PLASMA CONFINEMENT IN A TRAP WITH A MAGNETIC FIELD THAT INCREASES TOWARD THE PERIPHERY

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The behavior of a plasma with a density of $10^{13} - 10^{14}$ cm^{-3} in a trap with a magnetic field that increases toward the periphery has been investigated. Ultrahigh-speed photographs show that plasma instabilities in such traps reduce the containment time.

THE present work is an extension of investigations which have been published earlier concerning the behavior of plasma in magnetic traps with fields which increase toward the periphery.[1,2] It has been shown in these investigations that the system can be filled with plasma by means of a coaxial electrodynamic injector which accelerates bunches of hydrogen plasma. The lifetime of the plasma formed in this way is of the order of tens of microseconds. The experiments described below have been carried out primarily for the purpose of investigating the effect of the mode of operation of the injector on the concentration of charged particles in the trap; in addition, it was desired to obtain information concerning the shape of the plasma formation in the trap as a function of time.

The first set of the experiments was carried out with a trap for accelerated bunches (TAB-1); the vacuum chamber of this system is stainless steel and is 100 cm high and 21 cm in diameter. The appropriate magnetic field configuration is obtained by connecting two solenoids, mounted on the vacuum chamber, in opposition. The maximum magnetic field in the gap between the coils is 1500 oe. The chamber pressure is $1 - 2 \times 10^{-6}$ mm Hg. The results reported below have been obtained with a 2.5-μF capacitor bank in the coaxial injector circuit[2,4]; the condenser-bank voltage was varied from 3 to 11 kv.

A Langmuir probe is used to measure the plasma parameters. The molybdenum cylindrical probe is placed at a point of zero magnetic field; the surface area of the probe is 0.6 mm^2. Various potentials (with respect to the chamber walls) are applied to the probe and the probe current as a function as time is observed by means of a pulsed oscilloscope.

In Fig. 1 we show a typical oscillogram of the saturation ion current to the probe with the solenoids in operation; the magnetic field in the gap between the coils is 1000 oe. It is apparent from this oscillogram that the plasma remains in the trap for a considerable period of time after the discharge current in the injector circuit no longer flows. The plasma containment time, i.e., the time during which the current to the probe falls off by a factor of e, is approximately 40 μsec in this case.

Conventional methods have been used to determine the electron temperature and the concentration of charged particles from the probe characteristics. In the experiments described here it was difficult to plot the probe characteristics because of the poor reproducibility of the oscillograms; hence, each point on the probe characteristic represents an average of 5 measurements.

In carrying out these experiments measures were taken to avoid arc discharges at the probes. Arcs are sometimes produced when a negative potential is applied to the probe, and these arcs cause considerably distortion of the oscillograms; in order to avoid arcs the probe is first processed for a long time in a discharge.

The probe measurements show that the charged-particle density in the trap increases rather rapidly as the injector voltage is increased. This behavior is illustrated in Fig. 2, which shows the ion saturation current at the probe J as a function of injector voltage. It is well known that J is proportional to the ion concentration if the temperature of the charged particles remains constant. Measurements carried out at two values of the injector voltage ($V_1 = 8$ kv and $V_2 = 11$ kv) indicate that the electron temperature does, in fact, remain essentially constant; in both cases the electron temperature (in energy units) is approximately 10 ev. Thus, the curve in the figure essentially represents the ion concentration in the trap as a function of injector voltage. The maximum plasma density (at V = 11 kv) is approximately 2×10^{13} cm^{-3}. It will be obvious that the absolute value of the charged-particle density quoted here must be used with

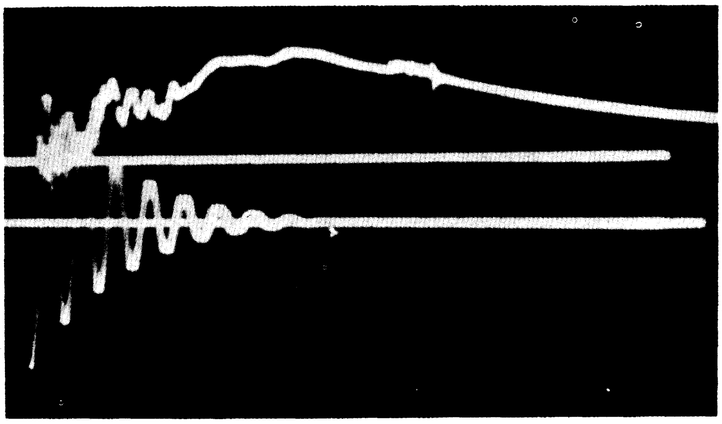

FIG. 1. The upper trace is an oscillogram of the ion probe current with the magnetic field on. The lower trace is the discharge current in the injector circuit. The sweep length is approximately 75 μsec.

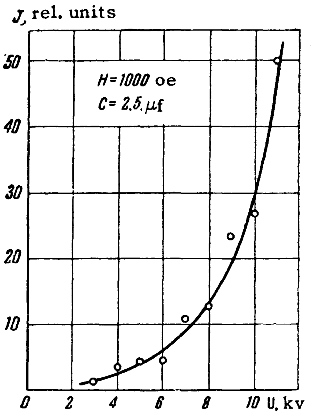

FIG. 2. The saturation ion current J as a function of the initial injector voltage U.

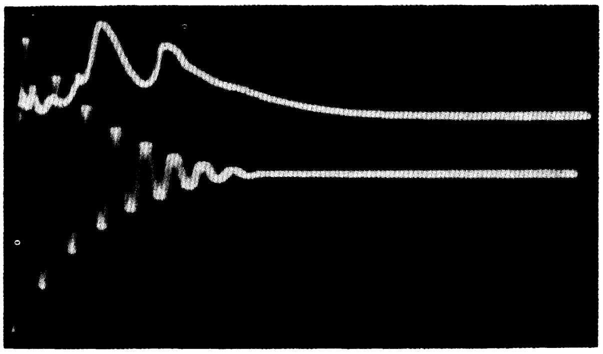

FIG. 3. The upper trace is the ion probe current with no magnetic trapping field. The lower trace is the current in the injector circuit. The sweep length is approximately 75 μsec.

care. When either one or both of the solenoids are inoperative, i.e., in the absence of a trapping magnetic field, the vacuum chamber is not filled by plasma. Figure 3 shows the probe current obtained with the solenoids disconnected. In this oscillogram the gain of the system has been increased by a factor of thirty as compared with that used in the oscillogram shown in Fig. 1. A comparison of both oscillograms indicates once again that the plasma containment time in traps of this kind is of the order of tens of microseconds.

The shape of the plasma formation in the trap at different stages of the process has been investigated by taking pictures with an ultrahigh-speed movie camera. We may note that the photographic method was first used for studying the behavior of a plasma injected into a magnetic trap from a low power titanium-hydride source by Finkelstein et al.[5] In these experiments no time sweep was employed so that the behavior of the plasma as a function of time could not be investigated.

The TAB-1 system is not convenient for plasma photography because of the small size of the viewing windows in the chamber walls. For this reason, a small magnetic trap with a glass vacuum chamber (Fig. 4) was built for the ultrahigh speed photography. The magnetic field is produced by passing a current pulse through the coils shown in the diagram. The duration of the magnetic field pulse is 2000 μsec while the magnetic field in the region of

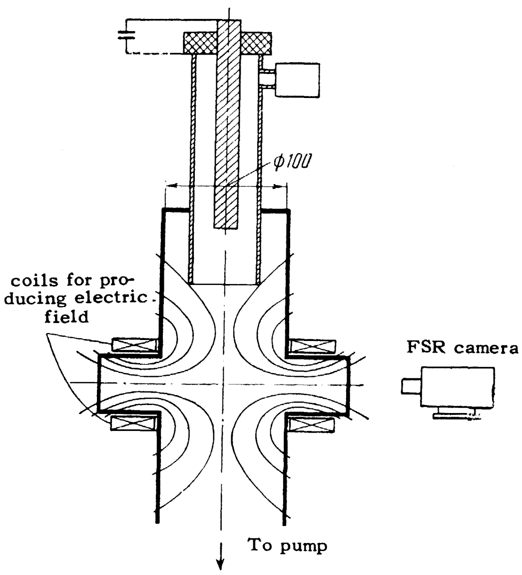

FIG. 4. Diagram of the magnetic trap designed for ultrahigh-speed movie photography of injection, capture, and plasma containment.

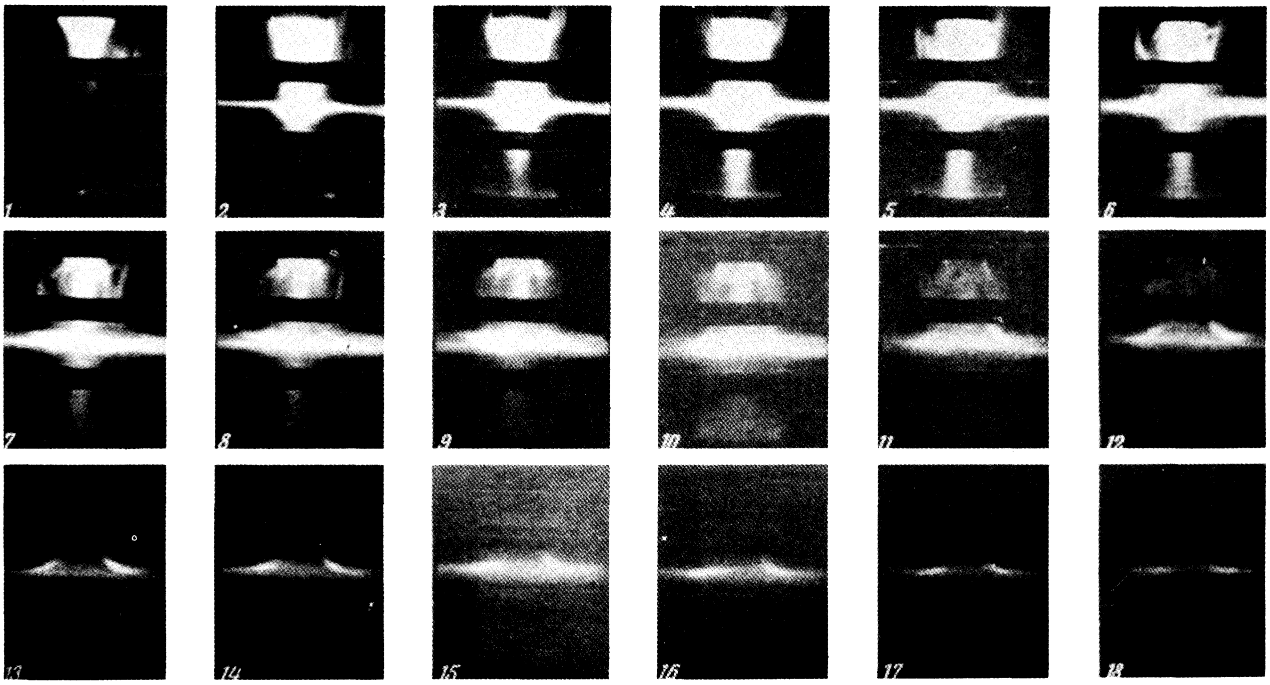

FIG. 5. Results obtained by ultrahigh-speed movie photography of the plasma with a magnetic trapping field. "Normal" plasma behavior. The time interval between frames is 4 μsec.

the magnetic gap is 6000 oe. The construction of the injector is the same as before; however, to increase the intensity of the emission in the trap the distance between the center of the trap and the injector is reduced considerably. For the same reason the capacity of the condenser bank is increased to 3.6 μf while the initial voltage is increased to 14 kv. Because low-inductance feeders are used there is no increase in the oscillation period of the discharge current in the injector. The injector condenser bank is discharged when the magnetic field approaches the peak value.

An SFR camera is used for ultrahigh-speed photography of the discharge; the synchronizing pulse from this camera makes it possible to switch on the magnetic field supply at the required time and also serves to trigger the discharge in the injector. In Fig. 5 we show photographs of injection and plasma capture in the trap obtained at 5×10^5 frames per second. In order to conserve space, we have shown frames separated by a time interval of 4 μsec (the intermediate photographs are not shown). The first frame shows clearly the plasma flow toward the magnetic "barrier"; in this frame one can also see weak emission from the surface from the lower flange of the chamber caused by the heavy fast particles which are produced in the operation of the electrodynamic injector. The energy of these particles is apparently so high that their trajectories are not affected in passing through the magnetic field of the trap.

As is to be expected, the radial dimensions of the plasma flow are reduced as it penetrates into the region of strong magnetic field. After passing through the magnetic barrier, the plasma is concentrated in the central portion of the trap; part escapes along the symmetry axis of the system. The plasma which is captured in the trap becomes a disc-shaped body of rotation. As is apparent from the photographs, this plasma formation exists stably for the entire lifetime of the plasma in the trap. The sharp boundary of the emission from the surface of the glass wall of the chamber serves as an indication of the width of the magnetic "gap" through which charged particles escape from the system.

The subsequent frames indicate that the plasma is contained in the trap for a time of the order of tens of microseconds after the injector ceases to operate. This result is in agreement with data obtained with probe and photoelectric measurements.

In an earlier work[2] the dependence of gap width on magnetic field was investigated by a calorimetric method. The results of the experiments were found to be in agreement with a classical mechanism for plasma diffusion across the magnetic field. A shortcoming of these data is the lack of information concerning the time behavior of the plasma diffusion processes. The images of the plasma formation obtained in these frames allow us to measure the width of the gap at different times.

It is reasonable to associate the experimentally observed gap expansion with the diffusion of plasma across the magnetic field. Using the formula for the width of the magnetic gap[3], we can make a rough estimate of the mean concentration of charged particles n from a knowledge (even if inaccurate) of the electron temperature in the plasma. Using the magnetic field indicated above and an electron temperature of 10 ev, we find $n \sim 3 \times 10^{14}\ \text{cm}^{-3}$. This value of plasma density corresponds to an experimentally measured gap expansion of 5 mm in a time ranging from 10 to 25 μsec from the beginning of the process.

In Fig. 6 we show frames obtained under the same conditions as before but with the magnetic field switched off. The intense emission from the inner surface of the flanges and the walls observed in these photographs indicates that the plasma is able to escape to the walls easily; that is to say, the plasma is not contained.

It should be noted that stable plasma containment is not by any means observed in all cases in which there is a trapping field. On the contrary, there is frequently a marked distortion of the plasma formation; at certain stages of the process the plasma escapes via paths other than the magnetic gaps. Fig. 7 shows photographs which illustrate this anomalous plasma behavior. In this case the plasma lifetime is somewhat shorter than in the case shown in Fig. 5. It should be emphasized that both pictures were obtained under the same experimental conditions, with the same value of magnetic field and injector voltages and with the same neutral gas flow from the valve into the in-

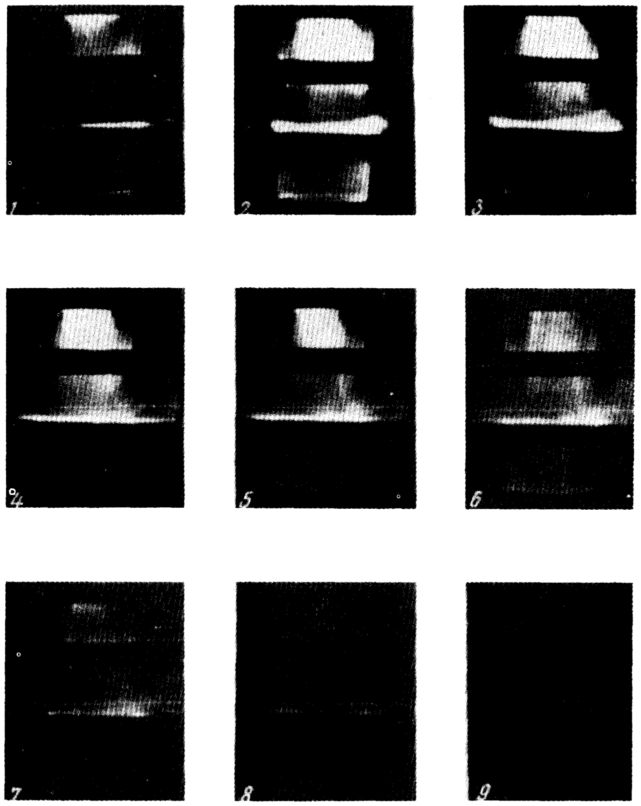

FIG. 6. Results obtained by ultrahigh-speed movie photography of the plasma with no magnetic field. The time interval between frames is 4 μsec.

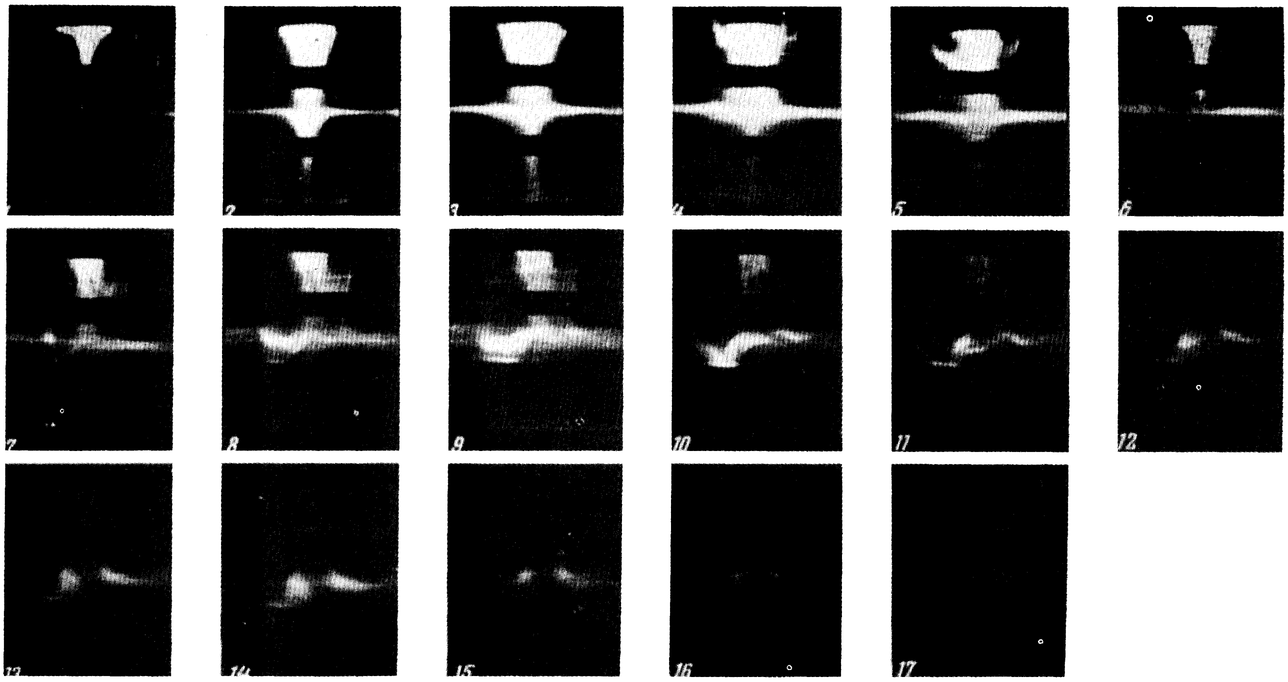

FIG. 7. Results obtained by ultrahigh-speed movie photography of the plasma with a magnetic trapping field. "Anomalous" plasma behavior. The time interval between frames is 4 μsec.

jector. Whether the observed effect is a manifestation of some kind of macroscopic instability or whether it is related to the method used to fill the trap with plasma can only be determined by further experiments.

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