16. A. E. Grün, "Lumineszenz-photometrische Messungen der Energieabsorption im Strahlungsfeld von Elektronen-Quellen eindimensionaler Fall in Luft," Z. Naturforsch., 12a, 89-95 (1957).
17. J. A. Gledhill, "The range-energy relation for 0.1-500-keV electrons," J. Phys., A6, 1420-1428 (1973).

OPTIMIZATION OF THE WORKING CONDITIONS IN AN ACCELERATOR WITH AN ANODE LAYER

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The characteristics of a two-stage ion accelerator with an anode layer [1, 2] indicate that there are at least two modes of operation: accelerative and anomalous. The occurrence of the anomalous state substantially restricts the performance of the accelerator. It is therefore extremely important to elucidate (at least qualitatively) the main factors that influence the change of mode. An experimental study has been made of the effects of the geometry of the working part on the characteristics, and a relationship is drawn up between the parameters and the working conditions at the limit of transition from the optimum accelerative mode to the anomalous one. The experiments were performed on a two-stage axial ion accelerator with an anode layer [1].

1. Effects of Working-Gap Geometry on Accelerator Characteristics. An accelerator with an anode layer usually works with a strong magnetic field in the working gap, $H \gtrsim 1000$ Oe. The thickness of the accelerating anode layer is considerably less than the thickness of the region where the ion beam propagates transverse to the magnetic field. The extent of this region is determined by the distance from the end of the discharge stage to the end of the magnetic system and by the zone of the leakage field, which is of the order of the distance between the poles. The electrons have a restricted mobility transverse to the magnetic field, so the space charge due to the ion beam in the magnetic field is compensated only by ionization of the residual gas and the possible entry of electrons along the magnetic field lines. Under these conditions, dynamic processes in the beam may lead not only to deterioration in the parameters but also to periodic beam shutdown [3-5]. It is therefore important to establish the relationship between the characteristics of the accelerator and the extent and geometry of the region containing the magnetic field.

Figure 1 shows the voltage—current characteristics of accelerating stages differing in magnet geometry and thus in geometry of the acceleration chamber (V_d = 150-200 V, H = 2 kOe, and p = $(2-4)\cdot 10^{-5}$ mm Hg). In the first case (Fig. 1a), the magnet has thick poles (40 mm) with a wide spacing (50 mm). The discharge unit is set up in the pole space with the accelerating layer essentially in a uniform magnetic field. The optimum acceleration conditions (with $I_a \simeq \text{const} \simeq e\dot{m}/M$, where $\dot{m}$ is the flow rate of working substance per second, M is the mass of an atom, and e is the charge on an ion) occurs only for $V_a \gtrsim 3$-4 kV. The negative slope of the voltage—current characteristic is very large at low V_a, so it is possible to follow the course of the characteristic in this region only for $I_a \gtrsim 3$A. As V_a is reduced, there is a step change from the optimum acceleration condition to a comparatively low-voltage condition, which is called anomalous, because the current in the accelerating stage may exceed the possible ion current considerably ($I_a > e\dot{m}/M$), while the formation of the ion beam deteriorates considerably. We take the critical voltage V_a^* for the transition to the anomalous state as the accelerating potential at the point where the slope of the voltage—current characteristic becomes negative or there is a jump from the accelerating condition to the anomalous one.

When the geometry of the accelerator is changed (Fig. 1b and c), the poles become considerably thinner, while the distance between them is reduced by more than a factor of 2. As a result, the length of the region where the ion beam propagates across the magnetic field is

*Deceased.

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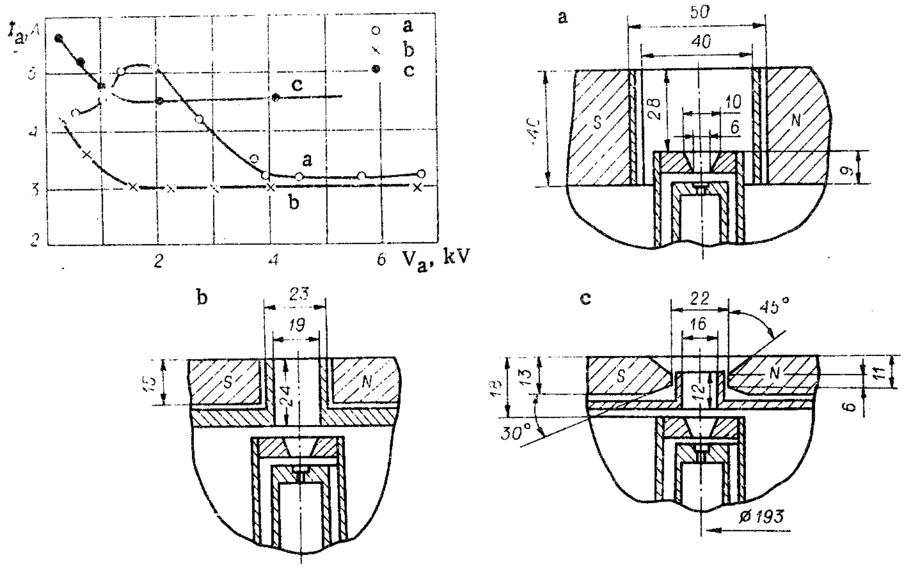

Fig. 1

shortened, while the walls of the acceleration chamber are close to the beam. Also, the discharge unit and at least part of the accelerating layer are placed outside the poles in a magnetic field increasing in the acceleration direction and having a curvature of the lines of force that facilitates ion-beam focusing. These changes have produced a substantial reduction in V_a^* and thus have extended the range of accelerating voltages for which the ion beam is produced optimally. For example, Fig. 1 shows that the optimum acceleration state occurs here for $V_a \geq 1.5$ kV, in contrast to about 3.9 kV for the case of thick poles.

In another series of experiments, the geometry of the magnet system was unchanged, but the acceleration depth l was varied, i.e., the distance from the outer margin of the magnet system to the end of the discharge stage. The value of l then determines whether the accelerating layer is in a region of increasing field, steady field, or falling field (Fig. 2, V_d = 150 V, H = 2 kOe, p = $(1.5\text{-}3)\cdot 10^{-5}$ mm Hg). In these experiments, location of the accelerating layer in a zone of increasing field is accompanied by increase in the length of the region where the ion beam propagates across the magnetic field, in distinction from the previous case (Fig. 1), where the length was reduced. Figure 2a shows the voltage—current characteristics for various l and a virtually constant flow of the working material (the points in Fig. 2a serve to denote the curves, which were recorded with a loop oscillograph). The characteristics show that an increase in the depth leads to a certain increase in V_a^*, but the slope becomes appreciably less steep and the stability of the accelerator improves as V_a is reduced. As a result, with l = 28 mm we have that the discharge gap and the accelerating layer are in the zone of increasing magnetic field, and a stable state exists with accelerating voltages below 1 kV, where the ion beam is well-shaped and the current in the accelerating stage exceeds the corresponding current in the optimum state by only about 10%.

Reduction in l, i.e., placing the accelerating layer closer to the end of the magnet, hinders the production of the optimum state and increases the current in the anomalous state. If $l \leq 5$ mm, where part of the accelerating layer is in the zone of falling magnetic field, there is no optimum state at all.

These experimental results show that the optimum geometry as regards production of low-energy ion beams is one with thin poles, a small gap between the poles, and location of the discharge unit beyond the internal end of the poles.

2. Parameter Relationships on Mode Change. The change in mode is most prominent in the case of thick poles with a large gap (Fig. 1a), so this geometry was mainly used [5] to examine the relationship between the parameters and the working conditions at the limit of transition from the optimum state to the anomalous one.

Figure 3 (V_d = 200 V, H = 1.3 kOe) shows V_a^* in relation to the accelerated ion current (the current I_a in the optimum working state) for two pressures in the vacuum chamber. The value of V_a^* increases appreciably with the ion current. The $V_a^*(I_a)$ curve shifts downwards as the concentration of neutral gas in the volume increases. The dependence of V_a^* on gas pressure p in the flight space is shown for constant I_a in Fig. 4. The pressure was adjusted

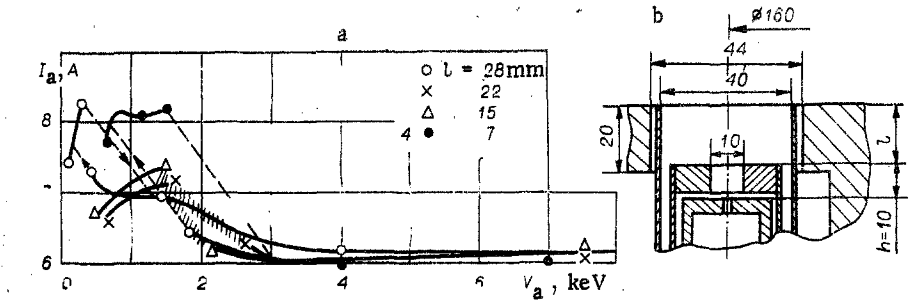

Fig. 2

via the rate of admission of argon to the vacuum chamber. The two series of points were obtained in experiments differing in chamber geometry and position of gas leak (points 1 are for the supply of Ar from the pole with $I_a = 3$ A and $V_d = 200$ V, $H = 1.8$ kOe, while points 2 are for Ar supplied far from the model with $I_a = 3.9$ A, $V_d = 200$ V, and $H = 1.3$ kOe). In one case (curve 1) the geometry corresponded precisely to Fig. 1a, and the gas was admitted at a distance of 1.5 m. In the other case (curve 2), two molybdenum rings were inserted in the pole gap in such a way that the distance between the walls of the acceleration chamber was 22 mm. The argon was supplied through a tube to the central pole of the accelerator. A deflection above the pole caused the gas to flow radially. The critical voltage fell as the neutral-gas density in the flight space increased. For example, for the first geometry we found that a change in pressure from $2 \cdot 10^{-5}$ to $2 \cdot 10^{-4}$ mm Hg reduced V_a^* from about 3.8 to about 1.5 kV with otherwise equal conditions (Fig. 4). However, this favorable effect from raising the pressure occurred only up to a certain limit. At pressures $p \gtrsim 3 \cdot 10^{-4}$ mm Hg, it was impossible to produce an optimum state at all: the voltage–current characteristic became continuously rising, while the current in the accelerating stage exceeded the flowrate of the working substance $\dot{e}m/M$ by a factor of two or more. Curve 3 corresponds to $V_a^* = \mathrm{const}/p^{1/3}$.

The transition from the optimum state and the excess of current over the flowrate ($I_a > \dot{e}m/M$) are due primarily to processes occurring within the magnetic field. This follows from observations with the use of a heated cathode set up in the beam in a zone where the magnetic field was weak (at about 10 cm from the end of the accelerator). There was not more effect on the currents in either state with the cathode switched on, although the emission current from the cathode was comparable with the ion current in the beam.

The value of V_a^* is substantially influenced by H; increase in H from 0.8 to 2 kOe reduced V_a^* by almost a factor of two. Figure 5 shows $V_a^*(H)$ (1 is for the model of Fig. 1a, $p = (1.5\text{–}2) \cdot 10^{-5}$ mm Hg, while 2 is for the model of Fig. 1c, $p = 6 \cdot 10^{-5}$ mm Hg, $I_a = 4$ A, and $V_d = 200$ V). The analogous curve 2 is for an accelerator with thinner poles and a small gap between them (Fig. 1c). In this geometry, the critical voltage was reduced by almost a factor of three for the same field strength relative to the geometry with thick poles (curve 1 of Fig. 1a). The general form of $V_a^*(H)$ remained as before and corresponded to $V_a^* = \mathrm{const}/H^{2/3}$.

4. Discussion.† The transition from the optimum state to the anomalous one on reducing the accelerating voltage is the main reason preventing the efficient production of strong ion beams at low energies. At present there is no definite answer to the question of what causes the change in condition. The following are some possible reasons.

It has been shown [3-5] that electrostatic instability can occur in an ion beam propagating transverse to a magnetic field, which leads to the formation of a virtual ion emitter (or anode). As a result, the beam splits up and a large fraction of the ions will pass to the wall of the ionization chamber. The flow of atoms from the wall (due to neutralization of the ions and cathode sputtering) passes partly to the accelerating layer, where the gas is reionized and accelerated. Then the I_a becomes greater than $\dot{e}m/M$. Also, a substantial backward flow in the layer may disrupt the structure of the layer and interfere with the stability, which also increases I_a, in particular due to secondary ion-electron emission from the walls.

An approximate expression has been given [2, 3] for the critical ion-current density in the beam above which the electrostatic instability can occur for the case of a beam propagating parallel to two equipotential walls:

†There is no Sec. 3 in the Russian original — Editor.

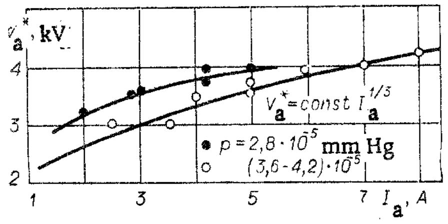

Fig. 3

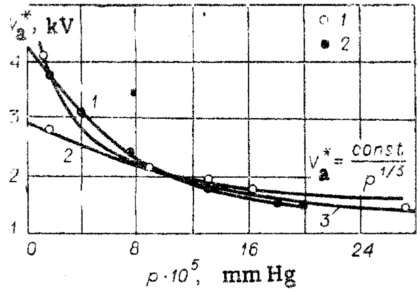

Fig. 4

$$j_{i\,\mathrm{cr}} = \frac{1}{1+\sqrt{6\varepsilon\frac{V_0}{\varphi_0}}}\frac{\alpha}{\pi}\sqrt{\frac{2e}{M}}\frac{V_0}{\sqrt{\varphi_0\varphi_2}}\frac{V_0^{3/2}}{h_i^2}, \tag{4.1}$$

where V_0 is the ion energy in eV, which is close to the accelerating voltage ($V_0 \approx V_a$); φ_0, potential of the beam relative to the wall; $e\varphi_2 \approx eT_e$, energy of the secondary ions arriving from the wall (T_e is the electron temperature); $\alpha = n_{i2}/n_{i1}$, density of the secondary plasma at the wall as referred to the density of the fast ions in the beam; h_i, beam height (size along the magnetic field); ε, degree of dynamic decompensation in the beam, which may be due either to fluctuations Δj_i in the ion current in the beam or to fluctuations ΔV_0 ($\varepsilon = \Delta j_i/j_i + \Delta V_0/2V_0$) in the energy of the fast ions. If we assume that the secondary plasma is produced only by collision of neutral particles with fast beam ions (ionization and charge transfer) [3], then α is given by

$$\alpha = \frac{1}{2}n_0(\sigma_{ii}+\sigma_{\mathrm{n}})h_i\sqrt{\frac{V_0}{\varphi_2}} = \frac{1}{2}\frac{h_i}{\lambda_i}\sqrt{\frac{V_0}{\varphi_2}},$$

where σ_t is the cross section for charge transfer, while n_0 and σ_{ii} are the neutral-atom concentration and the ionization cross section for neutral atoms by fast ions.

Then the critical current density is

$$j_{i\,\mathrm{cr}} = \frac{1}{2\pi\left(1+\sqrt{6\varepsilon\frac{V_0}{\varphi_0}}\right)}\sqrt{\frac{2e}{M}}\frac{V_0}{\varphi_2}\left(\frac{V_0}{\varphi_0}\right)^{1/2}\frac{V_0^{3/2}}{\lambda_i h_i}. \tag{4.2}$$

The degree of dynamic decompensation is known along with the parameters of the secondary plasma, while the beam propagates in a space surrounded by walls of complex shape, so we restrict ourselves to qualitative consideration in comparing (4.2) with experiment. The critical density can be put in the following form apart from the dependence of ($\sigma_{ii} + \sigma_t$) on the ion energy:

$$j_{i\,\mathrm{cr}} \sim n_0 V_0^k, \tag{4.3}$$

where k lies in the range $2.5 \leqslant k \leqslant 3$ as the degree of dynamic decompensation varies. Expression (4.3) can be put as

$$V_a^* \simeq V_{0\,\mathrm{cr}} \sim \left(\frac{j_i}{n_0}\right)^{1/k}. \tag{4.4}$$

In Fig. 6 (V_d = 150-200 V, H = 1.8 kOe) we show points for $V_a^*(I_a/p)$ obtained in various experiments for the geometry shown in Fig. 1a. Also, Figs. 3 and 4 show $V_a^* \sim I_a^{1/3}$ and $V_a^* \sim 1/p^{1/3}$. Clearly, the observed results correspond fairly closely to (4.4). At small p there are deviations from $V_a^* \sim 1/p^{1/3}$ (Fig. 4), as would be expected, since p is the gas pressure in the vacuum chamber and does not completely determine the value of n_0 in the beam. For $p \to 0$, n_0 and V_a^* will be determined by the proportion of neutral flux. Estimates show that failure to ionize only 1% of the working substance with an ion-current density of 0.1 A/cm² gives $n_0 \approx 2 \cdot 10^{11}$ 1/cm³, i.e., comparable with the density of the residual gas at a pressure of $p \approx 10^{-5}$ mm Hg. We see from (4.1) that the electrostatic instability is greatly facilitated if there is dynamic decompensation, i.e., if the ion density in the beam fluctuates with a characteristic time less than the autocompensation time. One of the reasons for decompensation is related to the properties of the anode layer. Measurements on an $E \perp H$ vacuum discharge [6] have shown that the electron density in the anode layer fluctuates with a wave-

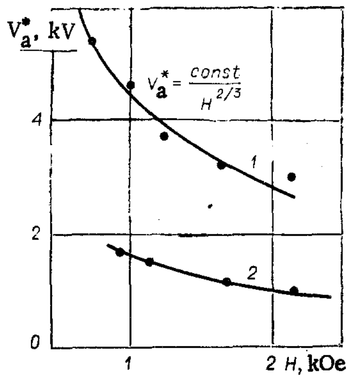

Fig. 5

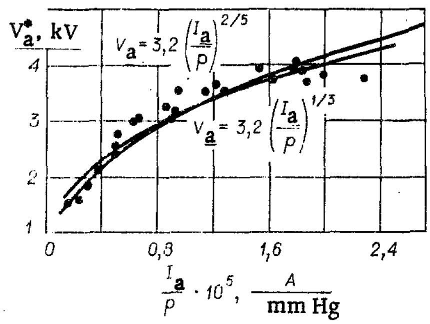

Fig. 6

form close to relaxation type and with a period close to the ionization period, while the relative amplitude is about 0.3. Such fluctuations in the production of the ion beam in the anode layer naturally lead to fluctuations in the current and in the ion speed. These fluctuations have been observed [4, 5].

In the case of a two-stage accelerator, the dynamic decompensation becomes more complicated, because the fluctuations in the ion beam are due to fluctuations in the ion source and in the accelerating stage. The coupling between the discharge and accelerating stages is evident in particular from the fact that the characteristics of a two-stage system are optimal in a restricted range of discharge voltages [1], where the discharge in the first stage is not self-maintaining. One assumes that here one has the best conformity between the discharge and accelerating stages. This no longer applies on going to a self-maintained discharge on raising the discharge voltage, and there is then [7] an increase in the amplitude of the fluctuations in the beam.

The condition for electrostatic instability does not contain the magnetic field directly. There is a certain effect from the magnetic field that is related to the degree of dynamic decompensation, because the amplitude of the fluctuations decreases as the field becomes stronger [4]. However, the main effect is due to processes in the accelerating layer. Consideration of the fluctuations in an accelerator with closed electron drift and an extended acceleration zone shows [8] that when

$$\frac{d}{dx}\left(\frac{n_i}{H}\right) > 0, \tag{4.5}$$

where x is the direction of ion acceleration, the system shows an instability that results in azimuthal waves, which are particularly unfavorable to the characteristics. The effects of the boundary conditions and the length of the acceleration zone were not considered in [8]. However, similar instabilities can occur in a number of cases for a relatively thin anode layer. In particular, we have the familiar experimental fact that in an $E \perp H$ discharge (in a Penning device, or in a direct or reversed magnetron, etc.) the structure of the anode layer is very much perturbed on going from a low-pressure condition to a high-pressure one, i.e., to strong ionization in the layer [9]. A similar effect was observed in these experiments on raising the pressure in the chamber above ~$3 \cdot 10^{-4}$ mm Hg, where the working condition deteriorated and the optimum acceleration state could not be attained. It is readily estimated that the returning current of neutral atoms was then comparable with the flux of material from the anode. A characteristic feature of these cases is that there is a large flux of material from the outer side of the layer, i.e., the conditions for compliance with (4.4) are set up. Therefore, the anode layer must be placed in a magnetic field increasing in the acceleration direction in order to retard development of the instability. A similar requirement arises from the consideration of some purely stationary factors in the optimal organization of the working process. The most obvious of these is the attainment of a focusing effect by curvature of the magnetic field lines. However, the most important is the problem of the azimuthal homogeneity of the ion beam, since the characteristics of the accelerator improve substantially with the azimuthal homogeneity (or supply of neutral atoms) [10]. Distortions in the azimuthal structure of the anode layer in the presence of inhomogeneity in the ion flux are also confirmed by the sputtering of the accelerator chamber by the ions [11]. In these experiments, the azimuthal inhomogeniety in supplying the working material from the anode was about 10%, and this is evidently the main reason why it was impossible to obtain the optimum acceleration condition on bringing the acceleration layer towards the end of the magnetic system.

LITERATURE CITED

1. S. D. Grishin, V. S. Erofeev, A. V. Zharinov, V. P. Naumkin, and I. N. Safronov, "Characteristics of a two-stage ion accelerator with an anode layer," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1978).
2. V. S. Erofeev and L. V. Liskov, "A Hall plasma accelerator with an anode layer," in: Physics and Applications of Plasma Accelerators [in Russian], Nauka i Tekhnika, Minsk (1974).
3. A. V. Zharinov, "Amplitude of the potential fluctuations in a quasineutral ion beam," Zh. Tekh. Fiz., 17, No. 9 (1973).
4. V. S. Erofeev, A. V. Zharinov, and E. A. Lyapin, "Low-frequency instability in a radial ion beam produced in a EH layer with a closed Hall current," in: Plasma Accelerators [in Russian], Mashinostroenie, Moscow (1972).
5. V. S. Erofeev, V. P. Naumkin, and I. N. Safronov, "Shift in modes and low-frequency oscillations in a two-stage accelerator with an anode layer," in: Proccedings of the Second All-Union Conference on Plasma Accelerators [in Russian], Inst. Fiz. Akad. Nauk BSSR, Minsk (1973).
6. N. A. Kervalishvili, "Instability in the low-pressure discharge in a transverse magnetic field," Zh. Tekh. Fiz., 38, No. 4 (1968).
7. E. A. Lyapin and E. V. Pelepelin, "Ion-current fluctuations in an accelerator with an anode layer," Fiz. Plazmy, 5, No. 3 (1979).
8. A. I. Morozov, Yu. V. Esipchuk, et al., "Effects of magnetic field configuration on the operation of an accelerator with closed electron drift," Zh. Tekh. Fiz., 42 (1972).
9. W. Knauer, A. Fafarmen, and R. L. Poeschel, "Instability of plasma sheath rotation and associated microwave generation in a Penning discharge," Appl. Phys. Lett., 3, No. 3 (1963).
10. V. S. Erofeev and I. N. Safronov, "Operation of a two-stage accelerator with an anode layer using cesium," in: Proceedings of the Fourth All-Union Conference on Plasma Accelerators and Ion Injectors [in Russian], Moscow (1978).
11. S. D. Grishin, V. S. Erofeev, L. V. Leskov, V. P. Naumkin, I. N. Safronov, and V. G. Silaev, "Interaction of an ion beam with the walls of an accelerator with an anode layer," in: Proceedings of the Second All-Union Conference on Plasma Accelerators [in Russian], Inst. Fiz. Akad. Nauk BSSR, Minsk (1973).