533.9

CONFINEMENT OF HIGH-DENSITY PLASMA IN ADIABATIC TRAPS

I. M. PODGORNYĬ

Usp. Fiz. Nauk 85, 65-86 (January, 1965)

THE last two years have seen a noticeable shift in the approach toward producing and confining high-temperature plasma in magnetic traps; several papers have appeared in which extended confinement has been reported under certain specified conditions and in many cases the confinement time was limited only by the natural loss due to Coulomb scattering or charge exchange. In other words, it is now possible to avoid hydrodynamic instabilities which, at one time, appeared to be an unavoidable danger. As yet these new results pertain to limited regions of density and temperature and it is still too early to draw any far-reaching conclusions; nevertheless, the first step has undoubtedly been taken in overcoming instabilities in adiabatic traps. There has also been a significant shift in the approach toward heating electrons and ions in adiabatic traps.

Research in high-temperature plasma confinement by magnetic fields has now reached a stage such that one expects that within the next few years the step will be taken to a new stage, in which the thermonuclear reactions will be so intense that it will no longer be necessary to carefully verify the thermonuclear origin of the neutrons in each device; one also expects that the number of neutrons emitted by the plasma will break a record of more than ten years standing—10^9 per pulse.

In the present survey we review recent achievements in heating and confinement of plasma in traps. Primary attention is given to experimental work on stable confinement. We omit from consideration all work devoted to problems of filling traps by means of ion beams such as that carried out with the Ogra device in the USSR and DCX in the USA; these investigations have been described in detail in the literature. For the same reason we shall not consider work carried out on Scylla devices.

By high-density plasma we mean one with density $n \geq 10^{11}$ cm^{-3}, that is to say, a plasma in which the dimensionless parameter

$$\beta = \frac{nkT}{H^2/8\pi}$$

is generally much smaller than unity.

1. PLASMA CONFINEMENT IN A SIMPLE ADIABATIC TRAP

Until very recently it was not possible to reconcile the results of earlier work reported by Post[1] on stable confinement of high-density plasma in adiabatic traps with data that had been obtained in 1959-1960 in the laboratory of L. A. Artsimovich.[2] In the latter work, under good vacuum conditions (in which charge exchange could be neglected) the lifetime of a low-density plasma ($\sim 10^9$ cm^{-3}) was less than a millisecond; moreover, wall probes indicated the loss of plasma from the trap in the direction perpendicular to the lines of force. The better vacuum conditions in the Soviet work seemed to imply that this work was more reliable and cast some doubt on the results reported by Post. These doubts were reinforced by the theoretical results available at that time: the magnetohydrodynamic analysis predicts the development of a flute instability in simple adiabatic traps with growth rate

$$\omega^2 \sim \frac{T_i + T_e}{MLR}, \qquad (1)$$

where T_i and T_e are respectively the ion and electron temperatures, M is the ion mass, L is the length of the trap and R is the dimension of the curved portion of the line of force. The development of the flute instability is a consequence of the fact that the field in an adiabatic mirror device does not increase in all directions in going from the center toward the periphery.

Using the experimentally obtained values, it is not difficult to show that the plasma lifetime in both devices ($T_i \sim 1$ keV) should be less than a microsecond; on the other hand, in the work reported by Post the lifetime was measured in milliseconds and in the work carried out at the Institute for Atomic Energy the lifetime was of the order of hundreds of microseconds. Various explanations were advanced to reconcile the difference in confinement time but the basis for the applicability of these explanations depends on the judgements of the authors of the respective papers.

A paper published recently by Perkins and Post[3] indicates the rapid development of hydrodynamic stability of the plasma at densities of 10^7—10^9 cm^{-3} and a high stability at higher densities. On the basis of these data the lack of agreement between the American and Soviet work can be reconciled to some extent. It is natural that the results would not agree completely since the experimental conditions, in particular the initial plasma configurations, were considerably different. As far as the theoretical interpretation of the experimental results is concerned, however, here again there is a certain amount of arbitrariness.

We wish to consider the experiments of Perkins and Post in somewhat greater detail. All of these experiments were carried out in a magnetic trap in which the field increases to a value of 17 kOe in 5 msec in the median plane and 25 kOe in the mirrors. Then the windings are "crowbarred" and the field decays with a time constant τ = 200 msec. The diameter of the vacuum chamber is 20 cm and the length approximately 80 cm. Injection is accomplished by means of a pulsed titanium source of hydrogen plasma[4] located on the axis at a distance of 2 meters from one of the mirrors. Molybdenum sputtering is used in the source chamber; a second sputtering arrangement is located in a chamber contiguous with the side of the other mirror. The molybdenum pump makes it possible to obtain an initial vacuum of approximately 10^{-9} mm Hg and evidently attenuates the flux of neutral gas from the source into the trap. The direction of plasma flow in the trap is controlled by a longitudinal magnetic field. The plasma is studied with scintillation probes (which record fast electrons), a wall probe, and a charged-particle collector at the wall. In spite of the limitations of the experimental methods the authors were able to obtain a large amount of experimental data.

Two different modes of operation of the device were used in this work:

1. Hot electron mode: hereinafter, we call this the "e" mode. The initial value of the magnetic field H_0 at which plasma is trapped is 50 Oe and the maximum field H_{max} = 17 kOe. At H_0 = 50 Oe and an ion energy greater than 1 eV the radius of curvature of the ion trajectory is comparable with the radius of the device so that ions with energies greater than 1 eV are not trapped by the field; in turn this implies that the ion energy after adiabatic compression cannot be greater than 100 eV. The electron energy after compression, as measured with a calibrated scintillation detector, is found to be 25 keV.

2. Hot ion mode ("i" mode); H_0 = 2 kOe, H_{max} = 17 kOe. In the "i" mode there are additional trapping coils which make it possible to increase the fraction of captured plasma to 30%.

The minimum dimensions of the compressed plasma are not known in either mode even for the most stable states. The time-averaged data reported in the paper were obtained with scintillation probes whose dimensions (0.6 cm) are comparable with the half-width of the measured radial distribution.

The criterion for the development of an instability, leading to the loss of plasma across the field, is taken to be the appearance of signals at the wall probes (scintillation probes) and the capacity probes; the signals at the onset of the instability are fairly periodic. Signals do not appear in the wall probes at low densities; at these densities the Debye radius is greater than the dimensions of the system. Increasing the density of charged particles in the trap results in the appearance of periodic signals. The appearance of the signals at the electrostatic probes is accompanied by

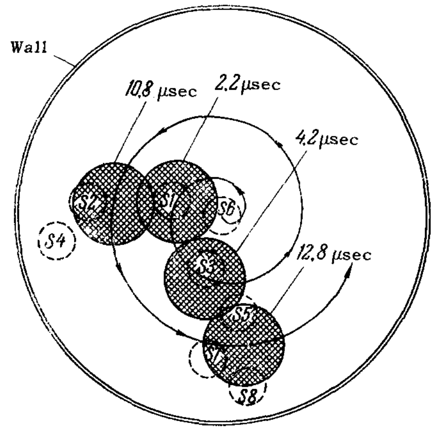

FIG. 1. Motion of the plasma column in the development of the instability. The dashed circles denote the scintillation detectors.

a sharp reduction in the plasma density at the center of the trap. At higher initial plasma densities a metastable regime is found. The signals at the wall probes disappear for smooth magnetic compression but can be produced rather easily by electrostatic or magnetic perturbations, for example, by "crowbarring" the current in the coils. At still higher densities $n \geq 10^{11}$ cm^{-3} the plasma becomes stable again. However, the lifetime of this stable plasma is less than 100 msec because of collisions and the subsequent loss of particles along the field. A stable plasma can be obtained by increasing the density or by increasing the initial pressure from 10^{-8} to 10^{-6} mm Hg. The dependence of stability on density appears to be common for both modes of operation.

The development of the instability is examined by locating a system of scintillation detectors beyond one of the mirrors; this makes it possible to trace the displacement of plasma across the lines of force of the magnetic field. Using this method it has been established that the appearance of signals at the wall probes means that the plasma column is simultaneously moving toward the wall and forming a twisted helix. The development of the instability in the quasi-stationary regime is shown in Fig. 1. Pulses at the wall probes indicate a constant angular velocity of the column, which rotates as a whole around the axis of the device. In general, in the "e" mode the period of rotation T = 2 μsec and the direction of rotation in the magnetic field is the same as that of a negative charge.

The plasma should actually acquire a negative charge in this situation since the condition for excess ion loss is

$$\frac{\langle \sigma v_i \rangle}{\langle \sigma v_e \rangle} > 1. \qquad (2)$$

Here, σ is the Coulomb scattering cross-section while v_i and v_e are the ion and electron velocities; when $T_e > 12T_i$ the plasma must be charged negatively. The condition in (2) is certainly satisfied for the "e" mode $T_e \sim 20$ keV, $T_i \sim 300-400$ eV. In the "i" mode the plasma generally rotates in the direction corresponding to that of a positive charge. The positive charge of the plasma under these conditions is evidently due to the fact that the ratio T_i/T_e is higher than in the "e" mode. In some cases, several milliseconds after the rotation begins the direction of rotation changes together with the sign of the net charge. The net charge polarity is determined from the polarity of the pulse at the electrostatic probe. The polarity of the net charge can reverse as a result of ion loss due to charge exchange; in this case T_e becomes $\sim 12T_i$.

The most striking results of these experiments are the reduction in the radial velocity near the wall of the vacuum chamber and the stable rotation of the plasma column as a whole with a constant angular velocity. In certain cases this rotation continued for 0.2 sec.

It is also interesting to note that when the plasma column moves close to the wall in the "e" mode the linear velocity for a rotational period $T = 2\,\mu$sec is 3×10^7 cm/sec, corresponding to a hydrogen ion energy of 400 eV. In order for ions with this energy to move in a circle of radius 20 cm almost 99% of the ion charge must be compensated by electron charge. Actually, however, the direction of rotation corresponds to the motion of a negative charge; consequently, the electron density in the column is greater than the ion density by approximately 1%.

It is difficult to explain all of the data obtained by Perkins and Post by any single model. The radial motion of the plasma is interpreted most easily in terms of a flute instability arising in a field with a positive curvature of the lines of force (the $l = 1$ mode corresponds to the displacement of the plasma as a whole). The experimentally determined radial velocity $v_r = 5 \times 10^5$ cm/sec corresponds to a charge-separation field of 50 V/cm.

It is somewhat more difficult to explain the stability of the plasma column near the axis at high plasma densities. Even more mysterious is the stability of rotation of the plasma around the axis at intermediate density values. One might attempt to explain the stability by saying that the rotating plasma column is in contact with the conducting end plates through a hypothetical cold plasma located in the mirror regions; this mechanism would permit the removal of excess plasma charge by virtue of the high conductivity along the field lines. However, the existence of cold plasma would make it difficult to produce and maintain the charge required for the rotational motion (around the axis) of the plasma column being displaced toward the wall.

Stable confinement of the high-density plasma might possibly be due to the effect of the finite Larmor radius. The theory actually predicts stability at very low density and at very high density ($H^2/4\pi\rho c^2 \ll 1$) if

$$\frac{L\rho_i}{r_0^2} > 1, \qquad (3)$$

where r_0 is the radius of the plasma column and ρ_i is the ion Larmor radius.

This stabilization effect does not appear at intermediate densities. The stable confinement reported in the American experiments is observed at a density for which the stability criterion is satisfied.

In comparing the results obtained in the Division of Plasma Research of the Institute of Atomic Energy and in the Livermore Radiation Laboratory it should be emphasized that the plasma is unstable at densities of approximately 10^9 cm^{-3} in both sets of experiments. On the basis of the available experimental data we may assume that the plasma decay mechanisms are considerably different in the two cases. This is not surprising because, as we have noted earlier, the boundary conditions are not the same in the two experiments.

In the experiments at the Institute for Atomic Energy the probe-current oscillograms do not exhibit a regular periodicity; also, the development of the instability does not lead to as rapid a decay for the instability regime described by Post. According to the analysis developed by Kadomtsev[5], the observed plasma lifetime can be attributed to a convective instability of the plasma. A magnetic tube characterized by high-density plasma separates neighboring lines of force and moves in the direction of weaker field. After interacting with the wall and losing some of particles of both signs this tube returns to the plasma and the motion to the wall is executed by other magnetic tubes, in which the plasma density is higher than in the surrounding plasma. On the basis of this analysis one obtains a plasma lifetime

$$\tau = Ca\sqrt{(1+p^2)\frac{RM}{\varrho_i kT_i}}, \qquad (4)$$

where a is the radius of the chamber, p is the ratio of the ion Larmor frequency to the ion Langmuir frequency, R is the radius of curvature of the line of force near the wall, ρ_i is the ion Larmor radius, M and T_i are the ion mass and temperature respectively, $T_i \gg T_e$, C is a coefficient which depends on the fractional density loss of a given tube upon interaction with the wall. The coefficient C depends on the geometry of the system and is of order 10.

Special experiments[6] carried out to verify the theory of convective plasma loss from the trap in the Division of Plasma Research at the Institute for Atomic Energy have yielded experimental results that are roughly in agreement with the theoretical predictions. In accordance with the convective plasma loss mechanism one observes irregular pulses on the probe-current oscillograms. A typical probe-current oscillogram is shown in the upper part of Fig. 4. Oscillograms of the current to probes located along a given line of force show fluctuations with good correlation. The correlation in current fluctuations to probes dis-

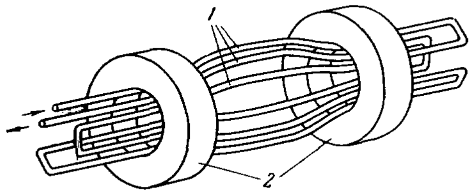

FIG. 2. Arrangement for producing the magnetic field. 1) rod, 2) coil.

placed in azimuth becomes poorer as the azimuthal displacement is increased and deteriorates rapidly for short pulses. When the probes are displaced by 180 degrees in azimuth it is difficult to discern any relation between the individual fluctuations.

The density dependence of the plasma lifetime observed in the range 10^7 to 10^9 cm^{-3} in these experiments is in fairly good agreement with the value of the constant C as determined theoretically.

2. SUPPRESSION OF HYDRODYNAMIC INSTABILITY BY MEANS OF STABILIZING WINDINGS

Experiments carried out at the Division of Plasma Research of the Institute of Atomic Energy at plasma densities of 10^7—10^9 cm^{-3} indicate that at pressures of 2×10^{-6} mm Hg the plasma lifetime in a simple adiabatic trap is 100 μsec with a magnetic field of 5 kOe.[7] As we have already pointed out, this value is one or two orders of magnitude greater than would be expected on the basis of a hydrodynamic analysis of a plasma with sharp boundaries in a field that falls off in the direction of the chamber walls, but is consistent with the theory of turbulent plasma diffusion.

A natural way to avoid the loss due to turbulent (or convective) diffusion is to use a field configuration that conserves the adiabatic invariant; to realize this purpose the magnetic field must increase in all directions toward the periphery. In particular, this property is possessed by a configuration obtained by combining a mirror field with the multipole field produced by a system of current-carrying rods located along the walls of the trap and connected in such a way that the current in neighboring rods flows in opposite directions. The rod configuration and the resulting magnetic field are shown in Figs. 2 and 3.

The advantages of these traps with stabilizing windings have been discussed by a number of authors.[4,8,10] The first experimental results on plasma confinement in combined fields were presented at the Salzburg conference.[7] As in the earlier experiments, the trap was filled by means of an ion magnetron.[6] The central electrode was a cold plasma pinch located at the axis of the trap. Because of the high conductivity along the magnetic field the pinch assumes the potential of the anode in the source. The cold plasma pinch is produced by an arc discharge in the longitudinal magnetic field. The source is located directly beyond one of the mirrors; at the other mirror there is an electrode at the same potential as the anode. The plasma flowing through the aperture in the anode forms a pinch with a diameter of 1—2 cm.

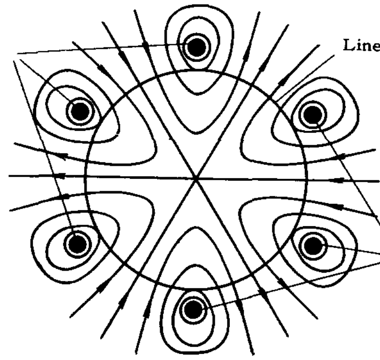

FIG. 3. Magnetic field geometry in a combined-field device.

The trap is filled with hot plasma by applying a potential difference between the pinch and the chamber wall. The potential applied to the plasma is +45 kV. The pulse length is 25 μsec. When the potential difference is removed the ions retain part of the energy acquired in moving through the crossed axial magnetic field and the radial electric field. The injection of cold plasma into the trap is terminated at the end of the voltage pulse. It might be noted that the mechanism by which the fast ions are produced is not completely clear at this point. If an appreciable energy of Larmor rotation is to be communicated to the ion the length of the leading edge of the pulse must be less than the Larmor rotation period. If this condition is not satisfied the energy of Larmor motion does not change in the applied electric field because of the conservation of the adiabatic invariant. However, in practice it is found that even with a relatively long front (several microseconds) the trap is filled with a plasma in which the mean ion energy is several kiloelectron volts.

The maximum density that can be achieved with the magnetron method is approximately 10^{10} cm^{-3}. In all cases the density is determined from the flux of fast neutral atoms formed by charge exchange in the interaction volume.

The plasma injected into the trap by the magnetron method is stabilized by six current-carrying rods; the current in neighboring rods flows in opposite directions and the rods are located uniformly in azimuth. In Fig. 3 are shown the lines of force for this system, which are evidently rather complicated. Only a relatively narrow bundle of lines, located close to the axis, passes through the mirrors. Most of the lines of force, which are off the axis, intersect the side wall of the chamber. To prevent the escape of particles through these "side mirrors" it is necessary to produce a rather large magnetic field by the current flowing through the stabilizing rods. The authors of this work

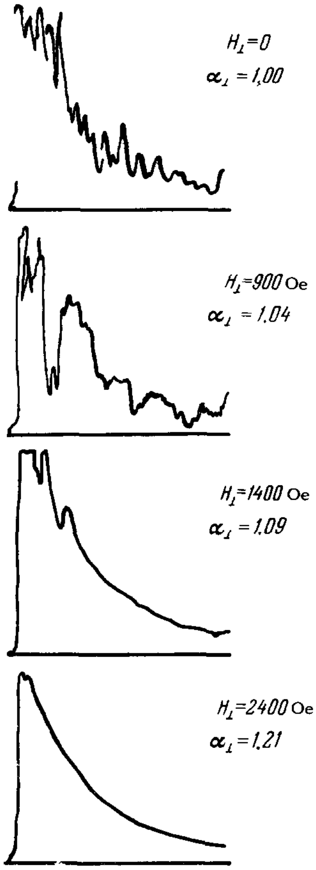

FIG. 4. Oscillograms of the probe current in the combined field device. The sweep length is respectively (from the top down): 1, 3 and 10 msec.

have introduced the notion of a transverse mirror ratio, which is defined as follows:

$$\alpha = \frac{\sqrt{H_0^2 + H_r^2}}{H_0}, \qquad (5)$$

where H_0 is the primary field at the axis and H_r is the field produced by the rods at the transverse mirror.

It is shown in this work that the plasma lifetime increases monotonically with α. As the rod current is increased the irregularities on the probe current disappear and the probe oscillograms are smoothed (Fig. 4). The dependence of the reciprocal plasma lifetime on the pressure of neutral gas in the chamber is given by a line that passes through the origin of coordinates. This kind of dependence indicates the absence, within the limits of the accuracy of these measurements, of plasma loss mechanisms other than charge exchange. For comparison, in Fig. 5 we show the function $1/\tau = f(P_0)$ in the range of initial pressures $P_0 = 10^{-1}$–10^{-5} mm Hg with the stabilizing winding switched on $\alpha_{st} = 1.5$ and switched off. In the latter case the line intersects the ordinate axis above the origin; the length of the vertical segment thus defined corresponds to the plasma lifetime (more precisely the reciprocal lifetime) as determined by what is evidently

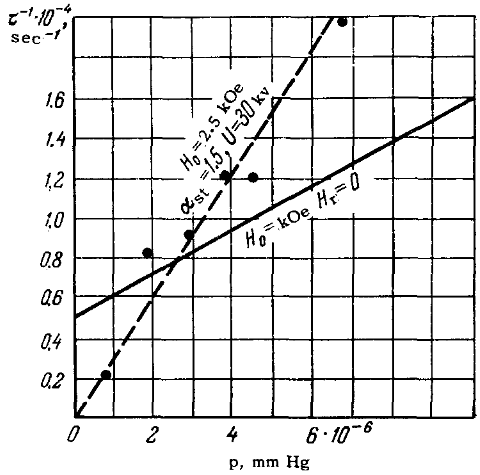

FIG. 5. The reciprocal lifetime as a function of hydrogen pressure in the chamber.

a convective instability.

Experiments on plasma stabilization by multipolar fields were repeated under better vacuum conditions in the PR-5 device.[12] The longitudinal magnetic field in the PR-5 device is 5000 Oe and the mirror ratio is 1.7. The stabilizing field at the wall of the vacuum chamber in PR-5 can be as high as 4500 Oe.

The half-period of the current in the rods is 55 msec. By using a number of compartments in the vacuum chamber it is possible to improve the vacuum conditions appreciably. Each compartment contains a titanium sputtering pump. The residual gas pressure in the chamber under operating conditions is 5×10^{-8} mm Hg. It was possible to produce a plasma density greater than 10^9 cm^{-3} with an electron temperature of 5 eV and a mean ion energy of approximately 5 keV.

The maximum plasma lifetime reported in[12] is 10–15 msec. The lifetime in these experiments is limited by charge exchange.

3. IXION AND HOMOPOLAR

There is another series of experiments with adiabatic traps which indicate the possibility of extended confinement of plasma in a simple field configuration. The trap is filled with hot plasma in these experiments by exploiting the rotation of a plasma in crossed magnetic and electric fields. Devices of this kind are the Homopolar at Lawrence Radiation Laboratory and the Ixion at Los Alamos. In both devices there is a trapping magnetic field configuration with a cylindrical electrode located along the axis of symmetry. In Ixion the electrode is actually a column of plasma which is injected through the mirror; in Homopolar a metal electrode is used. A potential difference of several tens of kilovolts is applied between the electrode and the chamber wall. Thus, there is a region of crossed fields—a radial electric field and an axial magnetic field, close to the median plane.

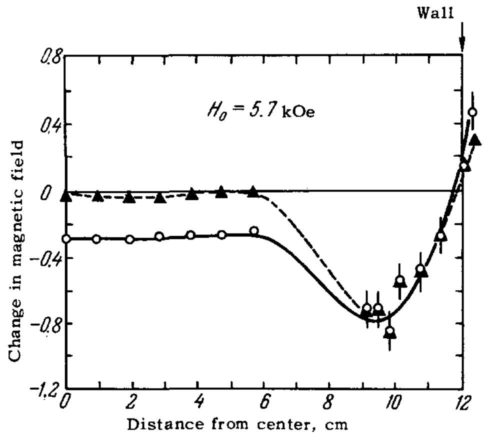

FIG. 6. Expulsion of the magnetic field in Ixion before (———) and after (---------) "crowbarring" the circuit.

The ion motion in the crossed fields is made up of the Larmor rotation with velocity cE/H and a drift (also with velocity cE/H) in the direction perpendicular to **E** and **H**. We may note that this motion actually holds only for particles which are formed in the crossed fields with zero initial velocity. In Homopolar, in contrast with the Soviet PR-5 device, the gas is ionized after the application of the radial electric field.

The drift directions are the same for electrons and ions in uniform crossed fields, that is to say, the plasma is displaced as a whole without giving rise to any current flow. In the case of cylindrical symmetry, which pertains to these devices, there is also a centrifugal force and a φ drift given by[13]

$$E_r e = \frac{e}{c} v_\varphi H_z - \frac{mv_\varphi^2}{r}.$$

The dependence of the drift on the particle mass leads to the appearance of an azimuthal current component in the plasma. If the last term in the equation is not important the current density is given by

$$j = ne\,(v_{\varphi_i} - v_{\varphi_e}) = -\frac{nMc^3E^2}{H^3 r}, \tag{6}$$

where r is the distance from the axis. Substituting values of the density ($\sim 10^{14}$ cm^{-3}) and fields characteristic of typical experiments[14] one sees that the azimuthal current density is hundreds of amperes per cm^2. It is reasonable to assume that this current flow causes compression of the plasma, as is the case in powerful pulsed discharges.

The self-compression effect of the discharge current tends to isolate the plasma from the walls. Magnetic measurements carried out on Ixion III with a rotating plasma indicate a weakening of the magnetic field as a consequence of its expulsion by the plasma and the flow of a circular current (Fig. 6). The contribution of each of these effects can be determined easily by measurements with magnetic probes, first with rotating plasma and then after the electrode voltage has been removed.[14]

Another characteristic feature of crossed fields with axial symmetry, in addition to the dependence of particle velocity on mass, is the dependence of particle drift velocity on distance from the axis. This dependence should provide a randomization of the rotational motion by virtue of the turbulent mixing of plasma layers which move with different velocity.

The rotation of the plasma and the resulting centrifugal force tend to truncate the loss cone characteristic of the adiabatic trap. This effect can perhaps best be described as containment of particles by the centrifugal force as they approach the axis of the system in moving along the line of force toward the mirror. Calculations of the limiting energy of longitudinal motion of particles contained in the trap, taking account of the centrifugal force, lead to the following expression:[16]

$$W_\parallel = W_\perp (R-1) + \frac{mv_\varphi^2}{2}\frac{R-1}{R}, \tag{7}$$

where R is the mirror ratio while $W_\perp$ and $W_\parallel$ are respectively the rotational energy and the energy associated with the translational motion along the lines of force.

A noteworthy feature of a rotating plasma device is the possibility of using it as a magnetohydrodynamic condenser in which the energy of the electric field is stored in the form of rotational plasma energy. The dielectric constant of the plasma

$$\varepsilon = \frac{4\pi\varrho c^2}{H^2}$$

can be as high as tens of thousands in these systems; this is a distinguishing feature as compared with ordinary condensers. The magnetohydrodynamic condenser is discharged by short-circuiting the external circuit. Experiments carried out with Homopolar[17] have shown that this capacity varies from 60 cm in vacuum to tens of μF in the rotating plasma mode with density 3×10^{15} cm^{-3} and velocity 8×10^6 cm/sec ($\beta = 12\%$). Experiments carried out in this same device have shown that the change in distribution of electric field along the radius of the device in the presence of the rotating plasma is relatively small (compared with the calculated change). The basic shortcoming of the magnetohydrodynamic condenser is the difficulty of preventing breakdown along the lines of force to the flanges. When dielectric flanges are used the current flow along lines of force that are at different electric potentials is short-circuited as a result of breakdown at the surface of the dielectric. Some special experiments have shown[15] that the sharp voltage drop in Ixion is due to radial breakdown at the surface of the dielectric flanges.

In experiments in rotating plasma devices carried out over many years it has not yet been possible to achieve a mode of operation in which the acceleration of the plasma is not impeded by its interaction with the flanges; as a result is has not been possible to obtain a plasma velocity greater than 10^7 cm/sec. In a paper published recently, however,[18] it has been reported that this difficulty has been overcome to a considerable degree and it was shown that a crossed-field rotating-plasma device could be used successfully for producing a high-temperature, high-density plasma and for achieving extended confinement in the magnetic field after the electric field was short-circuited. The plasma loss rate at densities greater than 10^{13} cm^{-3} can be explained entirely by the expected loss through the mirrors as a consequence of Coulomb collisions. Thus, as in the work of Post, here one has also observed stable confinement of a high-density plasma in a magnetic field of simple configuration.

We now consider the results obtained with the Homopolar V device to the extent that this is possible on the basis of the rather brief description in the published work.[18] The diameter of the vacuum chamber is 15 cm, the diameter of the electrode located along the axis is 5 cm. The coil system produces a longitudinal magnetic field with mirrors and the intensity is evidently 10 kOe. The field strength is not indicated in the paper and the value given here is estimated on the basis of the rotational velocity. The dimension of the region occupied by magnetic field is approximately 1 meter. The chamber is pumped down to an initial pressure of 1×10^{-7} mm Hg. A potential difference of 20—45 kV is applied between the electrodes from two condensers with a capacity of 1 μF about 100 μsec after the introduction of a deuterium charge of 0.02—0.05 cm^3 into the trap under normal conditions. The gas is introduced through an aperture in the electrode in the central portion of the chamber by means of a pulsed electromagnetic valve. The pulsed gas feed is a distinguishing feature of Homopolar V. In all earlier models the chamber was filled to the required gas pressure before operation.

The application of the electrode voltage produces a current pulse in the circuit; this pulse is about 15 kA and lasts for 1 μsec. This pulse causes essentially complete ionization of the gas; at the maximum current the transducer does not detect any fast neutral atoms that would be formed in charge exchange. The interaction of the current pulse with the magnetic field produces a plasma rotation with a velocity of 6×10^7 cm/sec which corresponds to a deuterium ion energy of 4 keV. The maximum energy of the charge exchange atoms as determined from the time of flight is also 4 keV. After the first current pulse the current drops to 10—15% of the peak value. The potential difference does not change significantly under these conditions.

Approximately 20 μsec after the current pulse there is a rather sharp drop in the potential of the central electrode, which is associated with breakdown along the lines of force; this removes the electric field. Although the removal of the electric field terminates the plasma rotation the energy contained in the Larmor rotation is conserved: in accordance with the principle of adiabatic invariance $W_\perp/H$ = const. Thus, since the change in electric field is slow (compared with the period of rotation), the energy of the Larmor rotation remains unchanged, i.e., after the electrode voltage is removed (by external short-circuiting or by internal breakdown) the trap remains filled with a high-temperature plasma in which the ions move in Larmor circles with velocity cE/H. Microwave transmission through the plasma shows that the density in the trap remains higher than 10^{13} cm^{-3} for a time interval of approximately 10 msec. Assuming that the loss of ions from the trap is due to ion-ion collisions we find that the ion energy for this lifetime is greater than 1 keV.

The parameters of the plasma used in this work are such that one expects the appearance of an appreciable pulse of neutrons due to the D-D reaction. The absence of exact data on the mean ion energy and the ion distribution does not allow us to determine accurately the order of magnitude of the expected neutron yield. The recorded neutron burst ($\sim 10^5$), which lasts for several tens of microseconds after the current decay, is not incompatible with the reported values of density and energy. Incidentally, this fact need not necessarily be assigned great importance since neutron bursts of this intensity were observed on one of the first Ixion models, in which the maximum ion energy in the crossed fields was less than 200 eV. One may conclude on the basis of the data reported here that extended plasma confinement has been observed in Homopolar as well as the device described by Post.

The effect of breakdown through the ends leads to the conjecture that there is a cold plasma which provides the removal of excess charge along the lines of force, thus stabilizing the flute instabilities. The high plasma density and high ion energy achieved in Homopolar V evidently indicate promising application for this method of producing high-temperature plasma.

4. TURBULENT HEATING OF PLASMA IN AN ADIABATIC TRAP

A research program carried out by E. K. Zavoĭskiĭ and his colleagues on turbulent plasma heating indicates a new possibility for producing hot plasma in adiabatic traps. The turbulent-heating method is based on the collective friction of an electron flow through a plasma. The loss of energy by a beam of fast electrons in a plasma has been studied extensively both theoretically and experimentally. It has been found that under certain specific conditions the loss of energy of the ordered electron flow can exceed the bremsstrahlung losses due to Coulomb collisions by several orders of magnitude.

The collective-friction effect arises when the velocity of ordered motion of the electron beam exceeds the mean thermal energy of the plasma electrons. In experiments on turbulent heating the electron stream has been produced directly in a plasma located in a fixed uniform magnetic field. The induced electric field was produced by propagating a hydrodynamic wave through the plasma in the radial direction. The wave is produced by passing a current pulse through a long cylindrical one-turn coil, thereby producing a pulsed high frequency magnetic field. The axis of the single-turn coil is parallel to the lines of force of the fixed field. The electron current density in the plasma in the presence of the wave is

$$j_\varphi = -env_\varphi = -\frac{c}{4\pi}\frac{d\tilde{H}_z}{dr} . \qquad (8)$$

In order to obtain a sufficiently high directed electron velocity v_φ it is necessary to produce a correspondingly high gradient of the high-frequency magnetic field $\tilde{H}$. In other words, the wavelength must be smaller than the diameter of the circuit. The optimum relation between the frequency of the circuit oscillation ν and its radius can be written as follows:

$$r_0 = \frac{V_A}{4\nu} , \qquad (9)$$

where $V_A = H/\sqrt{4\pi\rho}$ is the Alfvén velocity.

Analysis of the dispersion equation shows that the waves produced as a consequence of the two-stream instability are damped rapidly, transferring their energy to the electrons and the ions.

If effective heating is to be achieved the following relation must hold at each instant of time:

$$kTe \ll \frac{mv_\varphi^2}{2} .$$

Ion heating will occur if

$$\omega_p \frac{v_\varphi}{\dot{v}_\varphi} \frac{m}{M} > 1, \qquad (10)$$

where

$$\omega_p = \sqrt{\frac{4\pi ne^2}{m}}$$

is the Larmor frequency.

The heating efficiency, given by

$$\xi = \frac{nkT}{H^2/8\pi} ,$$

is close to unity and depends only on the circuit parameters. Investigations carried out over a wide range of density and temperature have verified this conclusion. The heating efficiency for the circuits used in these experiments has been of the order of tens of percent.

In[22] turbulent plasma heating was carried out in a magnetic trap 2 M long and 12 cm in diameter. The field strength at the center of the trap was 3000 Oe. The mirror ratio was varied from 1.5 to 3. The large ratio of trap length to diameter made it possible to produce an elongated region with uniform magnetic field, as required for the utilization of the turbulent plasma-heating technique. It was shown in experiments carried out earlier that a small deviation from parallelism between the lines of force of the fixed and variable magnetic fields (~ 5°) causes a sharp reduction in heating efficiency. The length of the circuit used for producing the high frequency is 90 cm, the frequency is 9 Mc and the peak field $\tilde{H}$ varies up to 500 Oe.

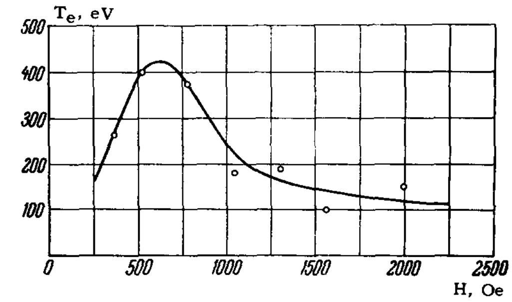

FIG. 7. The electron temperature as a function of the fixed magnetic field in the trap in turbulent heating ($\tilde{H}$ = 500 Oe).

Cold plasma was injected into the trap from an injector with hydrogen-saturated titanium buttons. The work was carried out at densities 2×10^{11}–4×10^{13} cm^{-3}. The electron energy in the hot plasma was measured in three ways: 1) by measuring the spectrum of the electron bremsstrahlung emitted through the mirrors, 2) by the rate of extinction of the neutral atoms and 3) by retarded-potential techniques. It was shown that the product of plasma density and electron temperature remains constant over a wide range of initial conditions. Under the experimental conditions reported $nkT_e \approx 10^{15}$ eV/cm^3 as n varies from 2×10^{11} to 4×10^{13} cm^{-3}.

The curve showing the dependence of electron temperature on fixed magnetic field exhibits a peak at $H \approx \tilde{H}$ and then falls off rather rapidly as the field increases (Fig. 7). The maximum ion temperature is found at higher fixed fields. With all other conditions remaining fixed the maximum ion temperature is observed at a magnetic field approximately three times greater than that corresponding to the peak electron temperature.

The maximum mean ion energy recorded by the retarded-potential techniques in these turbulent heating experiments[22] was 150–200 eV. The maximum electron temperature was 5000 eV.

The containment time for the fast electrons in the trap was determined from the decay curve showing the intensity of the He II 4685 Å line as a function of time (a small charge of helium is introduced into the chamber). When the circuit is triggered the intensity increases with the degree of ionization of the neutral helium and reaches a peak; it then falls off (Fig. 8) by virtue of the loss of fast electrons and the extinction of singly charged helium ions. Thus, the plasma lifetime as determined by the decay of the He II 4685 Å line gives a lower limit on the lifetime of the fast electrons. The lifetime measured in this way is essentially the same as that computed under the assumption that

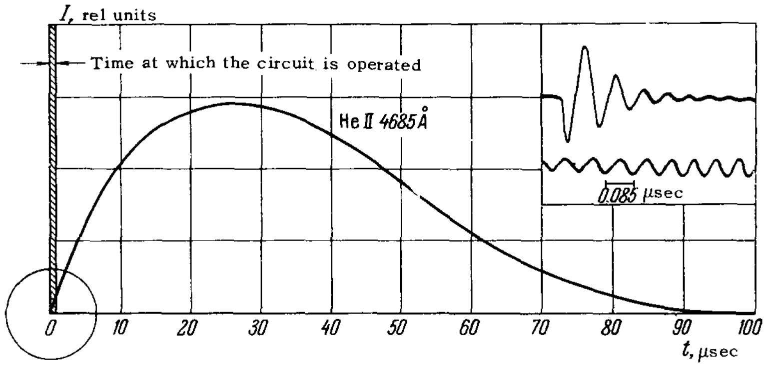

FIG. 8. The emission of the He II 4685 Å line as a function of time after turbulent heating.

the loss of fast electrons through the mirrors is due to electron-electron collisions. When $T_e = 500$ eV and $n = 10^{12}$ cm^{-3} the experimentally observed lifetime is 60 μsec. As far as the containment of fast ions is concerned we find with $T_e = 200$ eV, $T_i = 150$ eV and $n = 10^{12}$ cm^{-3} that the ion lifetime is approximately 130 μsec, corresponding to the geometric mean of the lifetimes for electrons and ions escaping from the trap by Coulomb collisions. When the mirrors are switched off the lifetime of the turbulently heated plasma is reduced sharply.

As yet the experimental data are inadequate for determining the mechanism by which ions are lost in this work. It is very probable, however, that the loss of hot ions is due to charge exchange on the neutral gas which enters from the injector after the plasmoid. Control experiments seem to show that charge exchange on residual gas is unimportant. The authors of the work believe that the observed plasma lifetime is not limited by convective instabilities—irregular oscillations characteristic of the convective instability have not been observed. This result is not surprising since the metal end plates of the chamber, and the conductivity along the lines of force by virtue of the cold plasma beyond the mirrors, can provide stabilization of the convective instability.

The utilization of turbulent plasma heating for achieving thermonuclear temperatures involves serious technical difficulties since this technique requires the production of high-amplitude radio-frequency magnetic fields. However, the results already obtained indicate that the method can be used successfully for preliminary heating of a plasma before adiabatic compression in a trap (see note added in proof at the end of the article).

5. ELECTRON CYCLOTRON HEATING IN ADIABATIC TRAPS

The application of cyclotron resonance for plasma heating is attractive in that it is possible to heat a plasma directly in the magnetic field of the trap as in turbulent heating; furthermore, the presence of electrodes in the chamber is not required, as is the case in a Homopolar device. Cyclotron heating in a vacuum chamber requires the introduction of a high-frequency field with a period equal to the Larmor rotation period of the charged particle in the magnetic field.

To explain the physical features of cyclotron plasma heating we assume that the chamber acts like a cavity resonator (a special resonator can also be introduced for this purpose) and that a standing wave is set up in which the electric vector E_x is perpendicular to the lines of force of the magnetic field. In the absence of high-frequency field the phases of the charged particles rotating about the Larmor circles are random. When the high-frequency field is applied only a small number of these particles are in phase with the wave. For these particles the velocity component v_x changes when the high-frequency electric field passes through zero, and these particles acquire energy continuously in the accelerating electric field. Particles whose phase is somewhat different from the resonance value acquire less energy. On the other hand, particles which execute Larmor motion in antiphase with the applied field loose energy continuously and finally fall into the accelerating phase after passing through zero energy. Effective heating of a given plasma component will be achieved when the energy acquired by the particles between collisions is greater than the mean energy they possessed initially. This condition can be written in the form

$$E_0 > \frac{2n\sigma}{e} W_0, \quad (11)$$

where E_0 is the peak electric field and σ is the Coulomb cross section.

Cyclotron heating of ions and electrons has been investigated by a number of authors. In almost all of the earlier work the energy acquired by the charged particles was less than tens of electron volts (cf. for example[23]).

In the beginning of 1963, however, two brief communications were published[24,25] which contained results indicating the possibility of heating electrons to temperatures of tens of keV. Unfortunately, the absence of many of the important data characterizing the experimental conditions make an analysis of the results difficult; there is little doubt, however, that a great

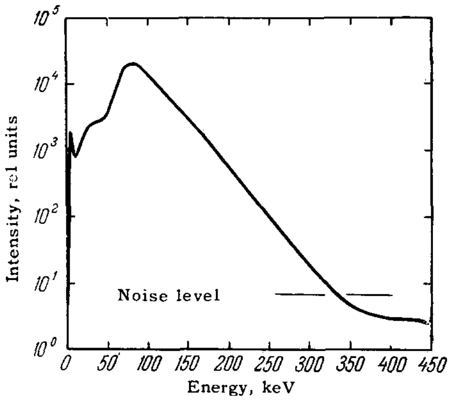

FIG. 9. The x-ray spectrum from the plasma heated by cyclotron resonance.

deal of energy was communicated to the plasma electrons.

In the work, carried out at Oak Ridge National Laboratory under Shipley, the vacuum chamber serves as a cavity resonator in which oscillations at a frequency close to the electron cyclotron frequency are excited. These oscillations are excited by an electron beam with an energy of approximately 5 keV at currents up to 0.5 A. The measured fundamental frequency of the cavity resonator in the absence of plasma is 0.8×10^9 cps. This frequency is approximately five times smaller than the electron Larmor frequency near the median plane. It is possible that the presence of plasma in the trap shifts the characteristic frequency of the system, making it equal to the cyclotron frequency of electrons. The magnetic field at the center of the trap is 1500 Oe. The mirror ratio is 3.

The beam of electrons which excites the oscillations is introduced through an aperture in the anode of a gun located at one of the mirrors. A reflector is located at the opposite mirror. The deuterium is injected continuously in a small cavity in the anode. It is evidently assumed that intense ionization of the gas occurs in this cavity; the pressure differential between the cavity and the main chamber is approximately 2 orders of magnitude (10^{-3}—10^{-5} mm Hg).

All of the data were obtained in this work by measuring the spectra and the intensity of the x-rays. Using a camera obscura and photographing the plasma at different distances it was shown that the bulk of the x-rays come from a volume which is symmetrically located with respect to the chamber axis. The volume from which the x-rays emanate is approximately 100 cm^3. The x-ray spectrum was taken with a spectrograph with a resolution of 3 keV and is shown in Fig. 9. The maximum detected photon energy is 250 keV. Assuming that the fast electrons in the plasma are characterized by a Maxwellian velocity distribution, and extrapolating the short-wave tail of the experimental curve $\exp(-h\nu/kT)$ the authors of the work obtained an electron temperature $T_e = 32$ keV.

The plasma density was determined by measuring the energy carried by the x-rays (per unit volume) and found to be 5.1 erg/cm^3 sec. Using the formula given by Spitzer[27] for the bremsstrahlung intensity, $E = 1.42 \times 10^{-27} Z^3 n^2 T_e^{1/2}$, and assuming that the radiative bremsstrahlung of the electrons occurs on deuterons ($Z = 1$), we obtain a plasma density 4×10^{11} cm^{-3} (for a temperature of 32 keV). The density thus obtained is too high by a large factor because in addition to the deuterium ions there are undoubtedly many ions of the residual gas and the anode material. Unfortunately, the pressure of the residual gas in the chamber is not indicated in this work. It is not likely that the density of neutral gas atoms was much smaller than the measured plasma density ($n = 4 \times 10^{11}$ cm^{-3}). The strong dependence of radiation yield on ion charge can lead to a significant error in the determination of plasma density and for this reason there are some serious doubts as to the validity of the order of magnitude of the estimate which is given.

In the second work on electron cyclotron heating in an adiabatic trap, which was also carried out at Oak Ridge, use was made of a 5 kW generator operating continuously at a frequency 10.8×10^9 cps. This work is an extension of work reported at the Salzburg conference in 1962 in which cyclotron heating was reported using a frequency of 2×10^9 cps and a 1 kW generator.[26] Before considering the new data we note that in the experiments described at Salzburg the authors reported a plasma with an electron energy of 10 keV which was confined for 0.05 sec. Investigation of the dependence of x-ray intensity and diamagnetic signal on magnetic field indicated a sharp resonance peak corresponding to the electron cyclotron resonance.

The new work was carried out in a magnetic trap with diameter 25—30 cm with a distance of 80—90 cm between mirrors (the dimensions are not given precisely). The plasma in this device is a source of hard x-rays with a limiting energy greater than 2.5 MeV and the neutron radiation intensity is 10^5 neutrons per second. From the analysis of the x-ray spectrum it follows that the plasma electrons have a mean energy in the hundreds of kilo-electron volts. The absence of a correction to the spectral distribution for the counter efficiency can only reduce the value of the electron temperature determined from the short-wave tail of the distribution.

The investigation of the x-ray spectrum has shown that most of the emitted neutrons are not formed in the D-D reaction. Assuming that the neutrons result from fission of deuterons by fast electrons and using a reasonable value of the volume and the measured value of the plasma density ($\sim 10^{12}$ cm^{-3}) the authors estimate the density of electrons with energies greater than 2.2 MeV as 10^9 electrons per cm^3. The neutron flux increases in proportion to the applied power as does the diamagnetic signal recorded by a magnetic probe; the intensity of the noise emitted by the plasma also increases.

The fall-off in the x-ray and neutron yields after

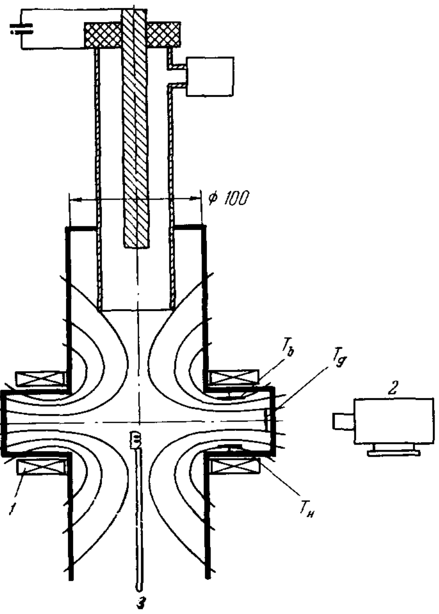

FIG. 10. Diagram of the cusp device. 1) Coils producing the magnetic field; 2) streak camera; 3) magnetic probe.

the high-frequency power is turned off is characterized by a time constant of 0.13 sec. Using the given values of the plasma density and lifetime one can independently estimate the electron temperature of the plasma under the assumption that plasma decay occurs by virtue of electron-electron collisions. In this case T_e is found to be 4×10^4 eV, which is an order of magnitude smaller than the electron temperature estimated from the x-ray spectrum. It is as yet difficult to draw any final conclusion as to whether the discrepancy in the estimates of electron temperature is a consequence of the development of instabilities leading to a more rapid loss of plasma or simply the inadequate accuracy in the determination of the plasma parameters. We note that the plasma lifetime data from the decay of the hard radiation should not be taken as final. The curves showing the radiation intensity as a function of time exhibit two features that are difficult to explain: a) the fall-off in neutron emission is delayed with respect to the fall-off in x-ray emission by a time interval of 0.1 sec; b) for a time of 0.1 sec after the high-frequency power is switched off the intensity of the emitted neutrons increases by more than one order of magnitude.

Although some of these results are open to criticism, we can still conclude that the work carried out at Oak Ridge has indicated the fundamental possibility of electron cyclotron heating of a plasma at frequencies of 10^{10} cps to achieve temperatures of tens of kiloelectron volts and higher. The possibility of using this type of heating in large traps and for high values of the magnetic field remains open to question.

It should also be noted that in recently published work on electron cyclotron heating of plasma to high energies the efficiency was low. For example, in the data of[26] the reported efficiency is less than 10^{-3}.

6. INJECTION OF PLASMOIDS IN A TRAP FORMED BY CUSP FIELDS

A magnetic trap formed by two coils connected in opposition (cusp) is favorably different from a simple adiabatic trap in that the magnetic field in this system increases in all directions toward the periphery (Fig. 10). In principle, this magnetic field, which increases in all directions toward the periphery, should provide high stability with respect to hydrodynamic perturbations.[8,28,29]

At first glance it would appear to be most attractive to contain the high-density plasma ($\beta = 1$) in the central region of the trap. The plasma expels the magnetic field and is confined in stable fashion by the magnetic barrier whose intensity increases toward the periphery. Plasma contained at the center of the trap can only escape along the lines of force, that is to say, either through the ends or through the circular slit. Considering the loss of high-temperature plasma through the slit and neglecting diffusion across the magnetic field one obtains the following expression for the containment time:[29]

$$\tau = 10^{-7} \frac{R^2 H}{T}, \tag{12}$$

where R is the radius of the trap in centimeters, H is the magnetic field in the circular slit and T is the plasma temperature in eV.

Taking account of plasma diffusion in the direction perpendicular to the magnetic field and the change in volume occupied by the plasma as it flows out through the slit yields a lifetime which is considerably smaller than that obtained from (12) (especially if the electron temperature is not too high); a rough estimate of the lifetime can be obtained from the expression[30]

$$\tau\ (\mu\text{sec}) = 0.7 T^{1/6}(\text{eV}) \left(\frac{W(\text{erg})\ R(\text{cm})}{H^2\ \text{Oe}} \right)^{4/15}. \tag{13}$$

Here, W is the total energy of the plasmoid contained in the trap $[W = Nk(T_i + T_e)]$.

With $H = 10^4$ Oe, $R = 100$ cm, and $T = 100$ eV the lifetime given by (12) is 0.1 sec. Taking account of the diffusional loss through the slits we find a lifetime that is almost two orders of magnitude smaller. Thus, the advantage of a cusp field geometry is purchased at a rather expensive price: this method of confinement reminds one of carrying liquid in a leaking container with walls strong enough to withstand the pressure of the fluid. If a method for filling the cusp system rapidly with hot plasma is not found, then the containment of the hot plasma in the central region of the trap is of interest only in connection with the development of ideas concerning "plugging of holes" in the magnetic barrier. In passing we note that the experi-

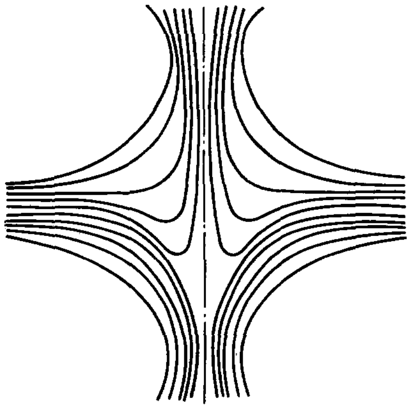

FIG. 11. Field configuration with plasma injection.

mentally observed lifetime of a high-density plasma in a cusp field is in agreement with that given by (13).

Another possibility for plasma containment in a trap of this kind consists of trapping the plasma at force lines that pass far from the null of the magnetic field, i.e., lines on which the adiabatic invariant is not disturbed. A plasma trapped in this way is effectively contained in a mirror system by virtue of the conservation of the adiabatic invariant and is also stable against loss to the periphery across the lines of force. However, there is a danger of an instability leading to the displacement of the plasma to the center. In this case particles falling into the region in which the adiabatic invariant is not conserved will be lost from the trap by escaping through an effective "slit." The development of the instability which displaces the plasma to the center must occur in a bounded region and it is impossible to predict a priori whether or not an instability will arise in this case. A definitive answer to this question can only be obtained experimentally.

The problem of heating plasma in cusp fields also has its own specific characteristics. The fact that the trap does not contain a region with uniform magnetic field means that the plasma can not be heated by cyclotron resonance or turbulent heating. There are considerable difficulties in using an ion magnetron or a Luce arc to fill the trap. If adiabatic compression is used the compressed plasma is displaced toward the region of weak field and the temperature rise of the plasma as a function of the current in the winding occurs at a much slower rate than is the case for plasma compression in a uniform field:

$$T \sim I^{4/7}, \qquad n \sim I^{6/7}, \tag{14}$$

where I is the coil current. We recall that in a uniform magnetic field $T \sim H^{4/5}$ and $n \sim H^{6/5}$.

In almost all experiments on plasma containment in cusps the trap has been filled by plasmoids accelerated in electrodynamic injectors. The notion of capturing a plasmoid is based on the assumption that in penetrating the magnetic barrier and falling into the trap the plasmoid undergoes an irreversible process[31] as a result of which it is trapped. In the American literature plasma trapping by irreversible processes is known as "entropy trapping." The basic mechanism leading to the randomization of the plasmoid is evidently partial capture of the magnetic field by the plasma[30,33] at the moment the plasmoid passes through the end slit. The circular current arising as a result of capture of the field can reach large values. The trapped field leads to an intense interaction of the plasma with the field of the second winding. In Fig. 11 we show the form of the lines of force distorted by virtue of the penetration of the plasmoids into the trap.

Experiments carried out on the Orekh device have shown that the lifetime of a plasma trapped on the line of force with density of about 10^{12} cm^{-3} and a temperature T = 20 eV is in agreement with the assumption of ion loss due to Coulomb collisions; this lifetime is about 200 μsec. These results cannot as yet be regarded as proof of the absence of an instability causing the displacement of the plasma toward the center of a trap since it is impossible to exclude the possibility of stabilization of the instability by virtue of the plasma conductivity along the lines of force.

Somewhat unexpected are the results obtained a year ago at a Los Angeles laboratory using the cusp devices Mark II and Mark III in which, according to the published data,[35] ions with energies of tens of kiloelectron volts were confined for times of many hundreds of microseconds. In this work it is indicated that neutrons were emitted from the active volume. The plasma density estimated from the neutron yield is 10^{15} cm^{-3}. Under the reported experimental conditions the radius of curvature of the ion trajectory is comparable with the dimensions of the trap. In view of the strong inhomogeneity of the field in a cusp device the extended confinement of these ions cannot be explained by conservation of the adiabatic invariant. To explain the observed lifetime the assumption is made that the fast electrons are contained in the trap adiabatically and that the ions are confined by the electric field due to the electron space charge. Some of the numerical data given in the work are contradictory. It is as yet difficult to make any definite judgement concerning the results given in this work, the more so since the reliability of some of the data was questioned by a leader in American research on plasma confinement in cusp fields.[36]

A basic difficulty related to the capture of accelerated plasmoids in a magnetic field is the fact that these plasmoids can penetrate the field rather easily. This situation evidently arises because of the weak interaction of fast plasmoids with the field because of the low electron temperature. It might be possible, for example, to raise the electron temperature by turbulent heating of the plasma as it penetrates the magnetic barrier.

New systems have been proposed[37] to obtain a trap with cusp fields which is hydromagnetically stable and in which there is no region in which the adiabatic invariant is not conserved. These are as yet still in the theoretical stage and have not been examined experimentally in more than a preliminary way.

Note added in proof: Experiments reported recently[20] on adiabatic compression of a plasma first heated by turbulent heating have verified the possibility of extended confinement of a plasma in an adiabatic trap of simple design. In these experiments a plasma with density of 2-5 × 10^{12} cm^{-3} and an electron temperature of 200 keV was confined in a magnetic field for several milliseconds.

[1] Post, Ellis, and Rosenbluth, Phys. Rev. Letters **4**, 166 (1960).

[2] Ioffe, Sobolev, Tel'kovskiĭ, and Yushmanov, JETP **40**, 40 (1961), Soviet Phys. JETP **13**, 27 (1961).

[3] W. A. Perkins and R. F. Post, Phys. Fluids **6**, 1937 (1963).

[4] Coensgen, Cummins, and Sherman, Phys. Fluids **2**, 350 (1959).

[5] B. B. Kadomtsev, JETP **40**, 328 (1961), Soviet Phys. JETP **13**, 223 (1961).

[6] M. S. Ioffe and E. E. Yushmanov, Nuclear Fusion, 1962, Supplement Vol. I, p. 177.

[7] Gott, Ioffe, and Tel'kovskiĭ, Nuclear Fusion, 1962, Supplement Vol. III, p. 1045.

[8] Berkowitz, Friedrichs, Goertzel, Grad, Killeen, and Rubin, Physics of Hot Plasma and Thermonuclear Reactions, Proc. of the Second Geneva Conference, Moscow, 1959, p. 146.

[9] L. A. Artsimovich, Upravlyaemye termoyadernye reaktsii (Controlled Thermonuclear Reactions), Moscow, Fizmatgiz, 1961.

[10] I. N. Golovin et al, UFN **73**, 685 (1961), Soviet Phys. Uspekhi **4**, 323 (1961).

[11] Ioffe, Sobolev, Tel'kovskiĭ, and Yushmanov, JETP **39**, 1602 (1960), Soviet Phys. JETP **12**, 1117 (1960).

[12] Baĭborodov, Ioffe, Petrov, and Sobolev, Atomnaya énergiya **14**, 443 (1963).

[13] Anderson, Baker, Bratenahl, Furth, Ise Jr., Kunkel, and Stone, Physics of Hot Plasma and Thermonuclear Reactions, Proc. of the Second Geneva Conference, Moscow, 1959, p. 466.

[14] D. A. Baker and J. E. Hammel, Phys. Fluids **4**, 1534 (1961).

[15] D. A. Baker and J. E. Hammel, Phys. Fluids **4**, 1549 (1961).

[16] Boyer, Hammel, Longmire, Nagle, Ribe, and Riesenfeld, Physics of Hot Plasma and Thermonuclear Reactions, Proc. of the Second Geneva Conference, Moscow, 1959, p. 317.

[17] Vedenov, Velikhov, and Sagdeev, Nuclear Fusion **1**, 82 (1961).

[18] Klaus, Baker and Layman, Phys. Fluids **5**, 1482 (1962).

[19] Babykin, Zavoĭskiĭ, Rudakov and Skoryupin, Nuclear Fusion, 1962, Supplement, Vol. III, p. 1073.

[20] Babykin, Gavrin, Zavoĭskiĭ, Rudakov, and Skoryupin, JETP **47**, 1597 (1964), Soviet Phys. JETP **20**, (1965).

[21] E. K. Zavoĭskiĭ, Atomnaya énergiya **14**, 57 (1963).

[22] Babykin, Gavrin, Zavoĭskiĭ, Rudakov, Skoryupin and Sholin, JETP **46**, 511 (1963), Soviet Phys. JETP **19**, 349 (1964).

[23] K. D. Sinel'nikov et al, Reports of Soviet Scientists, Second Geneva Conference on Peaceful Uses of Atomic Energy, Vol. I, p. 111.

[24] Alexeff, Neidigh, Reed, and Shipley, Phys. Rev. Letters **10**, 273 (1963).

[25] Ard, Becker, Dandl, Englund and Kerr, Phys. Rev. Letters **10**, 87 (1963).

[26] Becker, Dandl, Eason, Englund, Kerr and Ard, Nuclear Fusion, 1962, Supplement Vol. I, p. 345.

[27] L. Spitzer, Physics of Fully Ionized Gases, Interscience, 1957.

[28] O. B. Firsov, Fizika plazmy i problema ypravlyaemykh termoyadernykh reaktsiĭ (Plasma Physics and the Problem of Controlled Thermonuclear Reactions), Vol. III, Moscow, 1958, p. 327.

[29] S. Yu. Luk'yanov, and I. M. Podgornyĭ, JETP **37**, 27 (1959), Soviet Phys. JETP **10**, 18 (19601

[30] I. M. Podgornyĭ and V. N. Sumarokov, Nuclear Fusion, 1962, Supplement Vol. I, p. 87.

[31] S. Yu. Luk'yanov and I. M. Podgornyĭ, Atomnaya énergiya **11**, 336 (1961).

[32] J. Tuck, Phys. Rev. Letters **3**, 313 (1959).

[33] I. M. Podgornyi and V. N. Sumarokov, Nuclear Engineering **C1**, 236 (1960).

[34] L. L. Gorelik et al., DAN SSSR **147**, 576 (1962), Soviet Phys. Doklady **7**, 102 (1963).

[35] J. E. Osher, Phys. Rev. Letters **10**, 124 (1963).

[36] J. Tuck, preprint (1963).

[37] I. M. Podgornyĭ and V. N. Sumarokov, ZhTF **34**, 833 (1964), Soviet Phys. Technical Physics **9**, 635 (1964).

Translated by H. Lashinsky