HEAT LOSSES IN A PULSED PLASMA ACCELERATOR

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The nonuniform distribution of the heat losses and of electric—current density in the profiled channel of a coaxial pulsed electromagnetic plasma accelerator was noted in [1].

It will be shown below that this nonuniformity is the main cause of high heat losses in the channel. By reducing the nonuniformity in the discharge distribution, we could experimentally reduce losses in the accelerating electrodes and increase the energy efficiency of the accelerator from 45 to 60%.

1. The experiments were performed on apparatus with the following parameters: the capacitance of the capacitor bank $C_0 = 1480\ \mu F$, working voltage $V_0 = 2–5$ kV (the initial energy $W_0 = 3.10^3 - 1.85 \cdot 10^4$ J). initial inductance of circuit $L_0 = 60$ nH, maximum discharge currents $I_m = 80–450$ kA, current half-cycle $1/2\,T = 3.4 \cdot 10^{-5}$ sec, and mean plasma velocity $v = 4–8 \cdot 10^6$ cm/sec.

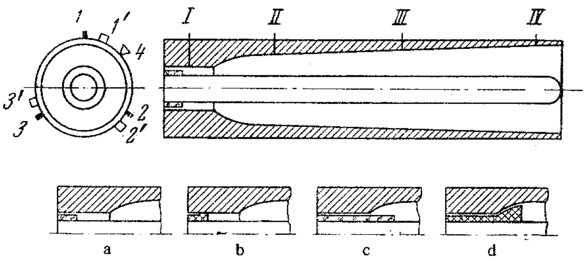

Fig. 1. Accelerating electrodes and four versions of initial section: a and b) quartz and teflon insulators in neck; c and d) quartz and teflon insulators in quasi-cylindrical channel; 1, 2, and 3) light guides; 1', 2', and 3') heat pickups; 4) keep-alive electrodes.

The studies were made under single-discharge conditions in a vacuum chamber with working pressure $P_0 = 5 \cdot 10^{-5} - 10^{-4}$ mm Hg.

The erosion material of the electrodes (copper or Dural) and of the insulators (quartz or teflon) was used as the working medium. Discharge in the channel was initiated by a special keep-alive electrode, to which was fed a high voltage pulse from a SFR high-speed motion-picture camera.

The following values were measured in the experiments; the initial energy of the capacitors and the initial pressure in the working chamber; the energy fed to the accelerating electrodes (from oscillograms of the total current and voltage drop across the electrodes); the distribution over the surface of the outer electrode of the total (during the discharge time) heat fluxes (with calorimetric heat pickups [1]); the light pattern for the development of discharge in the accelerator (with a SFR high-speed motion-picture camera using flexible light guides); the energy of the plasma jet, i. e., the energy efficiency* (with a calorimeter).

The energy of the plasma jet determined with a three-section cylindrical calorimeter 9 cm in diameter and 80 cm long (20 + 40 + 20). The calorimeter was installed 1 cm from the output section of the accelerating electrodes.

*Here, the energy efficiency is the ratio of the total energy of the plasma jet to the initial energy of the capacitors.

The shape of the accelerating-electrode channel is shown in Fig. 1. A feature of this channel is the narrow neck in the initial section, which becomes a quasi-cylindrical, circular channel. This profiling was used to stabilize discharge in the initial section and to ensure quasi-steady plasma acceleration over the entire length of the accelerator.

The accelerating electrodes had the following dimensions: length is 30 cm; the outside electrode diameter is 7.5 cm; the inside electrode diameter is 2 cm; the neck diameter is 3 cm. In the wall of the outside electrode 12 light guides and 12 heat pickups in four length sections, with three of each in each section, were installed. Their arrangement is shown in Fig. 1. Discharge was initiated by one of two keep-alive electrodes in the first section near the second section.

The shape of the initial section was varied and the material of the interelectrode insulator was chosen to control the discharge distribution. Four versions of the initial section were studied (see Fig. 1): (a) channel with narrow neck and quartz insulator; (b) channel with narrow neck and teflon insulator; (c) quasi-cylindrical channel with quartz insulator; (d) quasi-cylindrical channel with teflon insulator.

The measurements, which were made in the initial section of the accelerator, did not appreciably change its initial inductance.

2. Let us consider in detail the experimental results for each version at $V_0 = 3$ kV, ($W_0 = 6600$ J.)

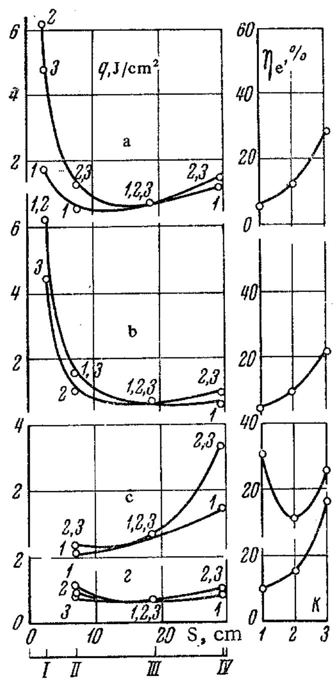

Fig. 2. Distribution of specific heat removal q over surface of outer electrode and energy of plasma jet η_e over sections of calorimeter (K). $V_0 = 3$ kV, $W_0 = 6600$ J.

The azimuthal and longitudinal distributions of heat removal, measured by the heat pickups, along with diagrams of the plasma-jet energy distribution over the sections of the calorimeter (1 is the section nearest to the calorimeter) are shown in Fig. 2. Figure 3 shows SFR-grams of the discharge patern obtained with the light guides. Here, the four photographs correspond to the four versions of the initial section and contain 13 frames each, which were taken at a speed of 1 500, 000 frames/sec and cover the entire first current half-cycle. In each frame, the 12 light points correspond to the 12 light guides. The four rows, from left to right, correspond to the sections, and each column, from top to bottom, corresponds to a heat pickup, which is situated on the circumference of the electrode, as shown in Fig. 1.

Version (a). With this version, the conditions and results were the same as in [1]. Additional information was obtained on the SFR-grams. The light pattern (Fig. 3, a) shows that discharge occurs near the third light guide in the first section (I-3) and the second and third light guides in the second section (II-2, II-3). Then the plasma fills the entire channel, and luminescence appears in all light guides of the third and fourth sections. Owing to azimuthal inhomgeneity of the discharge in the neck, light guides I-1, I-2, and II-1 remain dark during the entire current half-cycl e .

Similar conclusions can be drawn from the data of the heat pickups. From the graph of the heat-flux distribution (Fig. 2, a) it is apparent that the greatest heat flux is recorded in the first section by pickups I-2 and I-3, between which is light guide I-3. A correlation between the readings of the heat pickups and the light guides is also observed in the second section.

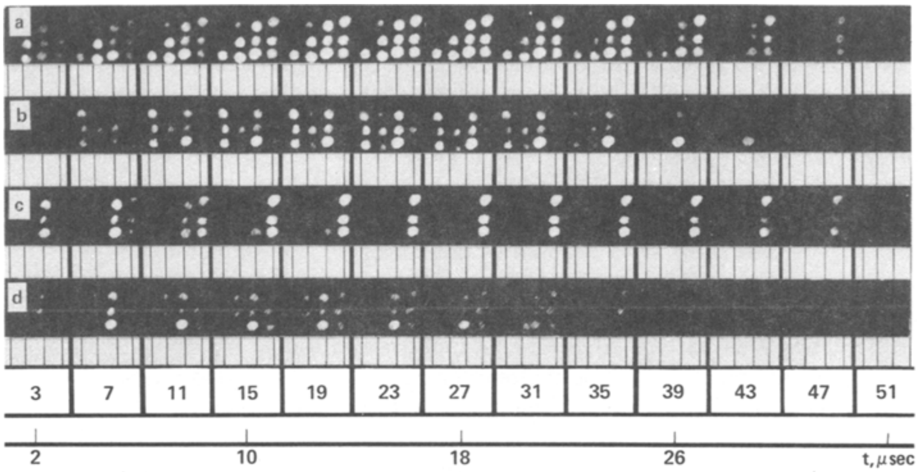

Fig. 3. SFR-grams of development for discharge in coaxial channel of accelerator. V_0 = 3kV, W_0 = 6600 J.

It follows from the current and voltage oscillograms that discharge in the accelerator is quickly extinguished. Only two current half-cycles are important; the main processes occur in the first half-cycle. The current maximum sets in 13 μsec after the beginning of discharge and is 250 kA, and the entire current in a half-cycle is 34 μsec.

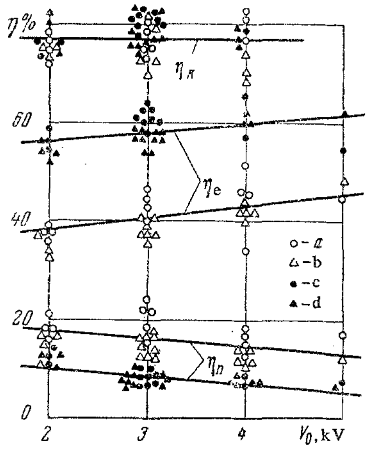

Fig. 4. Energy balance in pulse accelerator: η_k is the energy fed to the accelerating electrodes; η_e is the energy efficiency of accelerator; η_n are the losses to the electrodes as determined by the heat pickups.

Calculations of the energy fed to the accelerating electrodes, which were made from oscillograms, showed that 64% of the initial energy stored in the capacitors was fed to the electrodes by the end of the first half-cycle. In the second half-cycle, about 9% more of the initial energy is fed to the electrodes. In all, about 73% of the initial energy is fed to the electrodes. In all, about 73% of the initial energy was supplied to the electrodes in the experiment with version (a). The remaining 27% is lost in the capacitors and feed electrodes. In all further experiments, with accuracy to a few percent, the losses in the capacitors and feed circuit remained constant at about 25%.

The energy efficiency of the accelerator, as measured by the calorimeter, was 46% for version (a). Along with the heat-removal graph, Fig. 2, a, shows a graph of the energy distribution of the plasma jet over the sections of the calorimeter, from which it can been seen that the greater part of the energy is taken up by the last section of the calorimeter, which has a flat bottom, i.e., the plasma jet has narrow directivity and a small expansion angle.

Version (b). In this case, the quartz insulator in the neck was replaced by teflon (Fig. 1,b). Here, as can be seen from the graphs of the heat-flux distribution (Fig. 2,b) and the discharge distribution (Fig. 3,b), the azimuthal nonuniformity of the discharge in the neck is somewhat compensated, as compared with version (a). However, the longitudinal nonuniformity in the heat-flux distribution remained and the integral characteristics of the accelerator (total losses in channel, energy efficiency, etc.) were changed slightly.

Version (c). To reduce great longitudinal nonuniformity in the current distribution, whose main cause was evidently the narrow neck, the quartz insulator was moved from the neck 5 cm into the quasi-cylindrical part of the channel (Fig. 1c). The pickups and light guides of the first section gave zero readings in these experiments. Discharge was initiated in the second section.

The SFR-gram of the discharge (Fig. 3c) shows that in this case the discharge originates between the second and third sections, without being held in the initial section of the channel, and moves to the ends of the electrodes. This also follows from the graph of the heat-removal distribution (Fig. 2c). The total heat losses in the channel were reduced by approximately 10%, and the energy efficiency was correspondingly increased. As can be seen from Fig. 2c, however, the efficiency was increased due to an increase in the energy reaching the first section of the calorimeter. In this case, for the greater part of the current half-cycle the plasma is accelerated not within but at the ends of the electrodes and flows out in a widely divergent jet with thrust losses.

Version (d). In this version, the quartz insulator in the quasi-cylindrical channel is replaced by teflon (fig. 1d). Teflon is easily vaporized, and with it it is possible to "tie" the discharge to the initial section in the quasi-cylindrical channel. The SFR-gram (Fig. 3d) and the heat-removal distribution (Fig. 2d) show that both the azimuthal and longitudinal current distributions are fairly uniform in this case. The energy efficiency was increased to 60%, and the losses in the channel were reduced by approximately 10%. The uniform discharge distribution over the entire length of the accelerator made it possible to increase the energy efficiency to 60% while preserving the narrow directivity of the outflowing jet. It can be seen from Fig. 2d, that most of the energy of the plasma jet was recorded in the last section of the calorimeter.

3. The results of numerous experiments performed under the conditions considered above but for various initial voltages are shown in Fig. 4. The voltage is plotted on the axis of the abscissas, and the energy fed to the accelerating electrodes η_k, the energy efficiency of the accelerator η_e, and the total losses to the electrodes η_n are plotted on the axis of the ordinates as percentages of the initial energy. The total heat transfer to the electrodes was found assuming that the heat fluxes to the outside (anode) and inside (cathode) electrodes were the same [1].

From the graphs for the energy balance the following is apparent: 1) In all cases, 70–80% of the initial energy of the capacitors is supplied to the electrodes; the remaining energy (30–20%) is lost in the capacitors and the feed circuit; 2) in the initial-voltage range, $V_0 = 2–5$ kV (initial energy $W_0 = 3–18.5$ kJ), all energy characteristics, the energy efficiency, losses in the channel, and the energy fed to the electrodes are slightly dependent on voltage; 3) with conversion from a profiled channel with a narrow neck to a quasi-cylindrical channel, the energy efficiency is increased from 40–45% to 55–60% with simultaneous reduction of the heat losses to the accelerating electrodes.

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REFERENCE

1. A. M. Rushailo, "Measurement of thermal fluxes and estimation of electrode temperature in a pulsed electromagnetic plasma accelerator," PMTF [Journal of Applied Mechanics and Technical Physics] no. 4, 1965.

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