MAGNETIC TRAP WITH FIELD INCREASING TOWARD PERIPHERY

S. YU. LUK'YANOV and I. M. PODGORNYĬ

Submitted to JETP editor, February 1, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 27—32 (July, 1959)

Results are given for the investigation of a plasma formed by an electron beam in a trap characterized by a magnetic field which increases toward the periphery.

OF the many magnetic traps used to contain hot plasmas special interest attaches to systems in which the magnetic field increases toward the periphery. It follows from theoretical considerations,[1,2] that in systems of this kind it should be possible to satisfy the requirements for producing stable equilibrium in the plasma, i.e. the plasma is trapped in a space surrounded by a magnetic "barrier."

In attempting to build a thermonuclear reactor of the trap type one invariably encounters the difficult problem of how the trap is to be filled with high-temperature plasma. In principle, a high-temperature plasma can be produced in the trap by heating a cold plasma in the trap itself or by injecting fast particles into the trap. In traps with a magnetic field which increases toward the periphery, formed by a system of solenoids connected in opposition, it would appear that fast particles can be injected by a method which was proposed recently,[3] in which plasmas are accelerated by electrodynamic methods. Consider the motion of a plasma through a region surrounded by a magnetic barrier (Fig. 1). For a given shape and orientation with respect to the magnetic field H_1 which bounds the trap, the plasma will move into the system if the following condition is satisfied:

$$W \geqslant H_1^2\tau/8\pi. \quad (1)$$

Here W is the kinetic energy of the directed motion of the plasma and τ is the volume which it occupies after moving into the system. If the plasma expands by virtue of thermal motions or if part of the energy of the ordered motion is converted into heat as a result of collisions after the plasma enters the region of lower magnetic field H_2, the plasma particles become trapped.

Particles can escape from a trap of this kind by diffusion across the magnetic field lines or by entering regions of the magnetic barrier in which the magnetic force lines run into the walls of the container. In the geometry being considered here the force lines run into the sidewalls of the system

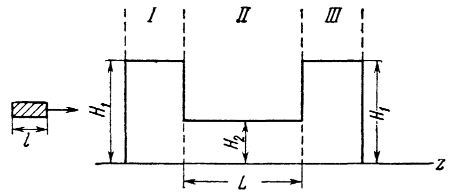

FIG. 1. Penetration of a plasma through a magnetic barrier.

in circles and the slits through which the particles escape are ring shaped. For short-term processes the width of these slits is given by the expression[2]

$$\delta_1 = 4\rho_e, \quad (2)$$

where ρ_e is the radius of curvature of a plasma electron in the magnetic field. More precisely, Eq. (2) gives the width of the slit immediately after the production of the plasma inside the trap in a space free from magnetic field. The escape of plasma through the slit obtains by virtue of the thermal velocity of the ions.

If there are collisions the width of the slit increases in time in accordance with the relation for ambipolar diffusion. Hence it would be expected that in the stationary state the width of the slit would increase without limit. This conclusion, however, is not valid. Diffusion broadening stops at that value of δ_1 for which a plasma particle has a greater chance of escaping through the slit after several reflections from the magnetic wall than experiencing a collision with another particle. At low pressures this value of δ_1 can be smaller than $4\rho_e$ and the width of the slit can be the same in pulsed or continuous operation. At higher pressures the diffusion broadening becomes appreciable and the limiting slit width can be estimated by equating the path length of the particle in the trap

$$\lambda_1 = 4V/S = 4V/a\delta_1 \quad (3)$$

and the path length between collisions

$$\lambda_2 = 1/n\sigma \quad (4)$$

(in these formulas V is the volume of the trap, S and a are the area and length of the slit, n is the number of particles per cubic centimeter, and σ is the collision cross section).

The foregoing applies to the case in which the plasma is produced in a space free from magnetic field. If, however, the plasma is produced in a region which is filled with field, for example by means of a beam of fast electrons emitted from the surface of a heated cathode, we must add to δ_1 the width due to the dimensions of the injector. Under conditions of low pressure and strong magnetic field the thermionic electrons ionize the gas, forming a plasma mainly along the lines of the magnetic field. Under these conditions the fractional effective width of the slit due to the dimensions of the cathode and the configuration of the magnetic field is determined by the simple relation

$$\delta_2 = H_0 r^2 / 2 H_m R. \tag{5}$$

Here H_0 and H_m are the magnetic fields in the cathode region and slit region respectively, r is the radius of the cathode and R is the radius of the circular slit ($a = 2\pi R$). In the general case the effective width of the slit can be estimated from the relation

$$\delta = \sqrt{\delta_1^2 + \delta_2^2}. \tag{6}$$

In addition to the circular slits, in the trap being considered here there are two curved slits at the ends of the system close to the axis of symmetry. The radii of these slits are also determined by δ_1 and δ_2. It is easy to see that a large area for the circular slits makes their role decisive in the escape of particles.

In the present paper we describe experiments carried out to study the behavior of a plasma formed by an electron beam injected along the axis of the trap. The experimental parameters were not optimum but were determined by the available experimental apparatus. The vacuum chamber was a cylinder of stainless steel 100 cm long and 21 cm in diameter with ports at the flanges. Mounted in the ports were electron sources which made it possible to obtain an electron beam current of 0.5 amps with an injection voltage up to 1 kv. The vacuum chamber was located inside the system of coils which produced the magnetic field. Each coil consisted of 30 turns of copper tubing cooled by circulating water. The peak current through each coil was 350 amp. The coils could be connected in different ways so that it was possible to obtain the magnetic field configuration desired for a given experiment. An iron jacket was used to reduce the reluctance of the magnetic circuit. The system was evacuated through a side port by means of an oil diffusion pump. In those cases in which the experiment was carried out with hydrogen the gas was admitted to the system through a palladium valve.

The current to the wall was measured by probes which could be moved along the outside chamber. In certain cases the devices for moving the probes were provided with thermocouples with which the temperature could be measured. The direction of motion of the charged particles was studied by means of an oriented probe which was located in the median plane of the chamber. This probe was made from a hollow metal tube which contained a current detector. There was a small aperture in the outer tube so that it was possible to detect particles which entered within a known solid angle.

The radiation spectrum of the hydrogen plasma in the trap exhibited distinct molecular bands. The existence of these bands indicates that the electron temperature in the plasma was not greater than several electron volts.

The first experiments were undertaken to determine the nature of longitudinal current distribution to the wall (parallel to the z axis) as a function of the gas pressure in the chamber. When these experiments were completed the coils were connected in opposition. In Fig. 2 is shown the absolute magnitude of the magnetic field strength along the axis of the system. The current in each coil was 300 amp; this current is typical for the series of experiments considered here.

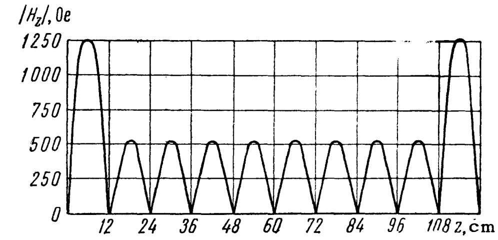

FIG. 2. Magnetic field distribution along the axis of a system; H_z is the magnetic field at the axis of the chamber.

It was shown by means of direct experiments that the charged particles escaped to the wall only through the circular slits in the magnetic field. In Fig. 3 is shown the variation of electron current to a probe kept at the potential of the wall while moved along the chamber; during these measurements the hydrogen pressure p_0 was maintained at 5×10^{-5} mm Hg. The clearly defined maxima in the current are opposite each circular magnetic slit; the intensity of these maxima falls off rapidly with slit number, i.e., with increasing distance from the source (the second source was not used in this experiment). A similar pattern is obtained

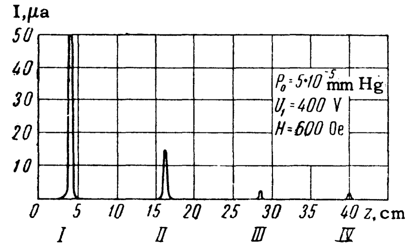

FIG. 3. Variation of current to the lateral probe as function of probe position.

if one studies the temperature distribution along the wall by means of a thermocouple which can be displaced along the z axis.

When the pressure changes the distribution of current between the slits also changes. Thus, when the chamber pressure is between 2 and 5×10^{-6} mm Hg and only one source is used almost all the charged particles escape through the circular slit closest to the source. However, when the pressure is increased the current at the first circular slit is reduced while the flow of particles through the successive slits is increased. In Fig. 4 is shown the variation of current through different slits as a function of the hydrogen pressure in the chamber. A characteristic feature of these curves is the marked dependence of current on pressure for slits located far from the injector. On the other hand the slit located closest to the electron beam exhibits a weak reduction as the chamber pressure is increased. Thus, with increasing pressure there is a clear-cut tendency toward the equalization of currents through the slits; this is a direct evidence of the increasing importance of collisions in the plasma.

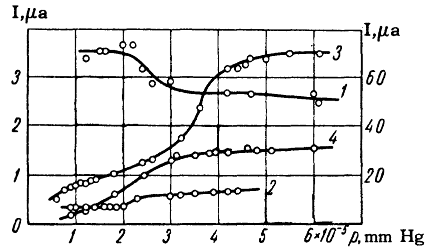

FIG. 4. The current through magnetic slits as a function of hydrogen pressure in the chamber. The number for each curve corresponds to the slit number. The scale at the right refers to Curves 1 and 2; the scale at the left corresponds to Curves 3 and 4.

Experiments carried out with the oriented probe indicated a small anisotropy in the current. However the asymmetry in the angular distribution was much smaller than what would be expected in the presence of a directed flow of electrons.

In the remaining experiments all the coils located on one side of the median plane were connected to produce a magnetic field in one direction while the coils on the other side were connected to produce a field in the opposite direction. This connection configuration made it possible to obtain a field up to approximately 1500 oersteds in the single lateral slit of the trap. With this field configuration the halfwidth of the slit was measured as a function of magnetic field at a fixed gas pressure. The measurements were carried out by means of a movable probe in front of the walls; this probe was a tungsten wire 0.5 mm in diameter and 30 mm long. The probe could be moved along the chamber as shown in Fig. 5. To obtain the distribution curve for the current through the slit, the current vs. probe position curve was differentiated graphically.

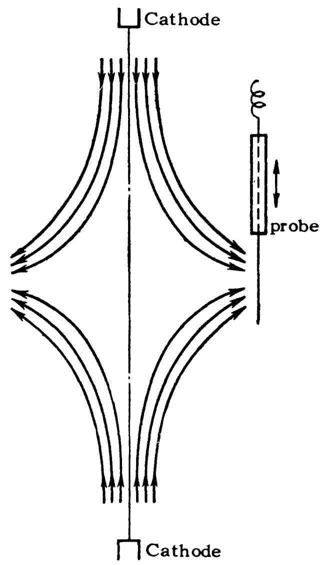

FIG. 5. Arrangement of the probe in the system.

In Fig. 6 are shown experimental curves for the dependence of effective slit width on magnetic field for several values of the energy in the primary electron beam U_1. The hydrogen pressure in the chamber p_0 was kept constant in these measurements (approximately 2×10^{-5} mm Hg).

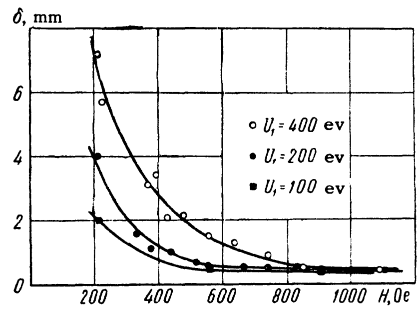

FIG. 6. The effective width of the magnetic slit δ as a function of field strength in the slit.

As is apparent from the figure, at strong magnetic fields (H > 800 oersteds) the effective width of the slit is independent of magnetic field and the energy of the primary electrons and is approximately 0.4 mm. We may note, however, that the value of δ remains constant even when the hydrogen pressure is increased to 5×10^{-4} mm Hg. At weak magnetic fields there is a rapid broadening of the slit which becomes especially pronounced at high primary electron energies.

We now propose an explanation for the observed behavior of $\delta = f(H)$. An estimate of δ_1 on the basis of Eqs. (3) and (4) indicates that this quantity is not greater than 0.1 mm in the pressure region of interest. Since there is essentially no change in the width of the slit as the pressure is increased by a factor of 10, apparently diffusion broadening need not be taken into account. The independence of δ on magnetic field at strong magnetic fields is direct evidence that the contribution of the $4\rho_e$ term to δ is not important. For reasonable values of the plasma electron energies (approximately 1 ev) $4\rho_e$ is less than 0.1 mm with $H = 1000$ oersteds and is correspondingly reduced at larger values of H. Thus it may be assumed that the measured values of the halfwidth in the curve for the electron current to the probe correspond to the electron-optical imaging of the surface of the cathode at the walls of the chamber. With $H_1 \approx H_2$, $r = 8.5$ mm and $R = 100$ mm, according to Eq. (5) δ_2 is 0.35 mm, in agreement with the experimental values of δ.

To explain the rise in the $\delta = f(H)$ curves at small values of H we must take account of the fact that the conditions for adiabatic invariance no longer hold when the Larmor radius of the primary electrons becomes comparable with the radius of curvature of the magnetic lines of force. Under these conditions the primary electrons "escape" from the lines of force and enter the "zero-field" region. Later, after a number of collisions with the magnetic walls these electrons again enter the strong-field region close to the slit, but have now acquired considerable transverse velocities. If the fraction of these electrons in the total current to the probe is significant (weak fields and high energies of the primary electrons tend to favor this condition) the effective width of the slit is again determined by the quantity $4\rho'_e$, where ρ'_e is the Larmor radius of electrons with high transverse energy. Qualitatively the experimental data are in good agreement with this picture.

In conclusion we may note that as the pressure in the chamber is increased to approximately 3×10^{-3} mm Hg the effective width of the slit in the strong field region increases. It is assumed that this effect is due to diffusion broadening.

The authors wish to take this opportunity to thank L. A. Artsimovich, R. Z. Sagdeev, and O. B. Firsov for interesting discussions and V. N. Sumarokov for help in carrying out the experiments.

[1] S. I. Braginskiĭ and B. B. Kadomtsev, Физика плазмы и проблема управляемых термоядерных реакций (Plasma Physics and the Problem of a Controlled Thermonuclear Reaction) Vol. III, U.S.S.R. Acad. Sci. Press, 1958, p. 300.

[2] O. B. Firsov, Физика плазмы и проблема управляемых термоядерных реакций (Plasma Physics and the Problem of a Controlled Thermonuclear Reaction) Vol. III, U.S.S.R. Acad. Sci. Press, 1958, P. 327.

[3] Artsimovich, Luk'yanov, Podgornyĭ, and Chuvatin, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 3 (1957), Soviet Phys. JETP **6**, 1 (1958).

Translated by H. Lashinsky
4