PECULIARITIES OF THE OPERATING REGIMES AND CHARACTERISTICS OF A TWO-STEP ACCELERATOR WITH AN ANODE LAYER WITH LOW VOLTAGES AND WEAK MAGNETIC FIELDS

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The characteristics of an accelerator with an anode layer (AAL) indicate that the efficiency of ionization and ion acceleration is high. At the same time, AAL have at least two characteristic regimes: the accelerator regime with optimal characteristics observed at high voltages and an anomalous regime, where the efficiency of the accelerator drops appreciably, and the beam is strongly focused [1].

There exist also other modifications of the regimes with appreciably different characteristics. The existence of an anomalous regime and its modifications for low voltages substantially limits the possibilities of AAL. The transition from one regime to another occurs when the parameters of the accelerator are changed (the accelerating voltage, magnetic field, etc.) and depends on the geometric dimensions of the channel of the accelerator and the magnetic system [2]. One element of the AAL is the ion source, in which the ionization and formation of the beam significantly affect the characteristics of the accelerator [3-5]. Preliminary studies of the operation of AAL at low accelerating voltages have shown that they have a number of peculiarities [4], which is of significant interest.

In this paper we describe the experimental results of a study of the operating regimes of AAL, the optimization of beam formation, and the characteristics of AAL at low voltages and with weak magnetic fields.

1. Description of the Power Supply Scheme, the Measurements, and the Experimental Conditions. The experiments were performed on a model of a two-step AAL whose construction is analogous to that described in [1, 4] and differs primarily by the geometric dimensions and length of the zone occupied by the strong magnetic field (the average diameter of the annular gap d = 200 mm, the interpole gap h = 30 mm, and the thickness of the poles δ = 3 mm).

In the course of the experiments the currents and voltages in the first (discharge) and second (accelerating) steps I_d, I_a, V_d, and V_a, the current at the collector I_{coll} and at the poles I_p, the solenoid magnetization current, and the current from the neutralizer I_{nr} were measured. These quantities were measured with an accuracy of 1.5%. Different modifications of the power supply and measurement schemes were employed (Fig. 1, where I is the traditional scheme with two power sources; II is the scheme with one power source; b, c, and d — the index of the scheme corresponds to the position of the switch). In the scheme I the anode-vapor distributor 1 together with the electrodes 2 form the first step of the accelerator, while the electrodes 2 and 3 form the second step. When the electrodes 2 are connected to the anode by placing the switch into the position b the basic scheme II is the scheme of the single-step AAL [6].

When the switch is in position c the electrodes 2 during accelerator operation are under a floating potential, while in the position d the potential of the electrodes 2 is fixed with the help of a capacitive voltage divider [7]. The anode and electrodes are placed in the interpole gap of the magnet system 4. The neutralizer 5 and the current collector are under the potential of the negative pole of the power source of the accelerator. The accelerator is placed in a vacuum chamber on a special weighing apparatus, making it possible to determine within 3% the reaction force of the beam F. Diffusion pumps were used to evacuate the chamber to a pressure of $5\cdot10^{-4}$-$1\cdot10^{-2}$ Pa.

The volume charge of the ions was compensated with an autonomous plasma neutralizer — an electron source of the flat cathode type [8], which was placed in the drift space 10-13 cm

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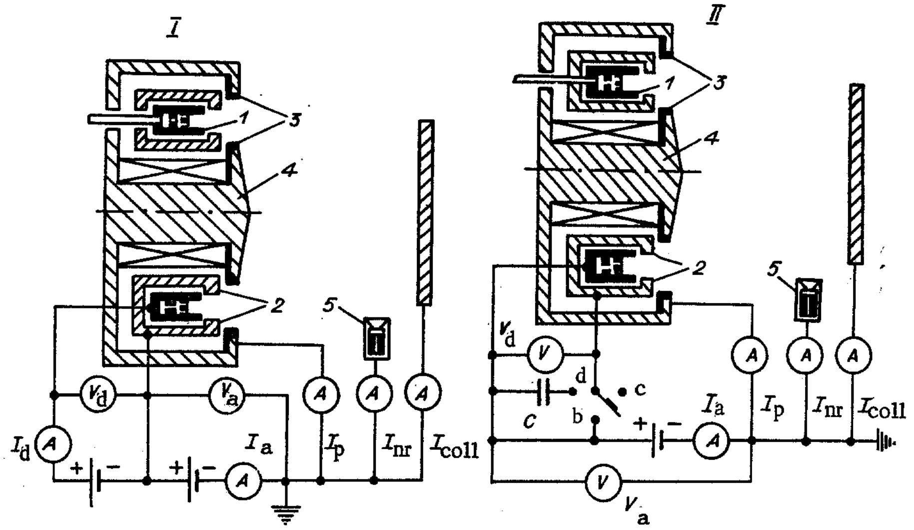

Fig. 1

from the accelerator cutoff and 2-3 cm from the beam. This source consists of a molybdenum tube 8 mm in diameter with a lanthanum hexaboride insert and end disks with openings. The working substance, for example, xenon or bismuth, flowed through these openings. For bismuth the cathode was preheated to a temperature of ≈1000°C with an additional heater, after which it operated in the self-heating mode. The positive electrode of this source was the ion beam itself, formed in the accelerator. As investigations showed [8], the energy of the electrons in such a source equaled to 10-15 eV/electron, which is close to the ionization potential of an atom. The gas efficiency coefficient k ≈ 200 electrons/atom, which is close to the limiting value $k^* = \sqrt{M_s/m_e}$, where M_s and m_e are the mass of an atom of the working substance in the source and the electron mass.

By weighing the container with the working substance before and after the experiment it was possible to determine to within ≈5% the average flow rate of bismuth $\dot{m}$. The average ion velocity $\langle v \rangle = F/\dot{m}$ and the accelerator efficiency $\eta = F/2\dot{m}W$ ($W = I_dV_d + I_aV_a$ is the power consumption) were determined from measurements of the reaction force of the beam and the flow rate of the working substance.

2. Experimental Results. The current–voltage characteristics (IVC) of the accelerator and the dependence of the efficiency on the accelerating voltage for different flow rates of the working substance (the flow rate is expressed in current units $I_m = e\dot{m}/M$, where e and M are the ion charge and mass) are presented in Figs. 2a and b for operation of AAL with (curves 1-4) and without (curves 5-7) a neutralizer; the lines correspond to the following regimes: 4, 5) I_m = 4.7 A, V_d = 250 V; 3, 7) I_m = 6.7 A, V_d = 180 V; 2, 6) I_m = 8.7 A, V_d = 120 V; 1, 8) I_m = 11.1 A, V_d = 80 V with a magnetic field H = 1 kOe and a pressure in the chamber $p = (0.6\text{-}1)\cdot 10^{-3}$ Pa (curve 8 shows the dependence of the average ion velocity ⟨v⟩ on the accelerating voltage). It is obvious that the best parameters of the two-step AAL are obtained on the section of the IVC with I_a = const, where the efficiency is optimum ($\eta \gtrsim 0.6$). At the same time, both cases are characterized by the existence of a minimum accelerating voltage V_a^*, below which a break occurs in the dependence I_a = const, the efficiency of the accelerator drops sharply ($\eta < 0.5$), and the ion beam becomes defocused. The voltage V_a^* corresponds to the critical voltage of the transition into the anomalous regime [1, 2].

For operation without a neutralizer the break in the anomalous regime in the AAL geometry studied occurs for $V_a^* \gtrsim 2$ kV (lines 5-7), and in addition the critical voltage increases as the flow rate increases and the field intensity in the accelerator channel decreases. This agrees well with the data of [2]. The use of a neutralizer makes it possible to displace the boundary of the anomalous regime into the region of significantly lower accelerating voltages right down to $V_a^* \sim 0.5$ kV (lines 1-3) while preserving high efficiencies and for low voltages.

The character of the change in V_a^* as the flow rate increases and the magnetic field decreases is directly opposite to the results of experiments performed without a neutralizer. Thus comparison of curves 4 and 2 shows that doubling the current density while holding the magnetic field fixed decreases V_a^* from ~0.9 kV to ~0.5 kV. The effect of the magnetic field

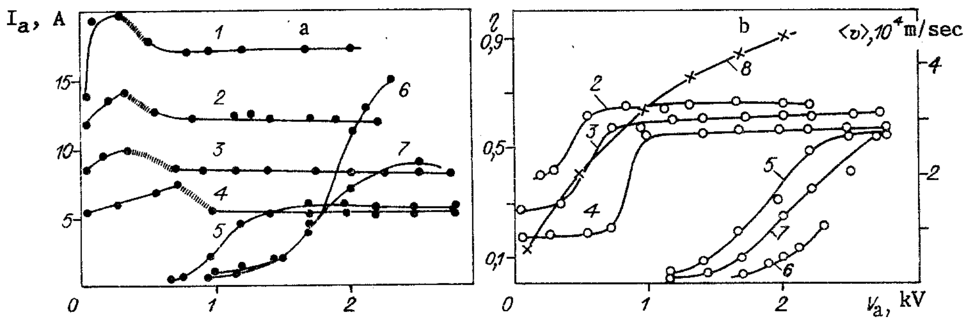

Fig. 2

on the change in V_a^* for a fixed flow rate is weaker than the effect of the flow rate.

In all experiments the current in the accelerating step on the section of the IVC I_a = const is much higher than the equivalent flow rate of the working substance ($I_a > I_m$). Nevertheless in the range of magnetic fields studied the efficiency of the accelerator reaches high values ($\eta \approx 0.6$-0.7) and the ion beam is well focused, unlike [1], where the efficiency of the two-step AAL dropped sharply as the magnetic field dropped below ~1 kOe and $V_a \lesssim 2$ kV. In addition, the average velocity increases in proportion to the square root of the accelerating voltage, which indicates acceleration by the electric field both in the region of low accelerating voltages and weak magnetic fields. For this reason, like in [1, 2], the operating regime on the section of the IVC with I_a = const > I_m must be regarded as accelerating. Analogous results were obtained on the other model, differing primarily by the geometric dimensions (d = 160 mm) [4].

Figure 3 shows the currents I_a and I_d and the efficiency versus the magnitude of the discharge voltage V_d for different flow rates [the lines 1 and 2 for I_m = 11.3 and 7.4 A with V_a = 1.3 kV, H = 0.95 kOe, p = $(0.6$-$0.8)\cdot 10^{-3}$ Pa]. The nonmonotonic dependence of the currents and efficiency on the discharge voltage, which in practice have several subregions with appreciably different variation of the currents and the efficiency, is interesting. It is obvious that the efficiency of the accelerator is optimum in a definite range of V_d [1, 2], depending, as pointed out above, on the flow rate of the working substance. Thus for a low flow rate density ($j_m \sim 0.1$ A/cm²) the maximum efficiency is observed in the range 180 V $\lesssim V_d \lesssim$ 240 V. Increasing V_d above a limiting value, as a rule, leads to pulsations and growth of the currents I_a and I_d and a drop in the efficiency. When the voltage is lowered ($V_d < V_{dm}$) the current in the discharge step drops, and the current in the accelerating step grows. A smooth reduction of V_d to zero is accompanied for strong magnetic fields (H $\gtrsim$ 1 kOe) by a drop in the efficiency to ~0.4.

The minimum value of V_{dm} decreases as the flow rate of the working substance increases. Thus for a density $j_m \approx 0.1$ A/cm² it equals ≈180 V, whereas when the flow rate was doubled it dropped to ≈80 V. In addition, for a fixed accelerating voltage the range of optimal values of V_d decreases. The relationship between the minimum discharge voltage and the critical accelerating voltage, however, is opposite to the dependence $V_{dm}(V_a^*)$ shown in Fig. 2, where V_a^* increases as V_d decreases. The difference between the model studied and the model in [2] is apparently determined both by the presence of the external source of electrons and the decrease in the length of the region with the magnetic field. These possibilities, unlike [2], lead to the fact that a decrease in V_d is not accompanied by a disappearance of the distinctly anomalous regime, when $I_a \gg I_m$, while the accelerator operates quite efficiently also for discharge voltages close to zero [4]. For weak magnetic fields (H $\lesssim$ 0.5 kOe) this regime is analogous to the operating regime of AAL with one power source (see Fig. 1, scheme IIb), while the accelerator is essentially a single-step AAL and has the characteristic peculiarities of the latter [6].

The IVC and dependence of the efficiency on the accelerating voltage in one- and two-step operating regimes of the AAL are presented in Fig. 4 (curve 1 is for scheme I in Fig. 1 — two-step AAL, H = 0.95 kOe, V_d = 200 V; curve 2 corresponds to the position b — a one-step AAL, H = 0.27 kOe and V_d = 0; curve 3 corresponds to the position c, an AAL with a floating electrode, H = 0.95 kOe; curve 4 corresponds to the position d, an AAL with a capacitive divider, H = 0.95 kOe). It is obvious that in the single-step regime (curve 2) the efficiency of the AAL reaches values of $\eta \approx 0.6$-0.7 in the range 0.2 kV $\lesssim V_a \lesssim$ 0.7 kV for H $\lesssim$ 0.3 kOe, $j_m \gtrsim 0.1$ A/cm² and drops to $\eta \lesssim 0.5$ for $V_a \gtrsim 0.9$ kV. For operation in the two-step scheme and with strong magnetic fields, for $V_a \lesssim$ 1-0.5 kV the efficiency, as noted

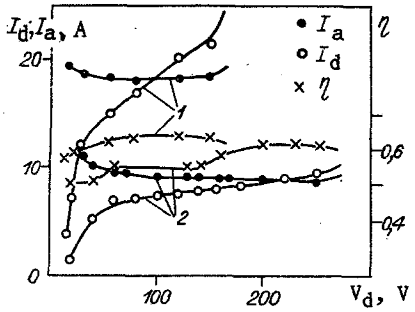

Fig. 3

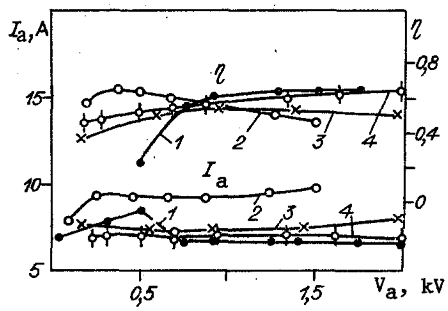

Fig. 4

above, drops sharply. For high accelerating voltages ($V_a \gtrsim 1$ kV) the efficiency of the two-step AAL is 10-20% higher than that of the single-step AAL. The difference is determined by the increasing current – voltage characteristic of the AAL for high voltages (≳1 kV). For weak magnetic fields ($H \lesssim 0.5$ kOe) the range of accelerating voltages for the two-step AAL with a high acceleration efficiency extends, like for the single-step AAL, to ~0.3 kV.

This change in the characteristics obviously indicates that ionization processes significantly affect the subsequent formation and acceleration of the ion beam in the anode layer. To clarify this feature the characteristic of the AAL was studied in special experiments using the same conditions for different power supply schemes (see Fig. 1), leading to a redistribution of the potential in the accelerator channel.

The IVC and efficiency for the power supply scheme studied for the two-step AAL are compared in Fig. 4. It is obvious that for high accelerating voltages the IVC with one power source (curves 3 and 4) is virtually identical to the IVC obtained in the standard two-step scheme, which agrees with the data of [7]. For low accelerating voltages, however, the IVC differ appreciably. In the scheme with the capacitive divider and a floating electrode, unlike the two-step AAL, there is no jump-like transition into the "anomalous" regime, so that the dependence $I_a(V)$ rapidly saturates and remains unchanged in virtually the entire range of accelerating voltages ($V_a \gtrsim 0.3$ kV). In addition, the magnitudes of the currents for the schemes with a capacitive divider and a two-step AAL are close, while for the one-step AAL the current is higher than for the two-step AAL.

For low flow rates ($j_m \lesssim 0.1$ A/cm^2) the efficiency in the range 0.2 kV $\lesssim V_a \lesssim$ 0.9 kV when operating with one power source and a capacitive divider is significantly higher (by ≳25%) than for the standard two-step power-supply scheme. When the flow rate is increased the efficiency increases; the optimal value is achieved for accelerating voltages $V_a \gtrsim 0.3$ kV. When the voltage is lowered below ~0.3 kV the efficiency drops smoothly. For the scheme with a floating electrode the efficiency of the AAL is lower than in the preceding case ($\eta \sim 0.5$).

For high accelerating voltages the potential difference between the anode and the cathode of the first step in the scheme with one power source and a divider is automatically set to a value close to the optimal discharge voltage V_d in the two-step AAL. For low voltages the potential difference changes in proportion to V_a. In addition, all schemes studied have in common the fact that the discharge also burns in the cavity formed by the anode and the electrodes 2 (see Fig. 1). The experiments performed showed that from the viewpoint of the optimal distribution of electric fields in the channel of the AAL for a wide range of voltages the most flexible scheme turned out to be the scheme of the two-step AAL with a capacitive divider.

Thus regimes with one power source when one part of the applied potential difference required for ionization of the working substance is established on the electrodes of the first step and the other is established on the electrodes of the second step have been realized in the two-step accelerator.

The effect of a magnetic field on the current and efficiency for a fixed accelerating voltage and different flow rates and power supply schemes is shown in Fig. 5a [1, 2) I_m = 6.5; 9.8 A, V_a = 1.2; 0.75-1.3 kV, V_d = 160; 120 V for a two-step AAL; 3) I_m = 6.2 A, V_a = 1 kV, V_d = 0 for a one-step AAL]. It is obvious that a decrease of H is accompanied by an increase in I_a and a relative increase of the efficiency in a definite region of parameters. The accelerator operates efficiently with an optimum value of H*, which increases as the flow rate increases.

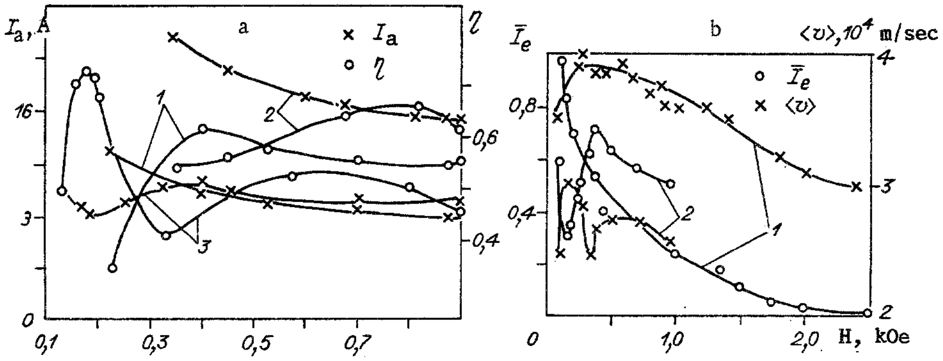

Fig. 5

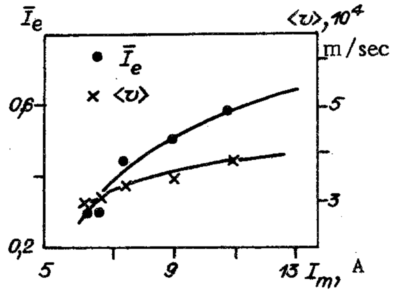

Fig. 6

For H < H* more significant growth of the current and drop in the efficiency are observed, while in the range studied H > H* they do not change as much. The dependence of the current on the magnetic field is observed clearly in Fig. 5b [1) two-step AAL, V_a = 1.3 kV, V_d = 160 V; 2) one-step AAL, V_a = 1 kV, V_d = 0], where the reduced current $\bar{I}_e = (I_a - I_m)/I_m$ essentially characterizes the change in the electronic component of the current with a fixed flow rate. The figure also shows the data obtained on different models of the two-step AAL [1, 4] with different geometric dimensions. All experimental results are satisfactorily clustered near one curve 1, close to the hyperbolic dependence $\bar{I}_e \sim$ const/H. In addition, the reduced electronic current reaches high values (~1) for weak magnetic fields (H ~ 0.2 kOe).

Figure 5b shows the analogous dependence (line 2) for AAL with one power supply (see Fig. 1, scheme IIb). The "resonance" change in $\bar{I}_e$ versus H in the region of weak magnetic fields (0.15-0.3 kOe), where for certain (optimal) values of H* the electron current decreases sharply (to $\bar{I}_e \sim 0.3$) and the efficiency increases (≈0.7), is interesting. Here the focusing of the beam, which has a sharper boundary than for other values of H, visibly improves. The discharge in the cavity formed by the anode 1 and the electrodes 2 (see Fig. 1) is brighter.

An analogous variation of the currents as a function of H occurred for operation on cesium in both the one-step [6] and the two-step AAL with different geometric dimensions (d = 60 mm, h = 15 mm, δ = 3 mm), indicating that the processes depending weakly on the geometric dimensions of the accelerator and the working substance are universal.

Figure 5b shows the typical dependence of the average velocity of directed ion motion on the magnetic field with a fixed voltage and flow rate in both operating regimes of the AAL. It is obvious that the average velocity has an optimal value for H* ≈ 0.2-0.3 kOe. Beyond the optimal value H* the velocity drops, and in addition its rate of change for H > H* is lower than for H < H*. In addition, changing the magnetic field from 2.5 to 0.3 kOe increases ⟨v⟩ by ~30%, and H* increases as the flow rate of the working substance increases and depends on the accelerating voltage.

It was found experimentally that increasing the flow rate while keeping the magnetic field fixed increases the reduced electronic current (Fig. 6, V_a = 1.3 kV, H = 1 kOe, V_d = 80-250 V, scheme I in Fig. 1). Thus for quite low flow rates ($j_m \lesssim 0.1$ A/cm²) the excess of the current above the flow rate equals ≈30%, while with a high flow rate ($j_m \sim 0.2$ A/cm²) I_a can exceed the equivalent flow rate of bismuth by ~60%. In addition, the average velocity also increases as the flow rate increases, so that doubling it in the range studied increases the average velocity by ≈30%.

The indicated change in the currents $I_a(I_m, H)$ while the accelerating voltage is held fixed is accompanied by an increase in the power, and for this reason one would expect that the efficiency of the accelerator would drop. An increase in the velocity, however, gives an optimal value of the efficiency ($\eta \gtrsim 0.6$) for magnetic fields $H > H^*$ for all accelerating voltages, where the rate of growth of I_a as H changes is less than or comparable to the increment to the average velocity of the ions. In the opposite case, for $H < H^*$, the acceleration efficiency drops. The residual gas pressure in the chamber volume has an appreciable effect on the electronic current. If the pressure is raised by a factor of 3-4 in the range studied I_a increases little (by ≈20%), while the efficiency drops (by ≈10%). In addition, the critical pressure (above which the currents grow rapidly, while the efficiency drops) increases as the magnetic field increases and the flow rate decreases. The range of pressures with optimum efficiency in the accelerator studied is significantly lower than in the accelerator with an extended zone with a strong magnetic field [2], while the critical pressure equals $\sim 4 \cdot 10^{-3}$ Pa.

Thus the investigations performed showed that optimization of the operating regimes, construction, and power supply scheme of the AAL gives a high efficiency of formation and acceleration of ion beams in a wide range of voltages ($V_a \gtrsim 0.2$ kV) and magnetic fields ($H \gtrsim 0.2$ kOe). This makes it possible to employ AAL extensively in different areas of engineering and technology.

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