INJECTION OF A PLASMA FROM A POWERFUL PULSED DISCHARGE INTO VACUUM

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Experiments are described in which plasma is ejected from a powerful pulsed discharge in hydrogen. The plasma parameters are investigated under various conditions of operation of the injector by photographic, photoelectric, and thermal probe methods. A plasma formation containing a total of the order of 10^{16} charged particles is shown to move in vacuum with a velocity $\sim 10^7$ cm/sec. The injection time is 2—5 μsec.

1. INTRODUCTION

THE interaction between a plasma and a magnetic field as well as the injection and confinement of a plasma in magnetic traps has been the subject of many investigations.[1-6] The behavior of a plasma inside a trap is determined in many respects by the properties of the plasma injector. The main parameters of a moving plasma, such as its velocity, temperature, and density, must be determined experimentally. It is equally important to choose an injector that ensures control of these parameters within certain limits. The electrodynamic coaxial accelerators described in the literature[7,8] can generate within several microseconds, under normal conditions, up to 1 cm^3 of hydrogen plasma moving in vacuum at velocities $5 \times 10^6 - 1.5 \times 10^7$ cm/sec.

The temperature of the particles forming an accelerated plasma layer apparently does not differ greatly from the temperature of the plasma produced during the earlier stages of development of a high-power pulsed discharge in cylindrical chambers.[9] It is impossible to increase appreciably the conductivity of the plasma in such a system ($\sigma \sim 10^{13}$ cgs esu).

Certain interest is attached to experiments on the production of a cumulative jet by contracting a conical plasma sheath.[10,11] When the jet moves in hydrogen at a gas pressure 0.2 mm Hg, the glow propagates at about 1×10^7 cm/sec.[11] However, it is difficult to estimate the properties of the plasma emerging from such a system into vacuum without special experiments.

Vasil'ev et al[12] demonstrated the possibility of obtaining a long lived (up to 40 μsec) dynamically stable current pinch. The plasma jets thus formed moved in hydrogen at a pressure 0.1 mm Hg with a velocity $\sim 5 \times 10^6$ cm/sec. Such a system can obviously be used as a plasma injector, although, just as in the preceding case, no data are given on the parameters of the "fountain pinch" propagating in the free space.

Plasma sources based on a different principle[13-15] have ejected plasmoids with velocity $\sim 1 \times 10^7$ cm/sec. The plasma itself, however, was of indefinite composition and, as a rule, of low temperature and density.

In the study of the interaction between a magnetic field and a high-conductivity plasma, such constructions are apparently of little use. In this case the systems of interest are those producing streams of pre-heated plasma.

It is known that during the instant of maximum contraction of the current pinch in a powerful pulsed discharge a certain amount of hot plasma with parameters $n = 10^{17}$ cm^{-3} and $T_i = 100$ ev[16] is produced on the chamber axis. This suggests the attractive idea of extracting such a plasma from the discharge zone into the vacuum. The present paper is devoted to an experimental investigation of such ejection.

If the plasma current pinch is strongly overcompressed, say with a diaphragm, then the self-magnetic forces of the current will produce an excess pressure at the pinch contraction. The pressure drop along the axis will tend to become equalized by the macroscopic plasma flow.[17,18] Filippov et al[19] have noted in an investigation of a pulsed hydrogen discharge in a chamber with conducting walls that the contraction of the discharge towards the axis is not uniform over the entire height of the chamber, and begins at one of the electrodes. In this case a natural neck is formed, as it were, in the discharge channel, which should lead to the formation of an axial plasma stream. On the other hand, owing to the conical character of the compression, a certain amount of plasma can be captured in the axial cumulative jet. Experimental apparatus was therefore designed to verify these premises and to measure the parameters of the plasma ejected into vacuum. The experiments were carried out with two models of the apparatus, small and large.

2. EXPERIMENTS WITH THE SMALL MODEL

The character of discharge formation in a chamber with conducting walls and the effect of ejecting of the plasma from the discharge were investigated by optical means, using the small apparatus. Figure 1 shows the construction of the apparatus and the shapes of its various elements. The discharge chamber was made of a copper cylinder 1, on one end of which electrode 2 was mounted on a porcelain insulator. The second electrode comprised the lateral surface and the second end of the chamber. The process inside the chamber could be viewed through small holes in the side walls of the cylinder. Symmetrical placement of the holes prevented distortion in the formation of the discharge. The plasma was ejected through a 40 mm diameter hole 3 in the end of the chamber. To observe the ejection in the backward direction, a corresponding hole was drilled in the second electrode. In either case, the plasma stream detached from the discharge zone propagated further in glass chamber 4, the pressure in which was determined by the initial pressure in the discharge volume. The experiments were carried out in hydrogen at initial pressures ranging from 0.1 to 1.0 mm Hg.

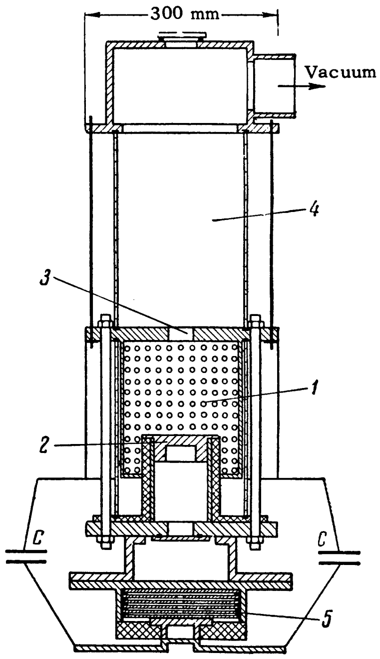

FIG. 1. Small model (explanation in text).

The discharge circuit was a 40 μf capacitor bank charged to 20—30 kv, with maximum discharge current 400 kiloamp. Switching was by means of vacuum discharge gap 5.

Motion pictures of the discharge taken with an SFR high-speed camera confirmed the predicted assumptions concerning the plasma ejection. Figures 2 and 3 show by way of an example certain frames taken at intervals $\tau = 0.5$ μsec apart at different initial hydrogen pressures and at different capacitor-bank polarities (the outlines of the photographed object are shown for clarity on the left of the illustrations).

The experiments made with the small model lead to the following picture of the process: the discharge contracts towards the chamber axis unevenly both in time and in space. The bright central rod formed at the electrodes increases along the axis with a velocity close to 1×10^7 cm/sec. The diameter of the rod does not exceed 1.5—2 cm. After passing through the opening in the bottom of the chamber, the plasma jet con-

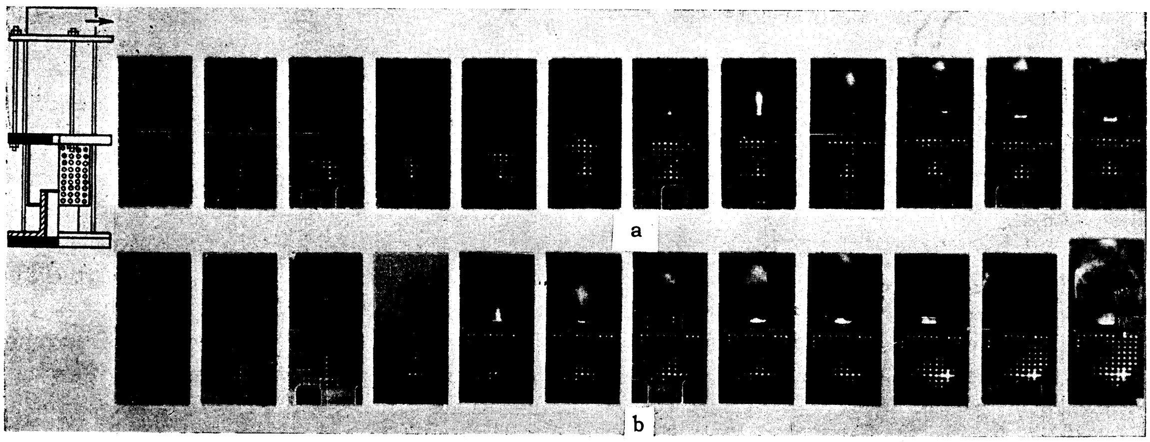

FIG. 2. High-speed motion pictures of plasma ejection from a discharge chamber with U = 30 kv, $P_0 = 0.1$ mm Hg: a – on positive electrode, b – on negative electrode.

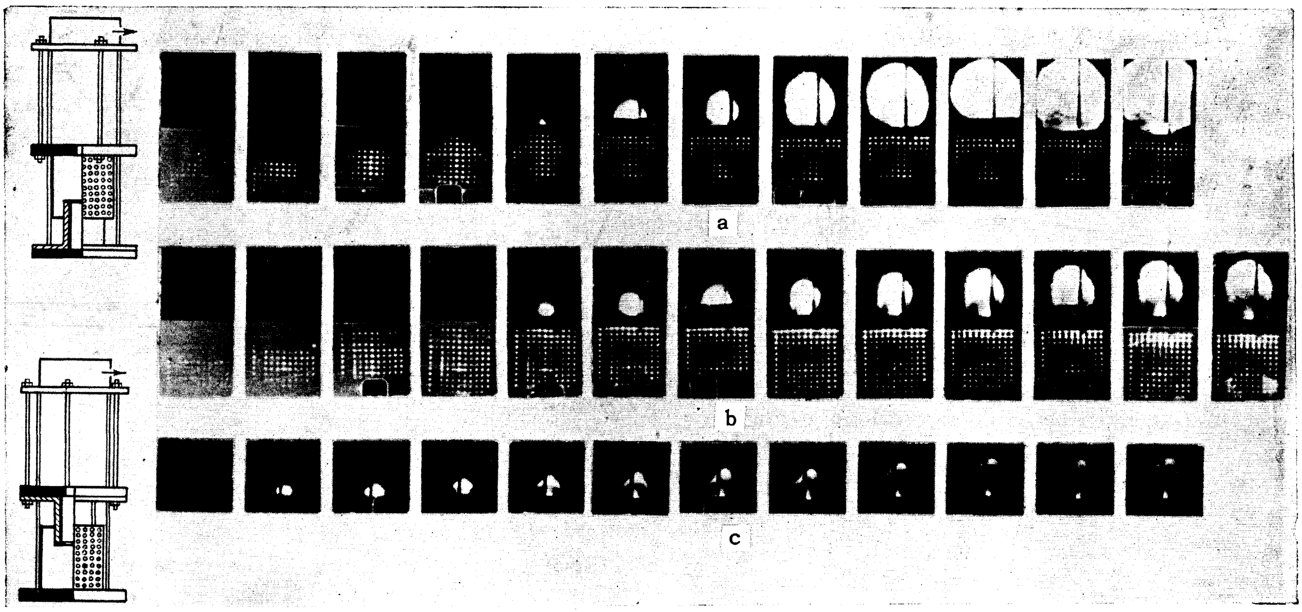

FIG. 3. Motion pictures of plasma ejection (U = 30 kv and P_0 = 1 mm Hg): a – on negative electrode, b – on positive electrode, c – ejection towards the electrode (V = 30 kv, P_0 = 0.1 mm Hg)

tinues to move outside the discharge zone. Plasma is also ejected in the opposite direction.

We recall that the plasma jet propagates in hydrogen at a pressure equal to the initial pressure in the discharge chamber, i.e., at P = 0.1–1.0 mm Hg. Calculation shows that the characteristic time for charge exchange with molecular hydrogen under similar conditions is $\sim 10^{-7}$ sec. Since the ejection time was several microseconds, much of the moving plasma was under these conditions the product of interaction between the primary plasma and the residual gas. These difficulties were overcome to some extent in the investigations made with the second, large experimental model.

3. EXPERIMENTS WITH THE LARGE MODEL

A diagram of the apparatus is shown in Fig. 4. Unlike the small model, the discharge chamber was separated from the observation chamber by two diaphragms with holes 5 and 10 mm in diameter. The space between the two diaphragms was evacuated with a BNM-1500 booster pump. The vacuum chamber was pumped out with a VNM-2000 diffusion pump. The differential pumping produced in the observation chamber a vacuum sufficient to make the charge exchange negligible. The pressure drop in both chambers was 1:2000 and remained approximately constant as the pressure in the discharge chamber was varied from 0.1 to 1.0 mm Hg. The distance from the diaphragm to the point of observation was too large to be covered by contamination from the diaphragm edges during the lifetime of the plasma jet.

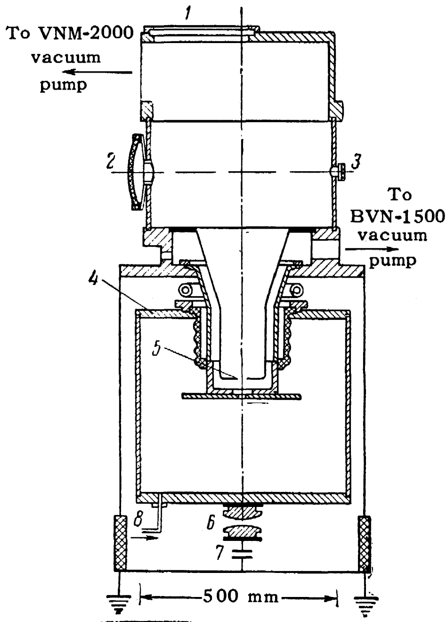

FIG. 4. Large model: 1, 2, 3 – viewing windows, 4 – discharge chamber, 5 – diaphragms, 6 – discharge gap, 7 – capacitor bank, C = 80μf, 8 – gas inlet

The rating of the discharge bank was C = 80 μf, and the charging voltage was 30–40 kv. The current at the maximum was about 500 kiloamp at an initial build-up rate of about 1×10^{11} amp/sec.

Attempts to use photographic methods failed because of the low brightness of the plasma moving in the vacuum. Only a photoelectric procedure in conjunction with thermal sounding made it possible to determine the dimensions of the plasmoid, the density of the charged particles in it, and its translational velocity.

The determination of the velocity by measuring the shift of the maxima of like pulses needs no special explanation. To illustrate the determina-

FIG. 5. Oscillogram of H_β line glow.

tion of the plasma velocity from the transit time, Fig. 5 shows an oscillogram corresponding to the H_β line, registered by two photoelectric receivers placed 15 cm apart in the direction of the plasma motion. Each receiver consisted of a UM-2 monochromator and an FÉU-12 photomultiplier, the collector signal of which was amplified and applied to the plates of an OK-17M double-beam oscilloscope.

Let us discuss the thermal sounding method in greater detail. The thermal probe was a copper-constantan thermocouple, on which was fastened an energy receiver in the form of a platinum foil 6 μ thick. The foil dimension was 8 × 8 mm. Such a probe, when placed in a particle current, registers the total energy transferred from these particles to the receiver. The thermal emf produced upon heating of the junction was measured with an M-95 millivoltmeter, with one scale division corresponding to $\sim 3 \times 10^2$ ergs transferred to the receiver. Knowing the time of interaction between the plasma current and the thermal probe, it is possible to estimate the plasma density averaged over this time interval.

An exact quantitative interpretation of the data obtained is a rather complicated matter, particularly when it comes to determining absolute quantities. However, control experiments set up to determine the role of the extraneous factors in the heating of the thermocouple have shown that this heating is due essentially to the moving protons of the plasma. During the course of the control experiments small ($\sim$ 1000 oe) magnetic fields were produced with the aid of coils placed directly in the vacuum. It was thus possible to show that the light radiated and the possible flow of neutral particles make a negligibly small contribution to the observed effect. In the data reduction it was assumed that the plasma particles give up all their energy as they collide with the surface of the heat receiver.

Using a system comprising several thermal probes placed along the radius of the chamber, data were obtained on the radial distribution of the particle current. The system was displaced along the chamber axis, and the distribution pattern could be studied at different distances from the diaphragm. In addition, three thermal probes were placed in the chamber, oriented to measure the axial, radial, and azimuthal energy fluxes at different distances from the diaphragm. Assuming that in the latter case the energy transferred was determined by the thermal motion of the plasma, we can draw certain qualitative conclusions concerning the ion temperature in the plasmoids.

Table I lists the plasma velocities V_z and the injection times $\Delta\tau$ for different injector operating modes and different chamber pressures, with C = 80 μf and U = 35 kv.

It should be noted that the modes of greatest interest are those in which the injection is in pulses ranging from 1.5 to 5 μsec (C = 80 μf, U = 16 kv, P_0 = 0.2 mm Hg). An illustration is Fig. 6, where the light pulse registered by a collimated photoelectric receiver is phased with the discharge current. In other cases, particularly at large capacitor-bank voltages and considerable initial pressures (up to 1 mm Hg), the light pulse is strongly stretched out (see Fig. 7, for which C = 80 μf, U = 35 kv, P_0 = 1 mm Hg). This apparently points to repeated additional discharges inside the chamber, leading to additional ejection of the plasma through the diaphragms. The photoelectric and thermal-sounding research methods do not yield in this case any definite conclusions concerning the translational velocity and density of the charged particles.

Figure 8 (P_0 = 1 mm Hg) shows the characteristic curve of radial distribution of a plasma current inside a vacuum chamber, from which we can

FIG. 6. Oscillogram of light pulse from plasma moving in a vacuum, phased with the current in the discharge chamber.

Table I

Injection direction	towards electrode						away from electrode		
Polarity of electrode	−			+			−		
P_0, mm Hg	0.1	0.2	0.5	0.1	0.2	0.5	0.1	0.2	0.5
$V_z \cdot 10^{-7}$, cm/sec	2.2	2.2	1.4	2.5	2.8	—	0.8	0.6	0.5
$\Delta\tau$, μsec	1.4	1.5	2.2	1.6	1.1	—	5	5	4

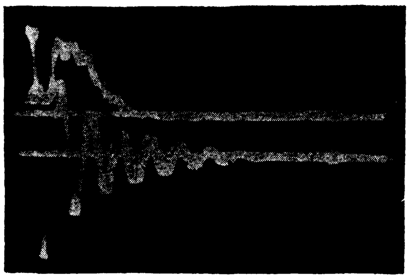

FIG. 7. Oscillogram of stretched-out light pulse.

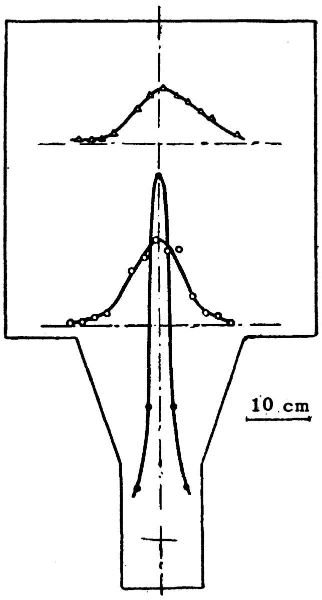

FIG. 8. Distribution of the density of a plasma moving in vacuum, at different distances from the diaphragm (the lower distribution curve is drawn to a scale 1:2).

estimate the localization of the plasma in free space. We give the values of the charged-particle density n, obtained by thermal-sounding measurement with heat receivers placed at different distances from the diaphragm:

Distance from upper diaphragm, cm:	6	35	54
Density of charged particles $n \times 10^{-13}$, cm^{-3}:	38	5,0	4.0
Total number of charged particles, $N \times 10^{-16}$:	3,8	4.0	3,8

A characteristic feature is that the total number of particles N, measured at different distances from the diaphragm, remains constant, within the measurement accuracy limit, thus showing that few particles are lost by the plasmoid as it moves along the chamber axis. Data on the number of protons injected into the vacuum in each discharge under different initial conditions and on the density of the charged particles, obtained under these conditions in the central section of the chamber, are summarized in Table II.

A rough estimate of the ion temperature of the plasmoid, based on experiments with differently oriented heat receivers, yields $T_i = 5 \times 10^5$ deg K.

4. CONCLUSIONS

1. The effect of injection of a certain amount of plasma into vacuum from a pulsed discharge in hydrogen has been experimentally demonstrated. It is shown that the plasma is ejected in two opposite directions along the discharge axis.

2. Operating conditions have been determined, under which the system can inject plasma in the form of individual pulses lasting 2—5 μsec. The length of the plasmoid is in this case 30—40 cm.

3. Photoelectric and calorimetric measurements yielded the total number of particles injected per pulse, an estimate of the density, and the axial velocity of the plasma. The following values in these experiments were obtained for the parameters in various modes: $N = 8 \times 10^{16}$, $n = 6 \times 10^{13}$ cm^{-3}, $V_z = 2.8 \times 10^7$ cm/sec.

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Table II

Injection direction	from electrode		towards electrode			
Polarity of electrode	—	—	—	—	+	+
Electric parameters	C=16 μf U=36 kv	C=80 μf U=16 kv	C=80 μf, U=36 kv			
P_0, mm Hg	0.2	0.2	0.2	1.0	0.2	1.0
Total number of particles injected per pulse	$4 \cdot 10^{16}$	$8 \cdot 10^{16}$	$4 \cdot 10^{14}$	$4 \cdot 10^{16}$	$8 \cdot 10^{14}$	$2 \cdot 10^{16}$
Plasma density 35 cm away from the diaphragm	$1 \cdot 10^{13}$	$3 \cdot 10^{13}$	$1 \cdot 10^{12}$	$5 \cdot 10^{13}$	$2 \cdot 10^{12}$	$6 \cdot 10^{13}$

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