Generation of intense fluxes of negative ions

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(Submitted 27 September 1982)
Zh. Eksp. Teor. Fiz. **84**, 2040–2045 (June 1983)

A coaxial diode with magnetic insulation has been used to obtain experimental values of the radial flux of negative H^- ions with energy 500–700 keV with a current up to 5 kA and current density comparable with the Langmuir limit. Magnetic insulation of the electrons was accomplished by an axial magnetic field of strength 15 kG. To separate the currents of negative ions and electrons we chose a special diode configuration with a drift space and diversion of the electron current from the shunt measuring the ion current. Part of the ion current was measured by the nuclear activation method. The sign of the charge of the ions was determined from their deflection in the magnetic field. For a fixed direction of the magnetic field we measured the asymmetry in activation of sections of a graphite target by ions which had passed through slits in the anode and were deflected in different directions in azimuth, depending on the sign of the charge. Experiments on production of negative ions were carried out for two-component flows (e–H^-) and three-component flows (e–H^-–H^+). In the latter case a thin dielectric film was placed on the anode and served as a source of positive ions. The data of the electrical measurements are in good agreement with the data of the nuclear measurements, but exceed the calculated values by several times. Possible causes of these discrepancies are discussed.

The production of intense fluxes of negative ions of hydrogen and heavier elements presents substantial interest. By efficient stripping it is easy to obtain from them powerful beams of neutral atoms which are suitable among other things for heating plasma in magnetic traps. In a number of cases, for example in transport and ballistic focusing onto a target in inertial schemes for controlled thermonuclear fusion, neutral beams have indisputable advantages over quasineutral beams where apparently one cannot avoid microfluctuations of the potential of the electrostatic field due to the beam itself, which results in poorer beam emittance. Finally, methods of charge-exchange injection which have been developed open the way for subsequent pre-acceleration of the ion beam, including acceleration in tandem high-current arrangements which remove the limitations associated with high-voltage technology.

Conversion to positive-ion beam generation based on the physics of high-current high-voltage diodes[1] has required a certain psychological barrier to be overcome, but in the course of several years has permitted the intensity to be increased by several orders of magnitude, bringing it up to pulsed currents of mega-amperes. It appears to us to be natural and opportune to attempt to take a similar step in application to negative ions. We note that in the best negative-ion sources of traditional type the maximum currents of H^- ions do not exceed a few amperes, and the current densities are $\lesssim 0.1\ \mathrm{A/cm^2}$, (Refs. 2 and 3).

An important parameter of plasma sources of negative ions is the ratio λ of the equilibrium concentrations of ions and electrons. Unfortunately, experimental data on the plasma produced as the result of explosive emission at the cathode of a high-current diode are unreliable and do not permit evaluation of the equilibrium concentrations even in order of magnitude. In any case, estimates made according to a simple scheme[3] show that λ can change from 10^{-5} to 10^{-2} with small variations of the assumed plasma parameters, especially the temperature, which corresponds as a rule to the region near the threshold of numerous charge-exchange reaction channels.

Rough experimental data on the composition of the near-cathode plasma can be obtained from analysis of the data of Ref. 4, in which the composition of the current loss in a line with magnetic insulation was studied. Proceeding from the assumption of thermodynamic equilibrium, the ratio of the concentrations, for parameters typical of the case of explosive emission, can be taken to be at the level $\lambda \approx 5\cdot 10^{-2}$. As will be evident below, this value is completely adequate to obtain currents comparable with the Boguslavskiĭ-Langmuir limiting current.

For calculation of the current limitation due to the combined action of the space charge of the electrons, negative ions, and possibly colliding positive ions, we shall consider a planar diode formed by two parallel conducting planes which are at a distance d from each other. The diode is placed in an external uniform magnetic field B_0 parallel to the electrodes. Assuming that the electron and ion flows are uniform in the y and z directions, that the ions cross the interelectrode gap traveling in a straight line in the x direction, and that all the emitted electrons return to the cathode (magnetic insulation for electrons), we obtain the following system of equations which describes the equilibrium states of the flows[5]:

$$\frac{d^2\gamma}{d\xi^2}=\frac{\partial\Psi}{\partial\gamma},\quad \frac{d^2A}{d\xi^2}=-\frac{\partial\Psi}{\partial A},\tag{1}$$

where the function Ψ involves additive terms which describe

 0038-5646/83/061188-04$04.00

the space charge of the electrons and negative ions emitted from the cathode and the positive ions emitted from the anode (the electrons return to the cathode and consequently the density of their charge is doubled):

$$\Psi=\begin{cases}(\gamma^2-1-A^2)^{1/2}+2\lambda(\gamma-1)^{1/2}\\ +(j^+/j_e)(\mu/2)^{1/2}(\gamma_0-\gamma)^{1/2}, & 0\leqslant\xi\leqslant\xi_e\\ 2\lambda(\gamma-1)^{1/2}+(j^+/j_e)(\mu/2)^{1/2}(\gamma_0-\gamma)^{1/2}, & \xi_e\leqslant\xi\leqslant\xi_0\end{cases}.$$

Here $\gamma(\xi)$ is the relativistic factor of the electrons, which in the present case plays the role of the electrostatic potential, $A(\xi)$ is the component of the vector potential in units of mc^2/e, $\xi=(8\pi e j_e/mc^3)^{1/2}x$ is a dimensionless transverse coordinate, ξ_e is the boundary of the electron layer, ξ_0 is the coordinate of the anode, $\gamma_0=\gamma(\xi_0)=1+eV/mc^2$, V is the voltage on the diode, and j_e and j^+ are the current densities of emission of electrons from the cathode and of positive ions from the anode which must be determined from the conditions of current limitation by space charge:

$$(d\gamma/d\xi)_{\xi=0}=0,\quad (d\gamma/d\xi)_{\xi=\xi_0}=0. \tag{2}$$

If there is no emission of positive ions from the anode, then the second of the conditions (2) is unnecessary. The current density of negative ions, which presents the main interest, is simply expressed in terms of j_e and the ratio μ of the electron and ion masses,

$$j^-=\lambda j_e(\mu/8)^{1/2}.$$

The boundary conditions for the vector potential in a diode with magnetic insulation can be of two forms. If the diode electrodes are transparent for the magnetic field of the beam, then

$$A(0)=0,\quad (dA/dx)_{\xi=\xi_0}=B_0e/mc^2. \tag{3}$$

However, if the current pulse is short and the magnetic flux is frozen inside the diode, then

$$A(0)=0,\quad A(\xi_0)=B_0de/mc^2. \tag{4}$$

The experiment described below was closer to the conditions (4), and the calculation was carried out with these conditions.

In Fig. 1 we show the calculated volt-ampere characteristics of an e–H^- diode (solid lines) for $\lambda=0.05$ and various values of B_0d. For comparison in the same figure we show the Langmuir limit for a one-component ion flow. In the region of small magnetic fields and voltages where the ion current is much less than the limiting value, it turns out to be directly proportional to the parameter λ. It is easy to see that already at a relatively small magnetization of the diode ($B_0ed/mc^2=1$ corresponds to $B_0d\approx1.7$ kG · cm) the achievable current density of H^- ions is rather high, although less than the limiting value, and therefore the exact value of λ turns out to be uncritical for experiments.

Inclusion in the calculation scheme of positive ions, which upon production of an anode plasma can travel in the direction opposite to the negative ions, naturally increases the current of H^-. The results of the calculation show (Fig. 1, dashes) that a rapid increase of the current of negative ions is observed in weakly magnetized diodes when the thickness of the electron layer exceeds half of the interelectrode distance.

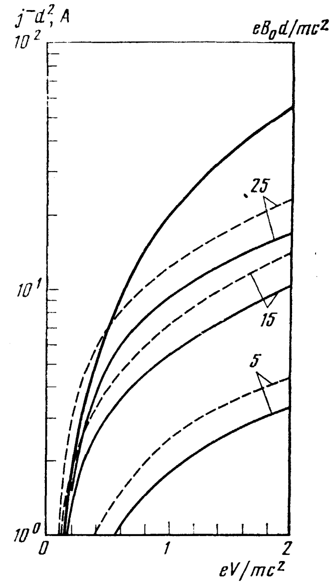

FIG. 1. Volt-ampere characteristics of two-component e–H^- diode (solid lines) and three-component e–H^-–H^+ diode (dashed lines) with magnetic insulation for the negative ions. The upper curve corresponds to the Langmuir limiting current for a one-component ion flow.

The experimental realizationof the scheme described is hindered by the uncertainty of the parameter λ. Although the exact value of λ is not so important, it must be sufficiently large for achievement of a current close to the limiting value. If we consider a limiting current density in the neighborhood $j^-\approx15$ A/cm^2 in a pulse of duration 100 nsec, then about 10^{13} particles should be carried away from the cathode. To avoid short-circuiting the plasma of the interelectrode gap ($d\lesssim1$ cm) it is necessary to assume an initial thickness of the cathode plasma layer of no more than 0.1 cm. Taking for the maximum content of H^- ions in the near-cathode plasma $5\cdot10^{-2}$, we obtain for the density of the near-cathode plasma the estimates 10^{15} cm^{-3}, and for the density of neutral gas in the layer 10^{16}–10^{17} cm^{-3}. At the present time the most appropriate means of obtaining such a plasma is breakdown along the surface of a dielectric, similar to what is done in generation of high-current beams of positive ions.[1] However, it msut be expected that the range of parameters of the plasma, in particular the temperature, which are optimal for generation of negative ions, will turn out to be somewhat narrower than for generation of positive ions. After testing several types of cathodes we settled on a metallic cathode covered with a layer of perforated polyethylene of thickness 1 mm. In contrast to film cathodes, cathodes of this type had a longer life and permitted sufficiently stable pulses of negative ion current to be obtained. A sufficient cathode life (about 10^2–10^3 pulses) is necessary in addition because to reach stable operation it must be aged for 15–20 pulses. The diameter of the cathode was 29 mm, that of the andoe 59 mm, and the length of the working region was 200 mm. The cylindrical anode had four slits which occupied half of its surface and were covered with a grid with 70% transparency. For magnetic insulation of the electrons we used an axial magnetic field of strength 15 kG produced by an external solenoid. The experiments were carried out at a

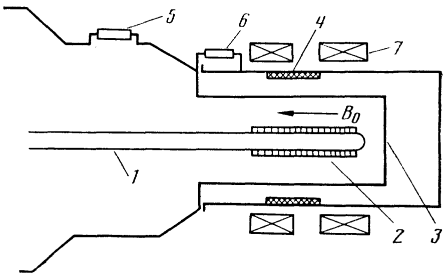

FIG. 2. Diagram of experiment on production of negative ions: 1—cathode rod, 2—cathode, 3—anode, 4—graphite target, 5—shunt for measurement of total diode current, 6—shunt for measurement of ion current, 7—solenoid.

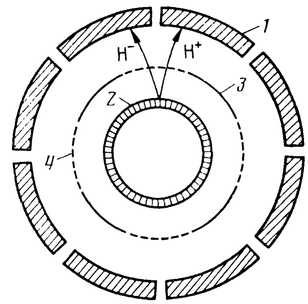

FIG. 3. Diagram of experiment on determination of the sign of the charge of the ions: 1—sectionalized graphite target, 2—cathode, 3—anode, 4—grid.

voltage on the diode 500–700 kV. The total diode current was 10–15 kA, and the greater part of it consisted of electron current to the end of the anode.

The main complication of the experiments consisted of reliable identification and determination of the current of negative ions. In a diode having the usual geometry the anode current is the sum of the current of the electron beam propagating along the lines of force of the magnetic field to the end of the chamber (the anode), the transverse current of negative ions, and the electron loss current resulting from nonideal magnetic insulation. For separation of the currents of negative ions and electrons we chose a diode geometry with a drift space between the anode and the chamber, and diversion of the longitudinal electron current from the shunt which measures the ion current (Fig. 2). Electrons with energy 500 keV have a Larmor radius 3 mm in a magnetic field of 15 kG and will return to the anode even if they are emitted into the drift space between the anode and the chamber. Experiments confirmed this assumption–on turning off the magnetic insulation, while the total diode current increased by several times, the transverse current changed insignificantly, within the spread from pulse to pulse.

To be sure that the current measured by the shunt is actually ionic, part of it was measured by the nuclear activation method. For this purpose we used a cylindrical sectionalized graphite target (diameter 79 mm, length 40 mm, 8 sections) surrounding the anode. In the experiments we used the reaction $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$ with $T_{1/2} = 9.96$ min and a threshold energy 457 keV. Annihilation γ rays were recorded by a pair-coincidence γ spectrometer. The duration of the pulse of ions with energy above the threshold for the present experiments was 10–60 nsec.

However, the nuclear diagnostics by themselves do not provide the possibility of determining the sign of the charge of the ions. First of all in the diode there can be positive ions accelerated to the anode on reversal of the polarity of the diode after the main pulse. Therefore we took measures to decrease and monitor the positive pulse, and in particular the working voltage was chosen in the near-threshold range 500–700 kV. In addition, it is impossible *a priori* to exclude also a hypothetical collective mechanism of acceleration of positive ions during the main pulse.[6] This hypothesis, however, is unlikely since in cases of cutoff of the magnetic insulation, when the current through the diode increased by several times and the conditions for collective acceleration could be optimal, there was no activation of the target.

Nevertheless direct monitoring of the sign of the charge of the ions was accomplished on the basis of their deflection in the magnetic field. It can be seen from Fig. 3 that the graphite target is cut into eight equal parts, and that the cut coincides in azimuth with the center of the gap in the anode. Negative ions traveling from the cathode to the target are deflected by the magnetic field and hit primarily the sections of the target with even numbers. The effectiveness of this device was checked with protons for a positive voltage pulse on the central rod. The activity of the target sections with odd numbers in this case was 30–50% greater than the activity of the sections with even numbers. Change of the direction of the magnetic field led to preferential activation of even sections.

The same experiments with a negative voltage pulse on the central rod showed that the activity of target sections with even numbers was 20–30% greater than of those with odd numbers. The not very large difference in the amount of activation is explained by the fact that the slits in the anode must be wide enough for sufficient activation of the target.

Experiments on production of negative ions were carried out for a two-component e–H^- flow and a three component e–H^-–H^+ flow. In the latter case we placed on the anode a thin dielectric film which served as a source of positive ions.

The results of the experiments with positive and negative ions are given in the table, where we have combined the data for the total currents and ion current densities recorded by means of the electric and nuclear methods of diagnostics. Conversion of the total current I and its density was accomplished on the assumption of uniform emission of ions from the working part of the cathode.

Since the theoretical calculations were carried out for a planar geometry while the experiments were in a cylindrical coaxial diode, a direct comparison of the absolute values of current densities is difficult. Therefore it is reasonable to compare not absolute values but their ratio to the Langmuir limiting current j_L calculated for the corresponding geometry.

As can be seen from the table, the data of the electrical measurements agree reasonably with the data of the nuclear measurements, but exceed the calculated values by several times. These discrepancies are explained by the motion of

TABLE I. 1: Results of experiments on ion production.

Ions (type of diode)	Nuclear diagnostics			Electrical diagnostics			Theory
	I, kA	j, A/cm^2	j/j_L	I, kA	j, A/cm^2	j/j_L	j/j_L
$H^+(e-H^+)$	9–15	50–85	3.3	12–16	70–90	4.5–3.5	1.0
$H^-(e-H^-)$	1.4–2.2	8–12	0.5	2–2.5	11–14	0.7–0.5	0.25
$H^-(e-H^--H^+)$	Not measured			4–5	22–28	1.4–1.0	0.35

the plasma away from the cathode, which leads to a decrease of the effective size of the accelerating gap. During the time of the pulse (≈ 100 nsec) a plasma moving across the magnetic field with a velocity $\sim 5\cdot 10^6$ cm/sec can overlap about half of the accelerating gap, which increases the Langmuir current and correspondingly the ion currents by 3–5 times. An argument in favor of this idea is the current density of positive ions obtained in the experiments, which also exceeds by 3–4 times the calculated value of the Langmuir current.

In addition, a difference in the data of the electrical and nuclear measurements may be due to the presence of impurities of heavier ions such as C^-, O^-, and the like. Separate studies will be required for determination of the mass composition of the beam.

Thus, in a high-current diode with magnetic insulation it is actually possible to approach the Langmuir limit and obtain in negative ions currents of 1.5–5 kA with current density ~ 10 A/cm^2, which is 2–3 orders of magnitude higher than the values obtained up to this time in classical sources. Obtaining a beam of parallel ions and measurement of its divergence will require changing from cylindrical and to planar geometry. However, since planar ion diodes with magnetic insulation have been well developed,[1,7] this step should not encounter fundamental difficulties.

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Translated by Clark S. Robinson