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EXISTENCE REGION FOR ARCING CONDITIONS WITH NEGATIVE ANODE POTENTIAL DROP

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Conditions for ignition of a high-current arc with negative anode potential drop U_a is investigated, and the region within which these conditions exist and causes for a transition into conditions with positive U_a are studied. It is noted that a regime with negative U_a is most preferable for most plasma units.

Two regimes are observed in working with different plasma units (MHD generators, plasmotrons, plasma accelerators, etc.) when investigating and using high-current arcs, namely, regimes with positive and with negative anode potential drop U_a [1]. Though these two regimes are often encountered when working with the same unit (one regime may pass into the other), they possess a number of distinctive properties.

The discharge is practically always uniformly distributed throughout the surface of the electrode in the regime of negative U_a, while it is tightened into a braid and contracted with positive U_a. Discharge current increases with minimal voltage increase for a negative U_a (we are speaking here of a highly developed high-current arc), while a small increase in current is accompanied by a significant increase of voltage for positive U_a, a large part of the voltage increment falling within the near-electrode zone [1, 2]. The current density through the electrode and the total heat release with positive U_a is greater than with negative U_a, other conditions being equal. Moreover, this refers to the specific heat flow in the anode spot. A number of studies have recently appeared (for example, [3-5]) in which it was discovered that heat release on the anode is less than that calculated for arcing with negative U_a, which is apparently due to an increase in the effective work function of the anode material in contact with the plasma [5-7]. No such effect is observed with positive U_a.

It is well known that a regime with positive U_a occurs in many plasma units (this has been proposed by investigators). For example, the anode drop is positive in high-current plasma accelerators. The opinion that atmospheric arcs burn with positive U_a has been widespread.

At the same time, a comparison of these properties of the two regimes implies that the regime with negative U_a is more preferable (from the point of view of decreasing energy losses in the construction, solving electrode-cooling problems, optimally organizing the working process in the unit, etc.). Therefore an investigation into the ignition regime for a high-current arc with negative anode drop, a study of the region within which this regime exists, and an explanation of the causes and conditions for a transition into a regime with positive U_a constitute the most important problems.

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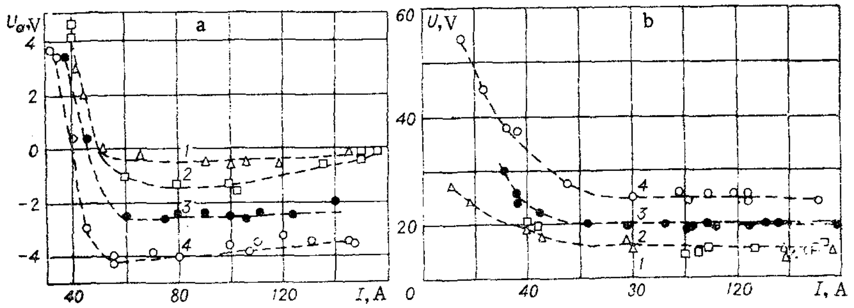

Fig. 1

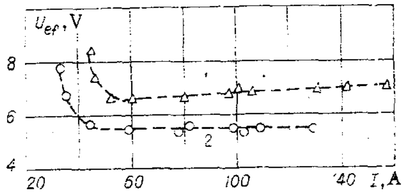

Fig. 2

Experiments were conducted in a vacuum chamber 0.25 m^3 in volume. After the chamber was evacuated it was filled with argon to a desired pressure between 5 mm Hg and 120 mm Hg. The discharge occurred between a rod cathode 3 mm in diameter and a plane radiation-cooled tungsten anode from fractions of a millimeter to 1 mm thick. The cathode–anode gap was 10 mm. The discharge was fed from a VSS-300 welded-contact rectifier. Neither bunching of the discharge on the anode nor erosion tracks was observed.

The following parameters were fixed in carrying out the experiments: current I, voltage U, pressure p, near-anode potential drop U_a, anode temperature T_a, specific q_a and total Q heat flows on the anode, anode spot diameter, current density j_a, concentration of charged particles in the plasma, and electron temperature T_e. The volt equivalent was also determined from the results of the measurements,

$$U_{ef} = \frac{Q}{I} = \frac{q_a}{j_a}.$$

Measurements of U_a and of the plasma parameters were carried out using cooled probes, and the probe characteristics were entered on the PDS-021 two-coordinate potentiometer. The plasma parameters were determined using a previous [8] technique. The measurement error for U_a was ± 0.5 V.

Calorimeters, based on the FD-1 germanium photodiode, were used to measure the heat flows. The technique of the measurements was given in [9].

The variation of U_a and of discharge voltage U as a function of current with different pressures in the chamber are, correspondingly, depicted in Figs. 1a and b (1: p = 120 mm Hg; 2: p = 60 mm Hg; 3: p = 15 mm Hg; 4: p = 5 mm Hg).

The curves in Fig. 2 illustrate the influence of current on U_{ef} (1: p = 120 mm Hg; 2: p = 5 mm Hg).

The measurements demonstrated that electron temperature weakly varies throughout this range of parameters and is at the level of about 1 eV. The concentration n of charged particles remained nearly invariant for currents $I \geqslant 50$ A and sharply decreased (by nearly a factor of 100) as current was decreased below 50 A. Concentration monotonically increased, varying from 10^{14} to $5 \cdot 10^{14}$ cm^{-3} as pressure was increased from 5 to 120 mm Hg.

The anode current density j_a was at the level of from several to tens of A/cm^2; heat flows q_a in the anode spot were at most 200 W/cm^2. The values of j_a and q_a increased either as the pressure or the discharge current increased.

The temperature in the anode spot T_a varied from 2000°K to 3000°K, weakly depended on current, and increased with increasing pressure. Such behavior for T_a occurred because the anode was cooled only by radiation.

In the analysis we will proceed on the basis of the simplest relations, using balance equations for the current and energy,

$$j_a = j_0^e \exp\left(-\frac{eU_a}{kT_e}\right) - j_0^i - j_s^e; \tag{1}$$

$$q_a = j_0^e \exp\left(-\frac{eU_a}{kT_e}\right)\left(\varphi + 2\frac{k}{e}\Delta T_e\right) + j_0^i\left(U_a + U_i - \varphi + 2\frac{k}{e}\Delta T_i\right) - j_s^e\varphi + q, \tag{2}$$

where j_a and q_a are the directly measured current densities and heat flow on the anode, ΔT_e and ΔT_i are the differences between the electron T_e and ion T_i temperatures of the plasma and the anode temperature T_a, U_a is the near-anode potential drop, U_i is the ionization energy of the drive gas, φ is the anode function, j_s^e is the thermionic current from the anode, k is Boltzmann's constant, e is electron charge, q is the heat flow from the plasma to the anode due to radiation and the presence of a neutral component, j_0^e and j_0^i are the random densities of the electron and ion currents determined by the plasma parameters defined on the boundary at which the near-anode layer experiences a sharp potential drop (i.e., in terms of the concentration n of charged particles and heat rates v_e and v_i),

$$j_0^e = \frac{1}{4} env_e = \frac{1}{4}\sqrt{\frac{8kT_e}{\pi m}}\, en,$$

$$j_0^i = \frac{1}{4} env_i = \frac{1}{4}\sqrt{\frac{8kT_i}{\pi M_i}}\, en.$$

It was assumed in Eqs. (1) and (2) that the near-anode potential jump is negative (i.e., the electrode potential is less than the plasma potential), so that the random ion current passes freely to the electrode (accumulating energy), while the electron current is partially trapped by the potential barrier U_a (charged particles in the plasma up to the boundary at which the potential sharply varies in the near-anode layer have a Maxwellian distribution). Ion emission from the anode is not taken into account, since it is assumed that surface ionization is absent. Let us also assume that Joule heat release in the electrode and heat dissipation in the construction (current supply) are low.

We may obtain from Eq. (1) the equation

$$U_a = \frac{kT_e}{e}\ln\frac{j_0^e}{j_a + j_0^i + j_s^e}. \tag{3}$$

Equation (3) implies that the anode drop remains negative whenever $j_0^e > j_a + j_0^i + j_s^e$. The magnitude of the negative anode drop may decrease in absolute value as current density j_a increases (which may be due, for example, to an increase in discharge current I), as thermionic current j_s^e increases (due to increasing anode temperature), and also due to a decrease in j_0^e (for example, due to a decrease in concentration n or temperature T_e).

If j_0^i and j_s^e are small in comparison with j_0^e (this condition often holds), we may speak of U_a changing sign when equality is reached,

$$j_a = j_0^e. \tag{4}$$

Let us discuss these experimental results and compare them to other data.

A regime with negative U_a is realized when $I \gtrsim 50$ A (cf. Fig. 1). U_a decreases in absolute value in accordance with Eq. (3) with increasing current I (and current density j_a) and (according to estimates) when $I^* \sim 10^3$ A, U_a will change sign. Such a change in sign of U_a has also been repeatedly observed in studying steady-state plasma accelerators [10]. The magnitude I* has been called the "critical" current. When $I > I^*$, the volt-ampere characteristics become significantly steeper (discharge voltage increases with slowly varying current) and anode heat release sharply increases, which often leads to a breakdown in the construction. The discharge is highly likely to contract as we pass beyond the critical current [10, 1].

One more feature of the dependences depicted in Fig. 1a should be borne in mind. The concentration n of charged particles increases with increasing pressure for nearly invariant temperature T_e. Consequently, j_0^e also increases, though U_a decreases in absolute value, which apparently contradicts Eq. (3). All these facts indicate that anode temperature increased in these experiments as pressure was increased, reaching $T_a = 3000$°K at $p = 120$ mm Hg, so that the thermionic current j_s^e from the anode strongly increased

TABLE 1

U_a, V	n.cm^{-3}	$\frac{k}{e}Te$, V	j_0^e,	j^e,	j_0^i,	j^i,	j_a,	q^e,	q^i,	q_a,
			A/cm²					W/cm²		
5	$5 \cdot 10^{16}$	1	10^5	10^5	10^2	10^0	10^5	10^6	10^1	10^6
−5	$5 \cdot 10^{16}$	1	10^5	$7 \cdot 10^2$	10^2	10^2	$6 \cdot 10^2$	$4{,}5 \cdot 10^3$	$1{,}5 \cdot 10^4$	$6 \cdot 10^3$
Experiment	10^{16}—10^{17} [12]	1—2 [19, 22, 23]	—	—	—	—	10^2—10^3 [19, 23, 24]	—	—	$4 \cdot 10^3$—$9 \cdot 10^3$ [23, 24]

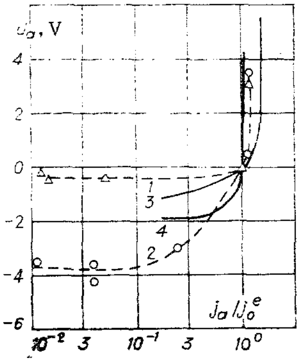

Fig. 3

(taking into account the anomalous factors discovered in [3-5]). Estimates have demonstrated that the increase in j_s^e is compensated by an increase in j_0^e and finally leads, in accordance with Eq. (3), to a decrease in absolute value of U_a.

Experiments demonstrated (cf. Fig. 1) that U_a changes sign from negative to positive as the discharge current is decreased below some critical I_* ($I_* \approx 50$ A within a wide range of pressures). Discharge voltage U here increases. This phenomenon is due to the sharp fall in the concentration n of charged particles (by a factor of 100) as current decreases below the critical I_*, which induces a decrease in j_0^e and, consequently, a decrease of the bremsstrahlung electron of the near-anode barrier, and then leads the formation of a positive U_a (to ensure the required anode density j_a) and an increase in discharge voltage. If we jointly examine Figs. 1a and b, we may conclude that the increase in U is due (basically) to an increase in U_a. The electric field strength and potential drop in the positive discharge column also increase here as a consequence of a decrease in the concentration of charged particles, though this contribution to the increase of U is not significant.

A strong increase in discharge voltage at currents less than $I_* \approx 50$ A has been repeatedly observed in experiments using argon and at atmospheric pressure [11]. An increase in electric field strength in a positive column was not great enough to explain the sharp increase in arcing voltage. Spectral measurements [12] have revealed a sharp drop in the concentration of charged particles at decreased currents.

Thus, an analysis of Eq. (3) indicates that a transition from arcing conditions with negative U_a into a regime with positive U_a can occur in two cases, namely, with increasing discharge current (or current density j_a) $I > I^*$ and as it decreases, $I < I_*$. In both cases, a change in sign occurs when Eq. (4) holds, though while it is reached in the first case due to an increase in j_a, in the second case it results from a decrease in j_0^e. Consequently, the nature of a change in sign for U_a is the same, that is, the anode region is reconstructed in order to maintain a given external discharge current circuit, so that the resulting shortage of electrons is compensated for.

The cause of the so-called "current crisis" in high-current plasma accelerators [10] thereby becomes understandable. Many studies have recently appeared dealing with this question [13-17]. A change in sign of the near-anode barrier as current increases, $I > I^*$ (i.e., maximal increase of anode current density, $j_a \gtrsim j_0^e$), or as the flow rate of the driver gas decreases, $G < G_*$ (i.e., maximal decrease of concentration of charged particles such that $j_0^e \lesssim j_a$), followed by a sharp increase of the accelerator supply voltage with a minimal increase in current and often inadmissibly high anode heat release,† is apparently the cause of such crisis phenomena.

Experimental data have demonstrated that ionic heating [in Eq. (2), the second term on the right] amounts to from a few parts to 10% of the total anode heat release. An analysis of Eq. (2) then implies that the volt equivalent U_{ef} in the regime of negative U_a (without taking into account radiant-convective heat flow q) will be of the order of magnitude of the effective work function φ of the anode material [more precisely, greater than φ by a magnitude on the order of $(k/e)T_e$]. It is precisely these figures that were obtained in the experiment (cf. Fig. 2). Similar results have been observed also in other studies (for example, [3]). The increase in U_{ef} with increased pressure is chiefly due to ionic heating. It should be expected that the role of ionic heating will increase in atmospheric arcs.

The volt equivalent sharply increases as we pass to positive U_a (cf. Fig. 2, [3]). This is explained by the fact that electrons determining the anode heat flows carry an energy eU_a units greater than $e\varphi + 2kT_e$, this excess possibly reaching tens of electron volts [1, 2]. The total heat flow Q therefore also increases.

That current density j_a significantly increases as we pass to a regime with positive U_a is far more important from the point of view of solving the electrode cooling problem, since all the electron current j_0^e passes through the anode; moreover, the specific heat flow q_a sharply increases. On the other hand, in a regime with a contracted discharge erosion, melting and other effects leading to rapid destruction of the electrode will of necessity appear.

Thus it has been established that the boundary at which one regime changes into a second regime (change of sign of U_a) is attained when condition (4) holds. We may conclude from these results, as well as from data of other studies dealing with the study of the point at which U_a changes sign, that this law is sufficiently general. Figure 3, in which U_a is depicted as a function of j_a/j_0^e (curve 1: p = 120 mm Hg; 2: p = 5 mm Hg; 3: data from [3]; 4: data from [14]), may serve as an illustration of this fact.

How often is a regime with negative U_a encountered in actual plasma units? It has been supposed until comparatively recently that U_a is positive in high-current plasma accelerators. This has been the case in coaxial channel amplifiers at currents of tens of kA [2]. Recent investigations have demonstrated that U_a is negative in most "normal" regimes of steady-state accelerators and is positive only in so-called regimes that are "over-maximal"; such regimes are usually accompanied by comparatively rapid electrode failure.

The opinion has been firmly established that U_a is positive in the course of investigating atmospheric arcs, in contrast to accelerators in which pressure varies within the discharge range from 0.1 to 10 mm Hg. It has been indicated that U_a is positive in such discharges [19]. However, by interpreting probe measurements given in [19], we may hypothesize the presence of negative U_a on cooled anodes in high-current arcs at atmospheric pressure (this has been already indicated in [20]). In fact, the difference between the floating potential of the probe and the plasma potential was not taken into account in [19]. This correction under the conditions of this article is 10 V, according to some data [21], so that the anode drop will be, not 5 V, as was obtained in [19], but −5 V.

If we assume that U_a is negative, the calculated values for current density and specific heat release given by Eqs. (1) and (2) will correspond to values that have been experimentally determined and that are not observed at positive U_a (cf. Table 1). This once again confirms the fact that U_a is negative at atmospheric pressure.

Many studies resulted from incorrect data given by Finkelburg [19], in which the anode drop in atmospheric arcs was determined calorimetrically [22-26]. It was first assumed in these works that U_a is

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†In fact, the picture in the near-anode region of plasma accelerators is indisputably more complex, due to the presence of strong interaction between the flow of conducting gas and the electric and magnetic fields. Contraction of the plasma from the anode and its overheating, in particular, may lead to the appearance of a crisis [15, 18]. Further, in plasma accelerators j_0^e is determined not only by the concentration n and temperature T_e, but also by the magnetic field strength H. It is difficult for electrons to move across the lines of force of a magnetic field, which leads to a decrease in the effective value of j_0^e. As a result, the crisis manifests itself particularly sharply and is accompanied by removal of the currents beyond the accelerator section.

positive, so that an interpretation of the results of the calorimetric measurements gave a false result, namely, the anode drop turned out to be positive, whereas in fact it must be negative. An analysis demonstrates that use of data from calorimetric measurements to determine U_a leads to errors in most cases if additional information is not employed.

Similar errors in determining the magnitude and sign of U_a by the calorimetric method can also be observed in investigations of high-current arcs at pressures below atmospheric (10-500 mm Hg) [27].

Thus, many experiments as well as some calculations [28] lead us to conclude that a positive anode potential drop exists within a comparatively small range of variation of discharge parameters. There is thus every basis for supposing that U_a can also be negative at high pressures (greater than atmospheric). It is convenient to organize the processes in plasma units in such a way that a transition to a regime with positive U_a is not realized, since it is less convenient from all points of view.

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EXCITATION OF ELECTROMAGNETIC OSCILLATION IN THE PLASMA ZONE OF AN ELECTRON – ION OSCILLATING DISCHARGE

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UDC 533.98

Experimental data are presented on the excitation of electromagnetic oscillations in the plasma of an electron – ion oscillating discharge. The mechanism by which the neutral medium is excited by means of a beam of oscillating electrons and the resulting excitation of electromagnetic radiation are considered. The experimental results reasonably agree with theoretical conclusions for the idealized case of the passage of an electron beam through a neutral medium. A possible mechanism for the acceleration of high-energy electrons by an electromagnetic wave is hypothesized.

It has been demonstrated in a number of works [1-3] that studied an electron – ion oscillating discharge in a magnetic field, that the discharge cavity divides into two mutually connected regions in which the electrons and ions oscillate at low pressures in a system of electrodes whose potential alternates in sign. The electron component of the plasma is continuously populated basically by ionization processes within the discharge. The ion component is continuously populated due to ionization of the atoms of the neutral gas by the oscillating electrons.

The ionization mechanism for a neutral medium by an electron beam was theoretically solved in [4]. It was demonstrated that bremsstrahlung and scattering is accompanied by a disturbance of the medium in some spatial zone, formed due to cascade ionization processes by the electrons of the neutral atoms. Oscillations with a frequency [4]

$$\omega=\left\{\frac{4\pi e^2}{M}\left(\frac{3\pi Z^2e^4n_0\sigma^2N^3v_0}{4\alpha E_0\Delta}\right)^{\frac{1}{2}}\right\}^{\frac{1}{2}},$$

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