg and an electron confinement time up to 40 sec. The electrons are captured in the trap by rapidly varying the electric field. The apparatus is intended for a detailed study of prolonged motion of individual electrons in a magnetic trap, and for investigations of the behavior of a rarefied plasma.

RODIONOV[1] and Gibson et al.[2-4] investigated prolonged confinement of charged particles in a magnetic trap. As is well known[5], confinement of particles is based on conservation of the particle magnetic moment of μ, which is an adiabatic invariant of the motion and is consequently generally speaking only approximately conserved. In the investigations cited above, non-adiabaticity was observed (escape of the particles from the trap as a result of a slow change in μ), and the conditions under which this non-adiabaticity could be neglected in practice were clarified, at any rate for traps used as thermonuclear reactors. It is of interest to investigate in greater detail prolonged motion of particles in a magnetic trap. In addition to thermonuclear applications, the results of such investigations can be important also for accelerator physics (especially nonlinear accelerators), the earth's radiation belts, etc.

From the methodological point of view, a common feature of the cited papers[1-4] was the use of so-called internal injection into the trap. This means that the source of the charged particles was radioactive gas of low density. An advantage of this method is the automatic capture of the particles in the trap without any additional attachments. However, work with radioactive gas complicates the experiment greatly, leads to uncontrolled capture conditions, and does not make it possible to attain the vacuum limit necessary to increase the lifetime of the particles in the trap.

In this paper we describe a trap with magnetic mirrors with a simple system of external injection from an electron gun, designed to operate with a vacuum $\sim 8 \times 10^{-10}$ mm Hg and for an electron confinement time up to 40 seconds (LN installation). This time is determined by the scattering of the electrons by the residual gas and increases with electron energy. The maximum electron energy in the LN reaches 100 keV. Further appreciable increase in energy is meaningless, since the increasing electron radiation in the magnetic field decreases the confinement time.

1. DESCRIPTION OF APPARATUS

A diagram of the LN installation is shown in Fig. 1. The geometrical dimensions were chosen such that the installation still remained relatively small and convenient to operate. The internal diameter of the vacuum chamber was 210 mm, and the length of the working part of the vacuum chamber approximately 1600 mm. The magnetic field was produced by two solenoids made of copper tubing cooled with running water. The configuration of the magnetic field could be varied by displacing the two solenoids along the trap axis, and also by superposition of additional turns and iron shims in different sections of the chamber. A typical magnetic field configuration is characterized by a distance of 70 cm between the coil centers and by a ratio of the maximum field (approximately at the

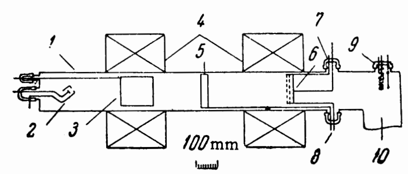

FIG. 1. Schematic section through the magnetic trap (to scale): 1 – vacuum chamber; 2 – electron gun; 3 – ring; 4 – solenoid; 5 – electrostatic probe; 6 – collector; 7, 8 – collector grids; 9 – manometer; 10 – to pump.

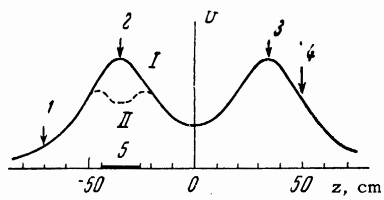

FIG. 2. Effective potential of magnetic trap on the axis: $U = H_z + e\varphi$; I – without electric field ($\varphi = 0$), II – with electric field of the ring; 1 – location of gun, 2 – first magnetic mirror, 3 – second magnetic mirror, 4 – location of collector, 5 – location of ring.

center of the coil) to minimum field (half way between coil) equal to 2.5 (see Fig. 2).

The magnets were fed from germanium diode rectifiers connected in a three-phase full-wave circuit. The current of each solenoid was separately adjustable from zero to 140 A, corresponding to a magnetic field up to 2500 Oe in the middle of the solenoid. To smooth the pulsations of the magnetic field even more, the forms of the solenoids were made of brass 10 mm thick. The maximum pulsation in the center of the trap did not exceed $\pm 2 \times 10^{-4}$ of the value of the magnetic field at this place. Special attention was paid in the construction and preparation of the solenoids to attaining maximum azimuthal symmetry of the magnetic field. The measured azimuthal asymmetry did not exceed 0.5% in the working region.

The injector to the trap was an electron gun with a ribbon-type directly-heated cathode such as described by Samoĭlov[6]. The maximum electron energy was 60 keV and the maximum current 1 A. Approximately 70% of the gun current was focused in a 3° angle. The voltage was applied to the gun, and also to the ring (see Fig. 1 and Sec. 2) by discharging the lines through TGI1-325/16 thyratrons with subsequent increase of the voltage by means of pulse transformers. All the electric leads from the trap were made with kovar-glass seals.

The vacuum was produced in the chamber by a diffusion pump (N5S1M) with improved fractionalization of the oil and with a booster pump (TsVL-100) connected in series. A two-stage liquid-nitrogen-cooled trap of special construction, cooled with liquid-nitrogen, with a pumping rate of approximately 150 liters per second was placed between the N5S1M and the chamber. All the vacuum seals were of the groove-wedge type with gaskets of annealed copper (M1) 0.6–0.7 mm thick, etched with nitric acid. The required pressure was approximately 25 kg per millimeter of gasket length. After prior pumping out of the system to $\sim 10^{-6}$ mm Hg, the vacuum chamber and the trap were heated at 350°C for 12 hours to outgas the internal surfaces. The vacuum was measured by an improved Bayard-Alpert manometer. The limit of the vacuum attained was 3×10^{-10} mm Hg with the gun filament turned off and approximately 8×10^{-10} mm Hg under operating conditions.

2. METHOD OF CAPTURING THE ELECTRONS IN THE TRAP

The electrons were injected in the trap along the magnetic field, through one of the mirrors, and captured by rapidly changing the electric field produced by a special electrode in the form of hollow cylinder of 160 mm diameter (ring, see Fig. 1).

At relatively low particle energy (up to ~ 100 keV), control of the beam by means of an electric field is simpler and more convenient than the use of a magnetic field[1)].

In the absence of the electric field, the effective potential of axial motion of the charged particle[7], $U = \mu H_z$, is proportional to the magnetic field and is of the form shown in Fig. 2. When the voltage is applied to the ring, the potential becomes $U = \mu H_z + e\varphi$ (φ—electric potential on the axis), and the magnetic mirror can either rise or fall (Fig. 2). If the electrons can freely enter the trap when the magnetic mirror is lowered, part of the electrons become trapped if the mirror is then raised sufficiently rapidly.

The gun injected electrons at an angle of 30° to the magnetic force lines and was located at such a distance from the magnetic mirror that the main

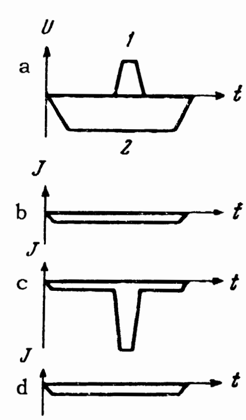

FIG. 3. Schematic form of oscillograms of the current J and of the voltage U: a – voltage on gun 2 and ring 1; b – current in collector in the absence of voltage on the ring, second mirror lower than the first, c – current in collector when voltage is applied to the ring, second mirror lower than the first; d – the same as c, but the second mirror is raised (see Sec. 2).

[1)]A similar capture system was used independently in[8].

part of the electron beam was reflected by the mirror. Approximately 10% of the gun current passed in this case through the mirror as a result of the beam divergence. During the adjustment of the system, the second mirror was lowered before the first, so that the entire current passing through the first mirror had to pass also through the second mirror and was recorded by a collector, as shown schematically in Fig. 3b. The duration of the current corresponded to the negative voltage pulse applied to the gun cathode (the anode was grounded), and constituted approximately 20 μsec (Fig. 3a). Approximately 10 μsec after turning the gun on, a positive pulse of approximately 2 μsec duration and of the same order of magnitude as the voltage on the gun was applied to the ring. Then practically the entire current of the gun passed through the wing inside the trap (Fig. 3c). In these experiments the gun current was 0.1 A. After tuning the system in accordance with the oscillograms of Figs. 3a, b, and c, the second mirror was raised to such a height that the current passing through the ring did not pass through the second mirror (Fig. 3b). Then, as the voltage on the ring dropped (on the trailing front of the pulse), the electrons were captured in the trap.

It may seem at first glance that for effective capture the trailing front of the pulse of the ring should be very short—of the order of the time of flight of the electron through the trap, i.e., $\sim 10^{-8}$ sec. It turns out, however, that this is not the case. The measurements have shown that when the duration of the trailing front is increased from 3×10^{-8} to 5×10^{-7} sec, the number of captured electrons does not change noticeably, and when the duration is increased to 5×10^{-6} sec, the number of electrons decreases only one-half. This is connected with the fact that during the entire time of capture the number of the electrons in the trap remains approximately constant and independent of the rate of rise of the first mirror, since the number of electrons leaving the trap is compensated by the same number entering from the gun. If the electrons were not acted upon by any disturbance, then the capture would take place in exactly the same way for any rate of mirror rise. However, by virtue of unavoidable disturbances in a real system, the efficiency of capture decreases somewhat, as noted above, because some of the electrons are lost immediately after the capture as a result of these disturbances. We chose for the trailing front of the ring pulse a duration 5×10^{-7} sec, thereby greatly simplifying the ring power-supply circuit without reducing the capture efficiency.

We note in conclusion that by changing the gun location and the voltage on the ring it is possible to vary the "depth" of capture of the electrons in the potential well (Fig. 2), i.e., to change arbitrarily the initial conditions of the captured electrons.

3. EXPERIMENTAL PROCEDURE

The observation of the captured electrons was carried out essentially by measuring the current to the collector, a round solid plate of 160 mm diameter (Figs. 1 and 2). Placed ahead of the collector were two grids, on which different voltages were applied to suppress the secondary electron emission from the collector and to separate the necessary component of the particle current from the trap. The main component is the current of slow electrons and ions, produced in the trap as a result of ionization of the residual gas by the captured fast electrons. The electron or ion current is separated by applying a suitable dc voltage to one of the collector grids or to the ring. In addition, a current of fast electrons passing through the second mirror as a result of scattering by the residual gas, or from other causes, flows to the collector. Under typical operating conditions, the fast-electron current was several per cent of the total current to the collector. The collector current was recorded either directly with an oscilloscope, the sensitivity of which reached 2 mV/cm for an input resistance of 1 megohm, or through an electrometric amplifier. To protect the measuring circuits against the direct current from the gun at the instant of capture, the collector was grounded for a time of approximately 200 μsec with the aid of a polarized relay (RP-5, contact insulation resistance $> 10^{12}$ ohm).

For a direct measurement of the density of the captured electrons, and also to observe the process of compensation, we used a cylindrical electrostatic probe[9] of 200 cm^2 area, located at 3 mm from the wall of the vacuum chamber (Fig. 1).

4. PRELIMINARY RESULTS

The LN installation was used to measure the confinement time τ_{conf} (the time necessary for the number of captured particles to decrease by a factor e) of fast electrons with energy of several times ten keV. It is desirable to ensure a maximum possible confinement time for the electrons in the trap and by the same token to be able to investigate the most subtle effects of their motion in the magnetic field.

The fast electrons captured in the magnetic trap ionize the residual gas, so that their space charge becomes compensated. The density of the slow electrons produced as a result of the ionization is negligibly small, owing to the small time of their confinement in the trap.

The maximum confinement time observed in the experiments was 15 seconds for an electron energy 20 keV in a vacuum of 10^{-9} mm Hg.

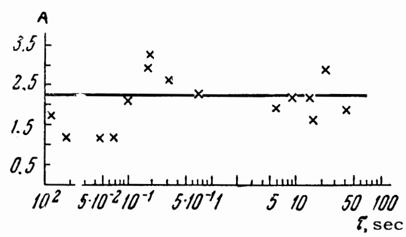

FIG. 4. Experimental results in the energy interval from 5 to 34 keV and in the pressure interval from 10^{-7} to 10^{-9} mm Hg.

The experimental results in the energy interval from 5 to 34 keV and in the pressure range from 10^{-7} to 10^{-9} mm Hg are shown in Fig. 4, where the abscissas represent the time (logarithmic scale) and the ordinates represent a combination made up of the following experimentally measured quantities: confinement time (τ_{conf}), electron energy (W), residual-gas pressure, and rms angle $\overline{\theta^2}$ through which the particle should be scattered in order to enter the loss cone:

$$A = \frac{\tau_{\text{sec}} \cdot P_{\text{torr}} \ln(W_{\text{keV}}/3.53)}{\overline{\theta^2}\, W_{\text{keV}}^{3/2}} \cdot 10^9$$

This combination should remain constant in different experiments. Its value of 2.2×10^{-9}, represented in the plot by the straight line, was calculated in accordance with[3]. The rms angle $\overline{\theta^2}$ was calculated in accordance with the geometry of the magnetic field and the injection conditions. Since the confinement time τ_{conf} reached 15 seconds, we could increase during the first 1.5—2 seconds the magnetic field by a factor 2—3, thus increasing the confinement time by adiabatic heating of the captured particles.

With an electron energy of 20 keV, a vacuum of 10^{-9} mm Hg, and a doubling of the magnetic field, τ_{conf} reached 40 seconds. In the latter case the number of oscillations of the electrons in the trap reached 5×10^9, and the number of Larmor revolutions reached 10^{11}. The equivalent confinement time corresponds in order of magnitude to the time of scattering of the electrons by the residual gas.

The large scatter of the experimental points on the figure is due to the fact that the vacuum could not be measured with accuracy better than 50%.

The value of the magnetic field in the center of the mirror varied from 50 to 1200 Oe. For the electron energy interval given above (Fig. 4), the adiabaticity parameter ($\rho\nabla H/H$, where ρ is the Larmor radius) did not exceed 0.04. With increasing electron energy, a considerable reduction in the confinement time was observed. According to the preliminary data, the limit of nonadiabaticity corresponds to a value $\rho\nabla H/H \sim 0.1$, which agrees in order of magnitude with the results of[3].

We take this opportunity to thank G. A. Blinov for much advice in obtaining the high vacuum and V. G. Ponomarenko for continuous help in the construction and adjustment of the installation.

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Translated by J. G. Adashko
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