Microsecond plasma opening switches

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A review is given of Soviet and foreign publications on a rapidly developing new direction in the field of high-current electronics—plasma opening switches which operate with inductive energy storage requiring microseconds. A brief historical review establishes the connection between modern microsecond plasma opening switches (MPOSs) and previously studied pulsed plasma accelerators and high-current plasma discharges. The main experimental results obtained during investigations of MPOSs and modifications of them are described and analyzed. Recommendations for the construction of generators with MPOSs are given. The currently available theoretical and numerical models of opening switches are analyzed and compared with experimental results.

INTRODUCTION

One of the main directions in the development of high-current electronics at the present stage is associated with the study of new approaches to the problem of obtaining nanosecond high-voltage pulses with power $\geqslant 10^{12}$ W. For example, there is considerable interest in inductive energy stores, the advantage of which is the high specific energy uptake (up to 10 J/cm^3) compared with the capacitive analogs ($\cong 0.1$ J/cm^3). At the same time, difficulties in the creation of a reliable high-resistance breaker capable of switching the stored energy to the load in a time less than 10^{-8} sec prevents the wide use of inductive energy stores in practice. Until recently, the main attention of investigators was devoted to electrical-explosion current breakers,[1] which proved themselves well in the submicrosecond range of energy extraction.

During the last 15 years, a new approach based on plasma opening switches (POSs, also known as plasma erosion opening switches: PEOSs) has been strongly developed. Their use makes it possible to increase the output power of the pulse of standard nanosecond accelerators,[2] to eliminate the harmful influence of the charge prepulse on the operation of a high-current diode,[3] and to reduce the time spread over which the pulses reach the common load in multimodular systems.[4]

In general features, the sequence of operation of a POS is as follows. Near the load of the pulse generator, a plasma bridge is created between the grounded and the charged electrodes. The current of the generator initially flows across this bridge, and partial (or complete) transfer of energy from the capacitive to the inductive store takes place. Under certain conditions, the conductivity of the plasma bridge decreases sharply, an eddy emf is generated, and the inductively stored energy is switched to the load.

Experiments with generators of powerful nanosecond pulses demonstrated the ability of POSs to extract energy from an inductive store to the load during a time $\leqslant 10$ nsec, to withstand a voltage of several megavolts, and to operate at currents of several mega-amperes.[2] This strengthened the interest in POSs operating in the microsecond range (MPOSs) in the hope of completely eliminating fast water stores in generators of the terawatt range.

It should be noted that the first experimental investigations in this direction already showed that the regime of operation of MPOSs largely resembled the operation of pulsed plasma accelerators and the development of high-current gas discharges, which were already investigated in the seventies.[5–9]

These studies established the existence of two regimes of operation of a pulsed plasma accelerator: "fast" (deflagration) and slow ("snowplow"). In operation in the "fast" regime, generation of ions with energy greater than 10^5 eV propagating in the axial direction was observed. The onset of ion generation coincided in time with the arrival of the current channel at the front boundary of the gas cloud and the appearance in the plasma of an anomalously high resistivity. The duration of this process and of the accompanying pulses of x rays and microwave radiation did not exceed 10^{-7} sec. The propagation of the current channel was characterized by a more rapid diffusion of it near the anode, since the current lines were bent by the Hall effect in the direction of the electron drift.

The theoretical description of the processes in each time stage required the use of different models.[5,6] The propagation dynamics of the current channel in the conduction stage was described in the framework of a two-dimensional hydrodynamic model with allowance for the Hall effect, while the appearance of the anomalously high plasma resistivity and the acceleration of the ions were described by the development of current instabilities.

The investigation[8,9] of high-current discharges in plasmas of density $n_i \cong 10^{13}$ cm^{-3} showed that at a current amplitude above a certain critical value the development of an anomalously high resistivity is also observed, and the

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main potential difference is localized in a narrow section of the plasma column with the lowest density and generates high-energy electron and ion streams. This phenomenon was associated with the formation and evolution of a double layer[10,11] formed if the external power source can ensure in the circuit a current greater than the limiting current of the plasma. The plasma-filled diodes used by Plyutto[12,13] to investigate the formation of high-power electron beams and the collective acceleration of ions at current and voltage amplitudes in the circuit not greater than 10^4 A and 10^4 V, respectively, can be seen as the prototype of a MPOS.

In the present stage, investigations of MPOSs were begun at the Institute of High-Current Electronics of the Siberian Branch of the USSR Academy of Sciences in 1984 with the generator Gamma.[14,15] In these experiments, a capacitive generator of powerful pulses was discharged to a plasma-filled diode that combined the functions of a MPOS and load. The results indicated the ability of a plasma opening switch to maintain a low-resistance state for 10^{-6} sec at currents of several hundred kiloamperes and then rapidly increase its resistance to about 10 Ω, leading to a twofold increase of the voltage in the diode compared with the output voltage of the generator. However, during the investigations it did not prove possible to obtain an impedance of the MPOS greater than 10 Ω. In addition, the electron beam generated on the opening of the MPOS was dispersed on the inner walls of the anode, destroying them. For this reason, the opening switch and load were separated by the construction in the later experiments.

Further development of the concept of a MPOS was associated with experiments with the generator Marina,[16] in which MPOSs of coaxial type like POSs of the nanosecond range[2] were investigated. These studies made it possible to determine the dependence of the MPOS resistance on the time, to estimate the displacement of the plasma in the conduction phase, to show that the voltage generated across the MPOS exceeded by more than three times the open-circuit voltage of the generator, reaching the value 2.5 MV, and to conclude that effective generation of high-power electron and ion beams was possible.

Since 1986, experimental investigations of MPOSs have also been made at NRL (Washington), at the I. V. Kurchatov Institute of Atomic Energy (Moscow), and at the Institute of Nuclear Physics (Tomsk). Later, such studies were also taken up by the P. N. Lebedev Physics Institute (Moscow), the D. V. Efremov Institute of Electrophysical Apparatus (Leningrad), the Maxwell Laboratory (San Diego, USA), and Cornell University (USA). At the present time, the most powerful facility with MPOSs is the generator GIT-4 (Institute of High-Current Electronics, Siberian Branch of the USSR Academy of Sciences, Tomsk), at which an output power of about 3 TW has been achieved. The more powerful generators GIT-16 (Institute of High-Current Electronics) and FALCONE (Physics International Company) are under construction.

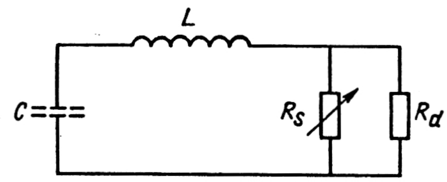

FIG. 1. Equivalent circuit of a generator with MPOS.

1. CONSTRUCTION OF GENERATORS WITH MICROSECOND PLASMA OPENING SWITCHES

As we already noted in the Introduction, interest in MPOSs arose after it had been shown that POSs could operate successfully in the nanosecond range, and this interest was natural, since the transition to the microsecond range would, while preserving the opening characteristics of the switch, make it possible to simplify and reduce the cost of pulsed generators considerably without reducing their high output power.

Like any generator, generators with MPOSs must be constructed in such a way as to generate a power pulse of given shape at a given load. For this, complete information about the parameters of the MPOSs is needed, but at the present time this cannot be obtained. For this reason, the currently constructed generators serve mainly to investigate the MPOSs themselves. Nevertheless, some general principles of the construction of generators with MPOSs can be determined from analysis of the equivalent circuit shown in Fig. 1. In this circuit, the MPOS is modeled by the resistance R_s, which at the initial time increases abruptly, while the load is modeled by the constant resistance R_d. Such a representation of a MPOS is justified by the fact that the MPOS impedance increases to its maximal value during a time in which the current in the inductive store can hardly decrease. In this case, the maximum-power regime of the inductive generator is realized under the condition $R_d=R_s$, and then the power in the load is $P=0.25I_s^2R_s$.

If the current I_s in the inductance L is obtained on discharge of the capacitor C, charged to voltage u_0, then $I_s=u_0/\rho_0$, where $\rho_0=(L/C)^{1/2}$, and then

$$P=0.25\frac{u_2^0}{\rho_0}\frac{(I_sR_s)}{u_0}. \qquad (1)$$

Investigations showed that $(I_sR_s)\cong\text{const}\cong 2$ MV. In this connection, it follows from the expression (1) that to obtain the highest possible power in the load it is necessary to have a primary store with large output voltage u_0 and low wave impedance ρ_0. This requirement is met by a multimodular arrangement of Marx generators. In contrast, to obtain the maximum power multiplication, which is equal to (I_sR_s/u_0), it is necessary to reduce the voltage of the primary store, i.e., the use of a MPOS for this purpose is expedient for a low-voltage current bank.

Let us consider the constructional details relating to the vacuum insulator separating the oil and vacuum volumes and the problem of shielding the capacitors of the

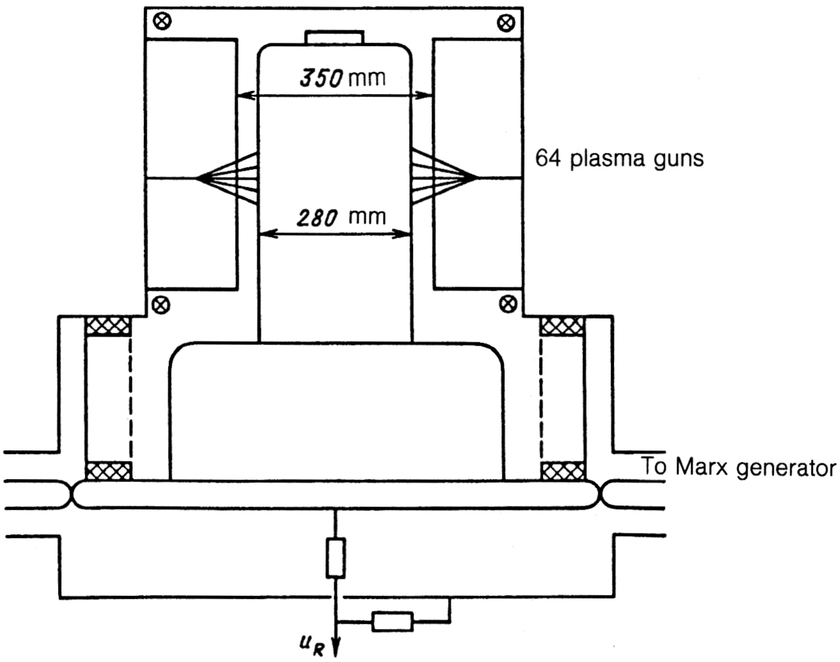

FIG. 2. Arrangement of experimental facility at the GIT-4 generator with MPOS.

generator. If the insulator is placed far from the MPOS, the regime of its operation is strained because of the long effect (about 1 μsec) of the high voltage in the phase when the current is delivered. In the event of electrical breakdown of the insulator, the inductance of the discharge circuit is reduced, and the amplitude of the current in the reverse half-wave can be greater than the amplitude in the direct half-wave. If the vacuum insulator is taken closer to the MPOS, its dielectric strength can also be affected by the intense radiation from the region of the MPOS. Therefore, in each particular case it is necessary to take into account these factors and their dependence on the employed capacitors and vacuum insulator and on the radiation from the region of the MPOS.

As an example, we consider the generator GIT-4, which was built at the Institute of High-Current Electronics in Tomsk at the end of 1986.[17] The primary store of the generator is made of 36 Marx generators connected in parallel. Each of them contains 48 capacitors of the type IK-0.4-100 and has output capacitance 0.133 μF and inductance 1.8 μH. The generators are arranged nine at a time in each of four oil tanks. On discharge, the energy is transmitted to the vacuum insulator through four oil lines; the inductance of the entire construction up to the vacuum insulator does not exceed 100 nH. For charging voltage 60 kV, the amplitude of the output voltage of negative polarity is $u_0 = 720$ kV ($W = 1.24$ MJ).

The vacuum insulator has a cylindrical shape and is made of 20 polyethylene rings that have a 45° bevel on the vacuum side and are separated by gradient rings. The vacuum part of the inductive store is made in the form of coaxial lines and was put in place without dismantling the vacuum insulator.

The search for optimum geometry of the MPOS and optimum relationship between the inductances of the vacuum and oil parts of the inductive store led to the arrangement of the experimental facility shown in Fig. 2. The central electrode of the facility, to which a negative-polarity pulse is applied, has diameter 280 mm and is separated from the outer grounded electrode, which is constructed in the form of a squirrel cage, by a distance of 35 cm. Plasma generated by 64 plasma guns of capillary type is injected through the opening in the squirrel cage radially along the direction to the central electrode. The inductance of the coaxial system from the sectioned insulator to the plasma injection plane is $L_v = 115$ nH. The insulator divides the complete inductive store into approximately equal parts. An electron diode with variable interelectrode gap serves as a load of the MPOS.

Figure 3 shows oscillograms of the current I in the inductive store, the voltage u_R across the insulator, the voltage $u_s = u_R - L_v(dI/dt)$ across the MPOS, the impedance $R_s \cong u_s/I$ of the MPOS, and the power $P_s = u_s I$. The amplitude of the output voltage in this case was 600 kV. It follows from the oscillograms that when the MPOS is actuated, breakdown of the vacuum insulator occurs when the voltage across it reaches 0.77 MV. The MPOS impedance increases at a rate $\sim 2\times10^7$ Ω/sec and does not exceed 1.08 Ω; the voltage that is then generated is 1.96 MV, and the power released into the MPOS is 3.42 TW.

As we have already noted, for $u_0 = 600$ kV the power of the GIT-4 generator in the matched load can exceed the power of its primary store by not more than 3.3 times (2 MV/0.6 MV). An additional increase of the power can be achieved by using a second stage with a POS of the nanosecond range.

Analysis shows that if the second stage of power multiplication with such a POS (POS2) has impedance $R(t)$ that rises during the time τ_R to the value R_0 and is actuated at the time when the current in the inductance L_2, which separates the MPOS and the POS2, increases to the value $I_0(1 - e^{-1})L_1/(L_1 + L_2)$, where L_1 is the inductance of the insulator–MPOS circuit, then in the load R_L it is possible to achieve the maximum power

$$P_2=0.2\frac{u_0^2}{\rho}\frac{R_0}{\rho}\frac{L_1^2L_2}{(L_1+L_2)^2(2L_2+R_0\tau_R)}, \tag{2}$$

where u_0 is the output voltage of the Marx generator; $\rho=(L_1/c)^{1/2}$ is the wave impedance of the discharge circuit up to the MPOS; and R_0 is the POS2 impedance. In this case, the maximum power regime corresponds to fulfillment of the conditions

$$R_L=\frac{2R_0L_2}{2L_2+R_0\tau_R}; \tag{3}$$

$$L_2=[\tfrac{1}{4}R_0\tau_R(L_1+\tfrac{1}{16}R_0\tau_R)]^{1/2}-\tfrac{1}{8}R_0\tau_R;$$

$$\tau_2=\frac{1}{2}\tau_R, \tag{4}$$

for which the inductance L_2 is arranged in the form of a vacuum coaxial with length corresponding to the time of passage τ_2 of the electromagnetic wave. In this case, the power multiplication after the second stage compared with the power of the primary store will be

$$k=\frac{2}{3}\frac{R_0L_1^2L_2}{(L_1+L_2)^2(2L_2+R_0\tau_R)}\sqrt{\frac{C}{L_1}}. \tag{5}$$

Experiments with a second stage made using the GIT-4 generator showed that for maximum current 600 kA in the POS2 and diameters 210 and 40 mm of the outer and inner electrodes, respectively, the POS2 impedance increased to $R_0=11\ \Omega$ during $\tau_R=12$ nsec. Using these data, and also the parameters of the GIT-4 ($u_0=720$ kV, $C=4.8\ \mu$F, $L_2=0.22\ \mu$H, $I_sR_s=2$ MV), we obtain for the maximum power in the load R_L the following values: $P_M=0.72$ TW from the primary store ($R_L=0.24\ \Omega$); $P_1=2.0$ TW in the first multiplication stage ($R_L=1\ \Omega$); and $P_2=3.7$ TW in the second multiplication stage ($L_2=70$ nH, $\tau_2=6$ nsec, $R_L=5.7\ \Omega$).

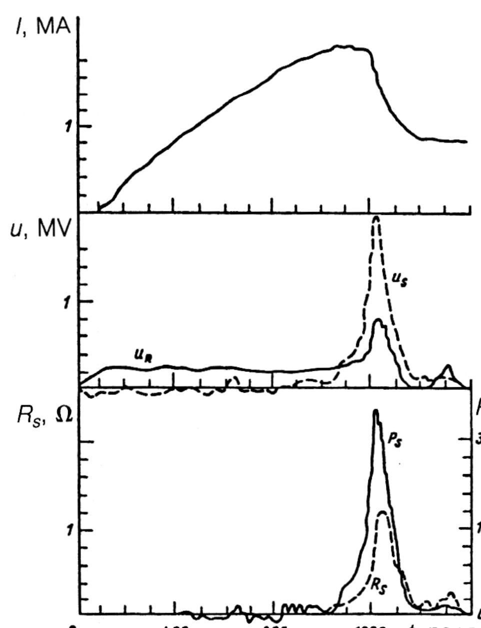

FIG. 3. Characteristic oscillograms of pulses obtained during operation of a MPOS with a generator GIT-4.

Thus, the second multiplication stage makes it possible to increase the power of the GIT-4 generator by more than 5 times.

To conclude this section, we consider the plasma sources and diagnostics.

To fill the interelectrode gap of the MPOS with plasma, various modifications of the pulsed plasma accelerators mentioned in the Introduction were used. These were usually plasma guns of coaxial type with electrical breakdown over the surface of an insulator placed between the coaxial electrodes.[18] Modifications of this type include plasma guns of capillary type,[19] which have a simpler construction. Surface plasma sources[20,21] have also been widely used; these form a chain of discharge gaps and make it possible to generate a large number of plasma bunches, thereby ensuring that the interelectrode gap of the POS is uniformly filled with plasma. These sources ensured generation of a multicomponent plasma (usually H^+ and C^+, C^{++}). To obtain single-component plasma streams, plasma guns with pulsed injection of gas (H_2, D_2, He, Ar, Kr) were used in the study of Ref. 22.

In the majority of the experiments, the plasma sources were arranged uniformly around the azimuth on the side of the outer electrode, which had longitudinal slits to ensure the necessary geometrical transparency. The distance to the central charged electrode was taken sufficiently large for space–time separation of the plasma bunch from the neutral component produced during operation of the plasma sources. The power was supplied to the plasma guns from low-inductance banks of capacitors with stored energy from a few kilojoules to tens of kilojoules, depending on the number of plasma guns and on the required amplitude of the current through the MPOS.

The parameters of the plasma generated by the plasma guns were studied by electrophysical and spectroscopic instruments. Allowance was made for the fact that for a coaxial plasma gun with erosion of the insulator the velocity and concentration of the plasma depend on the parameters u_B, C_B, L_B of the capacitor bank as follows (Ref. 23): $v_p=(\mu_0/4)[\ln(r_0/r_i)](u_B/M)(C_B^3/L_B)$ and $n\sim M/v_p$, where M is the mass of the plasma, and r_0 and r_i are the outer and inner radii of the plasma-gun electrodes. During the experiments with the MPOS, the values of v_p and n were usually varied in the range 5×10^6–2×10^7 cm/sec and 10^{13}–10^{14} cm^{-3}, respectively, and the time delay of the actuation of the generator relative to the onset of plasma generation was 1.5–10 μsec. The axial extension of the region originally occupied by plasma did not exceed 10–15 cm, and the radial separation between the central electrode and the outer coaxial electrode was varied in the range 2–12 cm.

To determine the current parameters of the MPOS, a Rogowski loop was used. In view of the complexity of the determination of the true voltage at the opening of the MPOS, the experiments were usually made with simultaneous use of capacitive or active-capacitive voltage dividers placed before and after the opening switch, in the readings of which a correction was introduced for the inductive component of the voltage across the voltage-divider–MPOS section. However, it should be borne in mind here that in the case of long lines and short fronts ($\tau_f \ll l/c$) wave processes and associated reflections of the electromagnetic wave occur. In addition, the amplitude of the voltage pulse across the MPOS can be recovered from the front of the current switched to the inductive load, but in this case it is necessary to take into account the possibility of erosion of the leading edge of the electromagnetic wave as it propagates along the vacuum coaxial cylinder.[24] The voltage across the MPOS can also be determined from the data of x-ray sensors used to detect the bremsstrahlung of the electrons.[25] The dynamics of the electron and ion streams in the MPOS was studied by means of collimated Faraday cylinders set up both inside the charged electrode and at different angles on the side of the outer electrode. The axial extension of the MPOS was determined from the distribution of the electron bremsstrahlung in this region and from the ion losses to the charged electrode. In the last case, the nuclear-activation method was also used. In some investigations, the qualitative picture of the plasma emission in the region of the MPOS was studied by means of individual frames of a film or using slow motion of the film.

2. THE CONDUCTION PHASE

The experimental investigations of the MPOS, which were made in a wide range of current amplitudes from tens of kiloamperes[26] to a few mega-amperes,[27] can be nominally divided into two parts: the investigation of the conduction phase and the investigation of the current switching phase.

The conduction phase determines above all the efficiency of transmission of the energy from the capacitive store to the inductive store. The main characteristics of the phase are the impedance of the opening switch, the maximum current amplitude, and the displacement of the plasma bridge from the generator to the load.

Electrophysical measurements showed that the growth of the current in the MPOS differed from the calculated value

$$I = u_0 (C/L)^{1/2} \sin[(LC)^{-1/2} t] \qquad (6)$$

and from the experimental value found when a short circuit was placed at the position of the plasma source.[28,29] This may have been due to the growth of the circuit inductance due to electrodynamic motion of the plasma under the influence of the force $\mathbf{j}_r \times \mathbf{B}_\theta$. This would lead to generation of a counter emf $\varepsilon = -I(dL/dt)$, reducing the voltage of the generator acting in the circuit. Another factor could be the development of plasma instabilities leading to growth of the resistance. Both effects lead to energy losses. In the first case, the loss is due to the increase of the kinetic energy of the plasma, and in the second case it is due to heating of the plasma. This complicates the matching of the MPOS to the load because of the possible penetration of plasma into the region of the load and the appearance at it of a prepulse voltage.

It was found in the studies of Refs. 26 and 30 that the resistance of the POS in the conduction phase did not exceed hundredths of an ohm; at the same time, the voltage across the switch increased to 1 kV by the time of the main discharge for negative polarity of the central electrode and to 3–6 kV for positive polarity of the electrode. The duration of the voltage prepulse was 100–300 nsec at time 0.9–1.2 μsec before the switching. In experiments with the generator Dubl' in operation to a short-circuited load ($L_L = 0.6\ \mu$H) the pulse of the switched current began 400–600 nsec before the onset of the main interruption of current through the POS ($t_c \cong 0.8$–$0.9\ \mu$sec), its amplitude reaching a few kiloamperes. This effect was most clearly manifested in the case of coaxial geometry of the POS with interelectrode gaps $r_A - r_c > 10$ cm and time delay to the current interruption of $\leqslant 0.9\ \mu$sec. In this case, the amplitude of the prepulse current increased to 20 kA.

Experiments with the MPOS showed that the maximum current amplitude depended (for otherwise unchanged parameters) on the diameter of the inner negative conductor, the number of plasma guns, the time delay between the injection of the plasma and the firing of the main generator, and the rate of growth of the current.

The dependence of the maximal current I_s on the diameter D_s of the inner conductor has the most pronounced nature and is decisive in changing the current by an order of magnitude. For example, experiments made with the generators Marina ($\cong$250 kA) and GIT-4 ($\cong$2.5 MA) showed[17,31] that a tenfold increase of I_s required a similar increase of D_s (from 30 to 280 mm) if the same method of plasma injection (from the outer anode conductor to the inner conductor) was used. Thus, we can write the relation $I_s/D_s = 7$–8 kA/mm = const, which tells us the minimum diameter of the central conductor that is needed to translate energy from the primary store to the inductive store for subsequent realization of high parameters of the current switching.

The current amplitude I_s also depends on the parameters of the initially injected plasma. The dependence of I_s on the number N of plasma guns was studied with the GIT-4 generator. The plasma concentration of the MPOS was not measured, so that in this case one can only speak of the change in the total amount of plasma injected into the volume of the MPOS. The current was found[31] to be proportional to the square root of the number of guns, i.e., $I_s \sim N^{0.5}$. Similar investigations with different numbers of surface spark plasma sources were made in experiments with the generator HAUK.[32] In this case, the plasma concentration was found to be proportional to the number of sources, and the current amplitude in the MPOS to depend on the concentration as the fourth root, $I_s \sim n^{0.25}$, in contrast to the POSs of the nanosecond range, for which this dependence has the form $I_s \sim n$.

The dependence of the current I_s on the delay time is used to choose the MPOS working regime. If the delay time is increased above a certain minimum value, the current I_s begins to increase until saturation is reached or a short-circuiting regime is realized. The minimum delay corresponds to the time needed for the plasma to cross the interelectrode gap of the MPOS.

The current amplitude I_s also depends on the rate of delivery of current to the MPOS. This can be changed by changing the output voltage u_0 of the Marx generator or by changing the inductance L_1 of the discharge circuit. The main result obtained in these experiments was that in the operation of the microsecond plasma opening switch the critical-current criterion is not manifested so clearly as for the nanosecond analog,[33] a result also confirmed by the studies of Refs. 34–36. When the current delivery rate $\dot{i}_s(t)$ is increased, the amplitude of the limiting current I_s increases, while the duration of the conduction phase is shortened, this process depending on the MPOS geometry. Thus, in the GIT-4 experiments for a coaxial MPOS in the geometry with 160 mm/210 mm (cathode diameter/anode diameter), an increase of the output voltage u_0 of the Marx generator from 300 to 480 kV led to a growth of I_s by about 11%, whereas in the geometries with 480 mm/580 mm and 280 mm/350 mm growth of u_0 from 480 to 720 kV gave a growth of I_s by about 55%. In experiments with a MPOS of axial type, the rate of growth $\dot{I}_s(t)$ of the current was changed by 2.4 times by changing L_1 from 600 to 250 nH. The increase in I_s was on the average 27%.[34]

The displacement of the plasma bridge was investigated by means of optical methods, magnetic probes, and detection of the fluxes of charged particles to the MPOS electrodes.

In Ref. 37, photographing (exposure time 80 nsec) from the end of the region of a coaxial MPOS ($I_s \cong 10^5$ A, $t_c \cong 10^6$ sec) revealed a decrease of the plasma luminosity long (500 nsec or more) before the onset of the current switching near a negative central electrode and in the middle of the interelectrode gap in the case of a positive central electrode. During the conduction phase, these regions with reduced plasma luminosity had a tendency to expand. The photographs also revealed radial jets, the number of which corresponded to the number of plasma guns.

Optical investigations (slow-motion regime) of a microsecond POS of coaxial geometry (negative central electrode) with the Dubl' generator[38] were made in two regimes of operation of the opening switch: a) without current breaking; b) in the working regime, with opening ($u_s = 1.2$ MV). In the first case, weak emission was observed at the cathode; it appeared near the time of maximum current of the generator, and the speed of its propagation along the cathode to the load (closed coaxial inductance) increased after the maximum of the current; at the same time, there was no emission at the anode. In the second case, cathode emission began long before the current switching, and it was also displaced toward the load. The speed of propagation of this emission increased, reaching the maximum value $\cong 3\times10^8$ cm/sec at the time of the current switching. At the time of the current switching, the intensity of the emission at the cathode increased sharply, and emission on the anode surface, which was displaced toward the load, appeared. Similar investigations of the emission dynamics of the cathode plasma were made in the study of Ref. 39 with the facilities POP and HAUK at amplitudes of the current through the POS of 200 and 700 kA and durations 0.8 and 1.2 μsec of the conduction phase, respectively. These investigations were made by means of optical fibers placed along the negative electrode. The results of these experiments indicated (Fig. 4) the existence of time delays for the appearance of radiation from the cathode surface, the magnitudes of these delays increasing in the direction toward the load.

Thus, the experiments described above confirm that already in the conduction phase plasma, evidently capable of explosive emission, is formed on the cathode surface, the region of generation of it being displaced toward the load with increasing current through the POS.

First investigations of the dynamics of magnetic-field penetration into the plasma for times of current delivery to a POS of coaxial geometry up to 240 nsec were reported in Ref. 40. The results of these investigations agreed with results obtained earlier by the same authors[41] working on nanosecond POSs ($t_c \cong 10^{-7}$ sec). For total length $l=12$ cm, the current flowed through width 3 cm in the channel in the first 40 nsec; 120 nsec later the current had penetrated to 6 cm, and during the last 40 nsec before the switching there was rapid penetration of the current to the remaining length of the POS. Flow of radial current behind the current channel was not observed. Subsequently, these investigations were continued with the generators POP and HAUK[39] and Dubl',[38] which differed only in the radial interelectrode gap ($r_A/r_c=2.8$ for POP, $r_A/r_c=1.64$ for HAUK, and $r_A/r_c=4.44$ for Dubl'). The results of Ref. 39 revealed mainly a radial profile of the current channel propagating along the POS in the direction of the load with $v_{cc} \cong (1\text{–}2)\times10^7$ cm/sec in the first 600 nsec of the duration of the conduction phase and with $v_{cc} \cong 10^8$ cm/sec in the following 200 nsec before the current switching. The picture of the current lines is shown in general form in Fig. 5, from which it follows that the stream of electrons emitted from the cathode surface initially moves along the cathode surface and only then is directed toward the anode. It was noted that the penetration of the current was more rapid near the anode than at the cathode. In Ref. 38, a radial profile of the current channel was also obtained in the first 400 nsec after the onset of delivery of the current, but the current lines were then bent toward the load because of the more rapid penetration of the current into the plasma in the anode region. The inclination of the current lines increased with the time and was maximal at the end of the conduction phase. The maximal displacement of the front of the current channel was observed, as in Ref. 51, during the last 100–50 nsec of the conduction phase, reaching the value $v_{cc} \cong 5\times10^8$ cm/sec, whereas its mean velocity in the cathode region during 850 nsec did not exceed 2×10^7 cm/sec, increasing sharply during the last 50 nsec before the switching. It was noted that the onset of the more rapid penetration of the current near the anode corresponded to the current channel reaching beyond the region of the initially created plasma. Subsequently, with

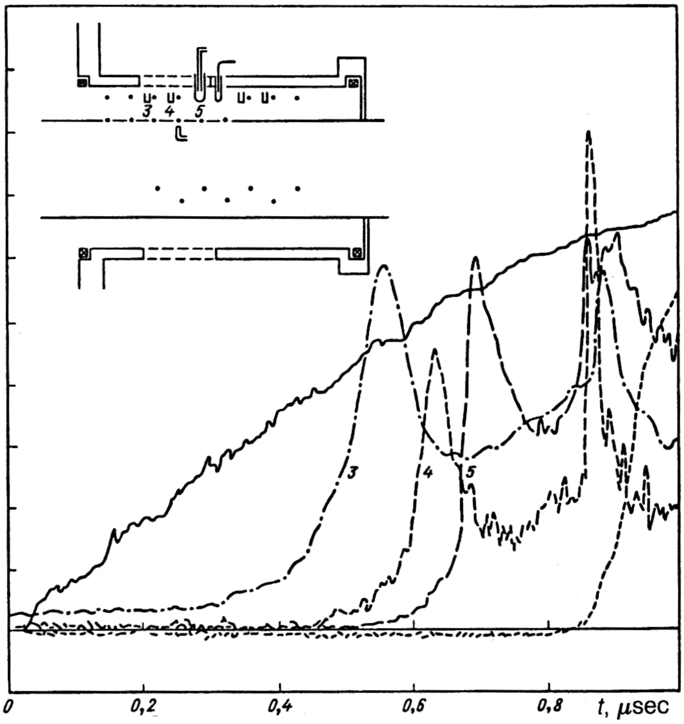

FIG. 4. Characteristic pulses of radiation near the cathode surface of the MPOS during the current conduction phase.

growth of the generator current, an increasingly large fraction of the current near the anode short-circuited behind the original plasma region, accelerating in the form of a tongue along the direction to the load near the anode.

The data show that the process of current diffusion in a POS takes place at a constant rate during approximately 800 nsec of the conduction phase. This indicates constancy of the mean value of σl, $\sigma l = \text{const}$ (l is the thickness of the plasma layer) and, therefore, a decrease of the plasma conductivity with increasing l. An estimate of the Spitzer conductivity of the plasma, $\sigma_S \cong 10^7 (T_e)^{3/2} \cong 10^{14}\ \text{sec}^{-1}$, gives a result exceeding the experimental value of the conductivity by 10^2–10^3 times, $\sigma_{\text{exp}} \cong 10^{11}$–$10^{12}\ \text{sec}^{-1}$. This last fact indicates the development of additional collision processes in the plasma that ensure the necessary electron collision frequency $\nu = ne/m_e\sigma_{\text{exp}} \cong 2.5 \times (10^9$–$10^{10})$, for which the ion-acoustic, Buneman, and lower-hybrid instabilities could be responsible.

The inclination of the current lines in the cathode region in the direction of the load is connected with the magnetization of the electron stream emitted from the cathode surface and drifting in the $\mathbf{E}_r \times \mathbf{B}_\theta$ fields, the resulting Hall voltage leading to their drift to the anode at the front of the current channel in the $\mathbf{E}_z \times \mathbf{B}_\theta$ fields.

Investigations into the penetration of the current and the corresponding magnetic field into the plasma were also made by studying the dynamics of the corpuscular streams (electrons to the anode and ions to the cathode) from the region of the POS. The first experimental results[42] on the study of radial electron streams in a coaxial POS ($I_s \cong 10^5$ A, $t_c \cong 1.2\ \mu$sec, central electrode of negative polarity) to the anode showed that the density of the electric current at the anode increased to 10^2 A/cm^2 in the median plane of the plasma injection from the central electrode. There was then observed to be a decrease of the electron current at this point, the onset of the decrease depending on the plasma parameters. Decrease of the plasma concentration led to an earlier decay of the electron current on the collector in the injection plane. With a further increase in the current of the generator, electron signals appeared on the following collectors, arranged at a distance from each other in the axial direction. The propagation velocity of the

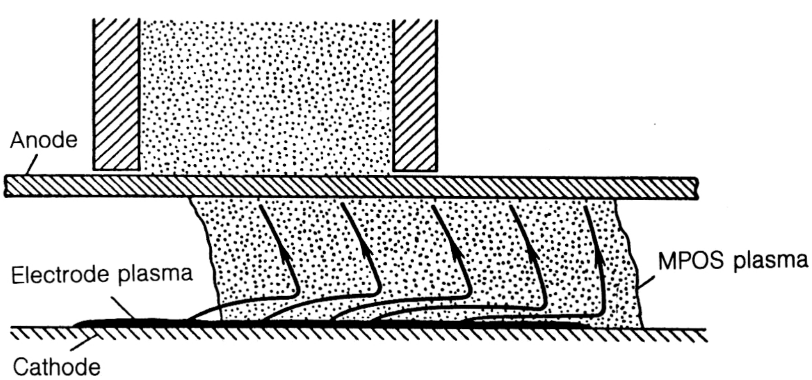

FIG. 5. Qualitative picture of the distribution of the current lines in a MPOS.[39]

current channel depended on the plasma concentration and was in the range 4×10^7–10^8 cm/sec. The amplitude of the electron current density increased along the direction to the load from 10 A/cm^2 at the generator boundary of the POS to 300 A/cm^2 on the side of the load. These data were confirmed by subsequent similar measurements using the generators Marina and Dubl'[43] and GIT-4.[27] This confirms the mechanism of successive penetration of the current into the plasma of the POS in the form of a current channel and also the magnetization of the electrons by their self-magnetic field behind it.

The paper of Ref. 37 reports first investigations of ion streams by means of collimated Faraday cylinders in the conduction stage of a microsecond coaxial POS for positive polarity of the central electrode and in the presence of an external axial magnetic field. The results of these investigations showed that already in the conduction phase there is a directed ion stream in the direction of the negative outer electrode with current amplitude exceeding the ion saturation current of the plasma. It was also noted that there was a time delay in the appearance of the ion signals along the length of the POS in the direction of the load. Similar investigations, but with negative polarity of the central electrode, were made in the studies of Refs. 38 and 39. In this case, the ion collimated Faraday cylinders were placed inside the charged electrode (see Fig. 4). The results of these investigations basically agreed with the conclusions of Ref. 37 and also revealed the gradual appearance of an ion current with amplitude much greater than the ion saturation current of the plasma along the length of the POS. It was characteristic that the signals from the Faraday cylinders at distances less than 40 cm from the plasma injection plane peaked already in the conduction phase, and then decreased monotonically.[38] Calculation of the integrated ion current showed that already at 300 nsec after the beginning of the delivery of the current to the POS its fraction in the total current exceeded the limit calculated using the $(m_e/m_i)^{1/2}$ relation and subsequently increased, reaching 20–30% by the end of the conduction phase. During these experiments, a correlation was established between the position of the current channel and the attainment by the ion current density of its maximum value at that point. In addition, the rapid increase of the total ion current at the end of the conduction stage (Fig. 6) corresponded to growth of the area of contact of the plasma of the opening switch with the cathode electrode, i.e., it corresponded to the onset at these times of the rapid motion of the current channel in the cathode region as it entered the load side of the plasma bridge. The results of measurement of the ion current can be related to the onset of erosion of the plasma behind the current channel in the cathode region already in the conduction phase. The voltage needed for this may arise through polarization of the plasma. The onset of plasma erosion already in the conduction phase may also explain the decrease in the ion current density at the current switching. The Child–Langmuir value of the ion current density will be determined in this case by the rate of growth of the voltage across the cathode double layer and by the plasma density at its anode boundary. However, there are other possible reasons for an increase of the ion current in the conduction phase of the POS, for example, a growth of the plasma concentration due to ionization of the neutral component or processes of secondary ionization of the C^+ ions.

The observed decrease of ion current at the beginning of the POS could be due to suppression of the neutralization processes of the assumed double layer resulting from the decrease in the thickness of the electron layer and growth in the size of the double layer. It must also be borne in mind that the decrease of the ion current density behind the current channel could also be due to electrodynamic motion of the plasma. In this case, owing to "sweeping up" of the plasma, its density will be maximal in the region of the current channel, explaining the maximum value of the ion current density in the channel.

3. THE PHASE OF THE CURRENT SWITCHING

The phase of the current switching is decisive in the operation of a MPOS, and the viability of the concept of an inductive generator with MPOS as a fast current opening switch depends on it. The main characteristic of this phase is the rate of change of the MPOS impedance on opening.

The first experiments with the generator Marina showed that at current $I_s\cong200$ kA the rate of growth of the MPOS impedance for a negative inner conductor could reach 10^9 Ω/sec. During 10–15 nsec, the impedance increased to $R_s=10$–15 Ω, so that the voltage across the MPOS reached 2–2.5 MV. The value of R_s was found to depend strongly on the diameter D_s of the inner conductor, the impedance R_s increasing with decreasing D_s. As we have already said, a minimum value of D_s was determined by the need to conserve the current I_s.

For unchanged diameter of the central conductor, an increase of u_0 led to an increase of the current I_s and a shortening of the duration of the conduction phase. At the same time, the current switching occurred in a section with steep growth of the current $I_s(t)$ in the MPOS, leading to an increase of R_s by 20–30%. Restoration of the duration of the conduction phase by increasing the time of delay of

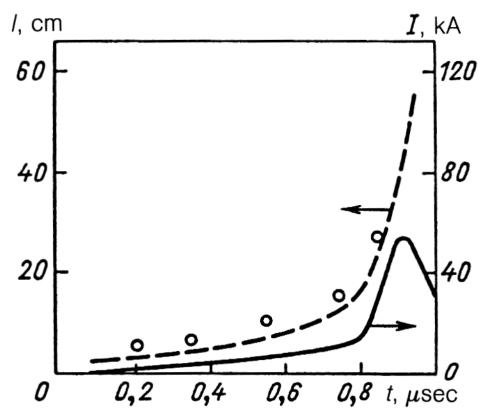

FIG. 6. Dependence of length of MPOS and of ion current on the time.

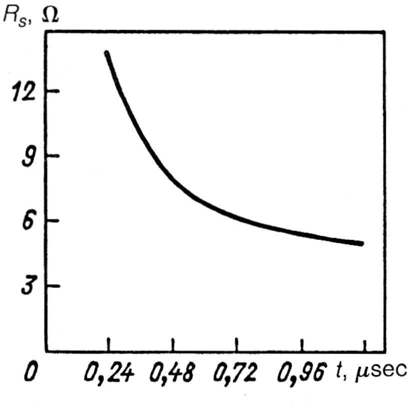

FIG. 7. Dependence of the MPOS impedance on the duration of the conduction phase.

actuation of the generator, the number of plasma guns, or the diameter of the central electrode invariably led to a decrease of R_s (Fig. 7). It should be mentioned here that many authors (at the Institute of High-Current Electronics at Tomsk, at the I. V. Kurchatov Institute of Atomic Energy, and at the Institute of Nuclear Physics at Tomsk Polytechnic Institute) observed cases of current switching in a MPOS when $\dot{I}(t) \leqslant 0$. With increasing I_s, the MPOS impedance R_s decreases, since it is necessary to increase the diameter of the central conductor. This is revealed particularly clearly by a comparison of the results obtained using the generators Marina and GIT-4, in which the currents differed by an order of magnitude. As we have already said, to increase the current in the GIT-4 it was necessary to increase the size of the cathode proportionately. However, the impedance R_s then decreased in proportion, so that the voltage across the switch remained as before:

$$u_s \cong I_s R_s \cong 2\text{–}2.5 \text{ MV}. \qquad (7)$$

The results can be explained by the example of parallel switching of several identical opening switches in identical discharge circuits. This leads to the same output voltage with proportionate increase of the total current and decrease of the equivalent resistance.

Reversal of the polarity of the inner electrode, from negative to positive, leads to a significant downgrading of the current switching characteristics of the MPOS. In the study of Ref. 28 the value of $\dot{R}_s$ changed in going from the "minus" regime to the "plus" regime from $(5\text{–}8) \times 10^8$ to 5×10^7 Ω/sec. Application of an external longitudinal magnetic field upgrades the MPOS parameters significantly in the "plus" regime and downgrades them in the "minus" regime.[44] Indeed, it was in the "plus" regime with an external magnetic field $B_z = 10$ kG that the record voltage for a MPOS, $\cong 4$ MV, was achieved.[45]

The direction of the plasma injection did not have a significant influence on the change in the impedance of a coaxial MPOS on opening. Figure 8 gives the results of the experiment of Ref. 28, which was made in the "minus" regime with plasma injection from the side of the anode (a) and the side of the cathode (b). In both cases, maximal impedance rates of growth of the MPOS, $(6\text{–}8) \times 10^8$ Ω/sec, and limiting values of R_s above 8–10 Ω were achieved. An important aspect of plasma injection from the side of the cathode is that in this case the energy expenditure in creating the plasma is an order of magnitude lower than in the case of plasma injection from the side of the anode.

The influence of the plasma composition on the switching characteristics was studied in Ref. 46. The plasma sources were plasma guns with pulsed injection of gas (H_2, D_2, He, N_2, Ar, Kr). These investigations revealed an improvement of the switching characteristics with decreasing atomic weight of the plasma ions. When hydrogen or deuterium plasma was used, $R_s \cong 20$ Ω and $u_s/u_0 \cong 4$ ($u_0 = 0.48$ MV), while in the case of Ar or Kr plasmas $R_s \cong 8$ Ω and $u_s/u_0 \cong 2$. In the experiments with plasma guns using N_2, Ar, and Kr gases, streams of protons with energy above 600 keV to the cathode electrode were observed; this indicated the importance of processes near the electrodes.[47]

Compared with the nanosecond analog, the impedance of a MPOS at the same current amplitudes I_s is appreciably lower. It was already shown in the first experiments[48] that for switching in the region of the MPOS a radially converging ion beam with current density decreasing in the direction of the load from 140 to 50 A/cm^2 was formed. The microdivergence of the generated high-power ion beam did not depend on the axial coordinate and was 5–7°, while the microdivergence in the azimuthal direction increased with increasing distance from the plasma source. The energy loss due to the ion stream for short-circuited ($L_L = 0.5$ μH) load was 4 ± 1 kJ and for "open-circuited" cathode was 5.3 ± 1.3 kJ at total energy losses in the POS of 6.2 ± 1 and 17 ± 4 kJ, respectively.[22] Measurements of the electron stream to the walls of the outer electrode showed the absence of significant loss in the region of the POS in the case of operation with short-circuited load ($\leqslant 0.65$ kJ, Fig. 9). For operation with open-circuited cathode, the electron losses increased sharply, owing to the formation of a high-power electron beam that drifted in the vacuum and had an energy content up to 12 kJ. The results indicate that in a MPOS the ion losses in the phase of the current switching may reach 70% of the integrated energy losses for an inductive load and 30% for the regime with open-circuited cathode. This is also a restriction on the maximum value of R_s.

Activation measurements showed that in the ion beam a large proportion of the energy is carried by the proton fraction. The upper limit of the energy of the generated ions basically corresponds to the voltage developed across the MPOS when it opens at current amplitudes up to 300 kA. On going to current amplitudes of 1 MA or more, this correspondence ceased to hold. For example, for experiments with the generator GIT-4 ($I_s \cong 1.2\text{–}1.4$ MA, $u_s = 800$ kV, $R_s = 1\text{–}3$ Ω) an estimate of the mean stream energy of the high-energy part of the protons based on the yield ratio $Y_{^{11}C}/Y_{^{15}O}$ on an NB target gave the value $(0.6\text{–}0.7) e u_s$, where e is the electron charge. This result, and also the fact that the contribution of the high-energy part of the ion stream was subject to pronounced (by up to

1.5 orders of magnitude) fluctuations despite fairly constant characteristics of the MPOS, indicates that a double layer may be formed not only in the cathode region but also in the anode region of the electrodes of the switch.

4. MODIFIED MPOS SCHEMES AND MATCHING OF THE MPOS TO DIFFERENT TYPES OF LOAD

The existing theoretical models and the experimental investigations that have been made indicate that the magnetic field of the current flowing through a MPOS plays a certain part in determining its characteristics. In this connection, the first modifications were aimed at increasing the self-magnetic field. By analogy with the nanosecond regime, a multiturn spiral was used for this purpose in the study of Ref. 49 as a section of the cathode electrode in the region of the POS. The additional inductance of this section made it possible to increase the magnetic field in the region of the POS by virtue of the axial component of the magnetic field. However, the data did not give an unambiguous answer because of lack of reproducibility of the results, this apparently being due to possible shorting of the interwinding gaps by the dense cathode plasma during the conduction phase ($\simeq 10^{-6}$ sec). Nevertheless, it was established that the axial extension of the MPOS was shortened by the arrangement with the helical section of plasma injection.[29] This effect was connected with the stopping of the plasma moving under the influence of the electrodynamic forces $\mathbf{j}\times\mathbf{B}$ by the additional axial magnetic field generated by the current flowing through the spiral.

In the study of Ref. 50, external magnetic fields of various configurations were used to reduce the electron losses in a POS. The main results of these experiments reduce to the following. Application of a homogeneous magnetic field to the region of the MPOS led to a downgrading of the switching characteristics. In this case, it was necessary to increase the time delays of actuation of the generator in order to allow the plasma, propagating at right angles to the lines of force of the magnetic field, to reach the surface of the central electrode. Application of an axial magnetic field to the region of the POS reduced the plasma flow velocity and made it easier for the neutral component from the plasma source to reach the cathode region. Besides this, the plasma electrons were magnetized, and this reduced still further the electron component of the conductivity in the conduction phase of the device. Nevertheless, as was noted above, only the use of an external longitudinal magnetic field made it possible in the study of Ref. 45, with positive polarity of the central electrode, to obtain efficient opening.

The creation of a magnetic field with "corkscrew" configuration on the side of the anode or cathode[50] in the immediate proximity of the plasma guns made possible practically complete suppression of the electrodynamic extraction of plasma from the region of the MPOS. For example, at current densities through the POS of $j\simeq 0.7$ kA/cm^2, total current $I_s \simeq 10^5$ A, and time 1.2 μsec to the current interruption, the axial extension of the switch was reduced from 25 to 10 cm. Besides this, in experiments made with the generator Dubl' using an analogous geometry of the magnetic field an improvement of the switching characteristics (by up to about 30%) was obtained.

The results of investigations of a microsecond POS in the case of two oppositely connected identical generators are described in Ref. 51. In this case, the magnetic field of the current from the generators began to diffuse into the plasma from two sides, and in the case of equal storage inductances this ruled out electrodynamic extraction of the plasma (Fig. 10a). Since a POS is, by itself, the source of a high-power ion beam, it was possible to increase the density of the ion current generated on the opening of the switch to 500 A/cm^2 as a result of the compression of the plasma in the median plane of the plasma sources. A shortcoming of this scheme is the large electron loss on the switching of the current due to the formation, in the center of the POS, of a region with a minimum of the magnetic field. A more attractive version is a modification of the POS[52] with an external azimuthal magnetic field (Fig. 10b). In this scheme, the magnetic energy is stored in the

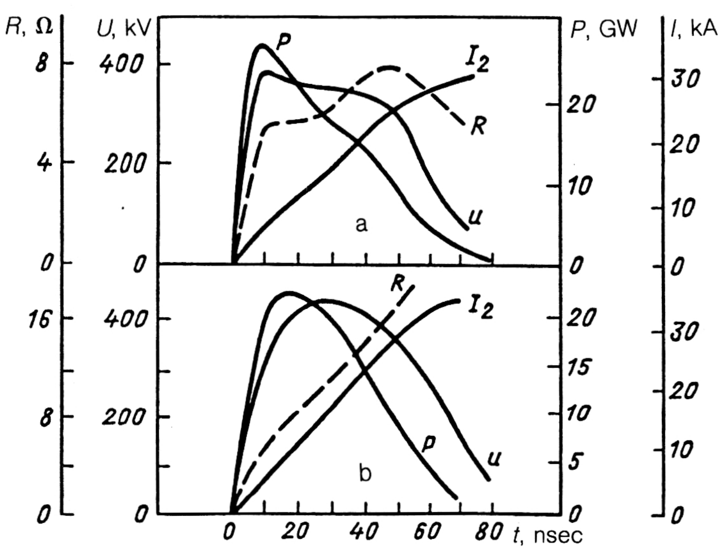

FIG. 8. Characteristic curves obtained during operation of a MPOS with a negative (a) and a positive (b) inner electrode.

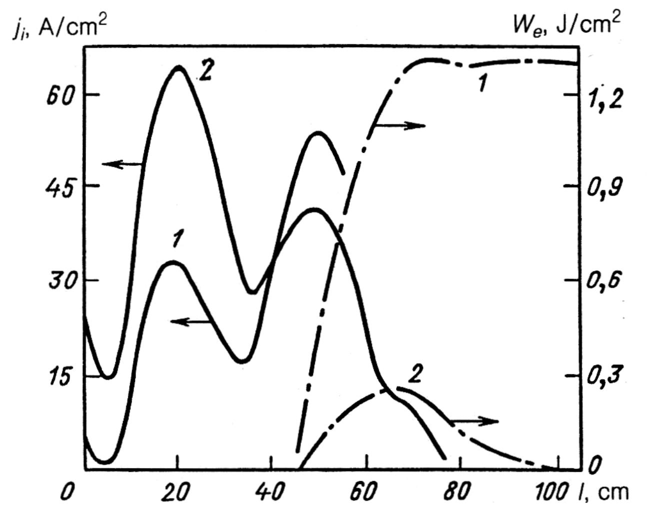

FIG. 9. Distributions of ion current density and energy-loss density of electrons along the MPOS in the current switching phase for open-circuit cathode (1) and switching to short-circuited load (2).

circuit formed by the anode support, the POS, and the grounded cathode. Then, by the passing of a fast current pulse from an additional generator, an azimuthal magnetic field is created in the region of the POS, and this can significantly improve the opening characteristics.

In the study of Ref. 53 the possibility of synchronizing several POSs working to one load by the introduction of a current feedback between the openers (Fig. 10c) was demonstrated. On the actuation of one of the POSs, the current flowing in its circuit was transferred to the circuit of another POS, causing accelerated actuation of it. The investigations showed that coupling between the switches must ensure switching of not less than 30% of the current of the first actuated POS to the second; at the same time, the asynchronism of the actuation of the two POSs did not exceed 100 nsec (the duration of the front of the switched current on actuation of the first POS).

When solving the problem of matching MPOSs with different types of loads, it is necessary to take into account the motion of the plasma and the streams of charged particles generated in the region of the MPOS.

A fairly complete analysis of the dynamics, before and after the POS, of the electron streams moving in the direction of the load in the interelectrode gap of a coaxial cable and transporting a considerable fraction of the current was made in Ref. 54. Before the opening switch, the appearance of an electron stream is connected with a sharp increase of the voltage and decrease of the current in the circuit, this leading to motion of the electrons from the cathode to the anode and to an increase in the thickness of the electron stream. After the POS, the formation of the electron

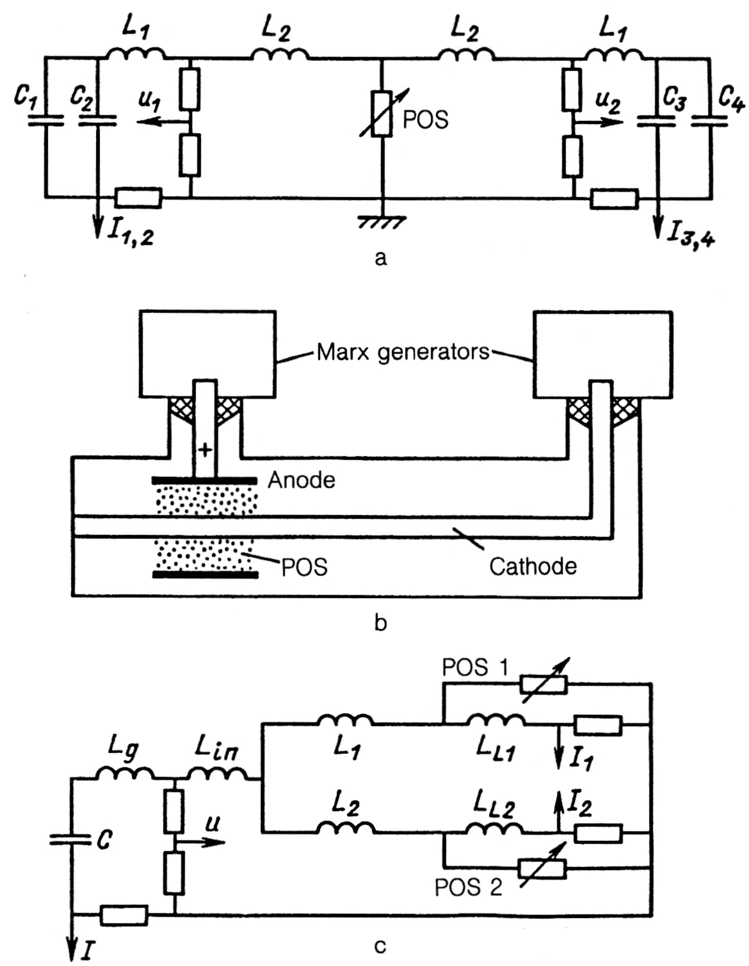

FIG. 10. Modified MPOS circuits.[51–53]

stream and its motion to the anode are due to a sharp increase of the vacuum impedance of the transmission line compared with the impedance of the POS.

When electron diodes are used as a load, this electron stream will, for an appropriately chosen geometry of the diode and a reduced length of the transmission line, be switched to the diode, making its own contribution to the generated electron beam. The situation is much more serious when one is operating with ion diodes. In this case, it is difficult for the drifting electron stream to pass through the interelectrode gap of the ion diode, especially when external magnetic fields are used in it. Moreover, because of electrodynamic drift, plasma may reach the region of the diode load if the latter is situated at a few tens of centimeters from the POS.[31] In this case, the plasma goes beyond the limit of the physical cathode, and on the opening of the POS there may be formation of an electron beam which propagates to the end of the outer electrode. The propagation of the electron beam in vacuum is due to its charge neutralization by ions extracted by the electric field of the space charge of the electrons from the plasma boundary of the POS and collectively accelerated during drift. Measurements of the characteristics of the propagation of the electron beam and of the energy spectrum of the collectively accelerated ions agree qualitatively with the results of investigations of the gas-dynamic acceleration of ions in reflection systems.[55]

In an investigation using plasma guns with pulsed deuterium injection in the operating regime of a MPOS, neutron fluxes up to 5×10^{10} neutrons/pulse were obtained in the case of H^+ and D^+ interaction with a lithium target. The energy of the collectively accelerated H^+ ions reached 4 MeV at maximum electron energy 1.2 MeV.[56]

As we have already noted, a MPOS is a modification of an ion diode with magnetic self-insulation of the electron stream.[57] Thus, in a POS geometry close to a "quasidiode" plasma-focus type a high-power ion beam was observed with energy $\geqslant$600 keV and up to 10^{17} particles per pulse ($\overline{I}_i \cong 300$ kA), this corresponding to 30–35% of the total current through the POS, but the angular divergence of such a high-power ion beam formed in the region of the "quasidiode" was at the level 15–20°. Moreover, there was no possibility of active control of its parameters.

The inclusion of an additional ion diode as a load of a MPOS can be achieved in two ways—before and after the MPOS. As was shown by the numerical analysis of Ref. 58 and the experiments of Ref. 43, an ion diode inserted before the MPOS is insulated by the magnetic field of the current that flows in the conduction phase. In this case, the closest position of the diode to the opener is possible. However, on opening, shunting of the MPOS is possible in the case $R_g < R_s$. To eliminate this phenomenon, it was proposed in Ref. 59 to use current diversion, i.e., to direct, by means of a special conductor, part of the current of the high-power ion beam generated in the diode to the region of the MPOS, the cathode of which is made in the form of a multiturn spiral. Investigations of the generation of high-power ion beams in coaxial magnetically insulated diodes with a passive plasma source at the anode and placed before the POS[48] demonstrated a high efficiency (up to 90%) of generation of the ion beam. The main shortcoming was the long (up to 15 nsec) time delay of the formation of the anode plasma relative to the start of generation by the eddy emf. Because of this, the ion current density reached the Child–Langmuir value only after 20–25 nsec. To increase the ion current and eliminate the time delay of its appearance, an active source of anode plasma was used. At current amplitude 250 kA in the MPOS, this made it possible to generate an ion beam with $\overline{I}_i \cong 50$–60 kA and energy content of about 3.3 kJ. Positioning of the ion diode after the MPOS eliminates the shortcoming associated with the shunting of the latter, though in this case it is necessary to solve problems associated both with an electron stream from the region of the MPOS and with electrodynamic drift of the plasma. An ion beam with energy content 2.5 kJ was obtained using the generator Marina with a coaxial ion diode without external magnetic insulation set up at distance 50 cm after the POS. The diode operated in the self-insulation regime with early formation of plasma and efficiency of generation of a high-power ion beam of about 30%.

To reduce the electrodynamic drift of the plasma and obtain the possibility of placing the ion diode in the immediate vicinity of the POS, an external electromagnetic field (Fig. 11a)[60] that simultaneously produced magnetic insulation of the electrons in the interelectrode gap of the diode was used. The investigations showed a weak dependence of the opening characteristics on the diode impedance in a wide range of its values. The main factor was the duration of the high-voltage pulse, which depended on the interelectrode gap and on the rate of bridging it by the anode and cathode plasma. For an energy of 96 kJ stored in the generator and 50 kJ transferred to the inductance, the energy content of the high-power ion beam detected in the magnetically insulated diode on the opening of the MPOS was 9 kJ at amplitude 120 kA of the ion current, ion energy 850 keV, and power 10^{11} W of the ion beam.

5. THEORETICAL IDEAS ON OPERATION OF MPOSs

Existing models of POSs can be divided nominally into those that describe the convection phase and those that describe the current switching phase. In their turn, the current switching models differ in either taking into account or ignoring the effects associated with the self-magnetic field of the current of the POS. The latter include the studies of Refs. 61 and 62, which treat a plasma-filled diode of planar geometry under the assumption $\tau_p \gg 4\pi\sigma l^2/c^2$ and in the presence of an external magnetic field $\omega_{eH} \gg \omega_{ep}$. Application of a rising voltage pulse to the anode–cathode gap of the diode gives rise to growth of a double layer at the cathode electrode with corresponding growth of the current through the diode to values that are determined by the parameters of the plasma—its concentration n_i, temperature T_i, and direction of the flow velocity v_p. The strength of the electric field in the double layer is sufficient for the occurrence of explosive emission and the formation of a bipolar electron–ion flow that satisfies the relation $I_i/I_e = (m_e/m_i)^{1/2}$; at the same time, the resistance of the double layer does not exceed $10^{-2}\ \Omega$. The width of the double layer during this phase ($t_1 \gg \omega_{pi}^{-1}$) increases from $\chi_0 = v_p/\omega_{pe}$ to $\chi = v_p/\omega_{pi}$ at constant rate equal to $v_x = (dI/dt)/en_pS\omega_{pe}$. The transition to the second stage of development of the double layer is associated with exhaustion of the ion-emission capability of the plasma near the cathode and onset of its erosion, this corresponding to fulfillment of the condition $I_i > I_{ip}$, where I_{ip} is the limiting saturation of the current, equal to

$$I_{ip} = Zen_i v_{iT} S \quad \text{for} \quad v_p = 0;$$

$I_{pi} = Zen_i S(v_{iT} + v_p)$ for $v_p > 0$ in the direction of the cathode;

$$I_{ip} = \left(\frac{m_i}{2\pi k T_i}\right)^{1/2} \int_{v_p}^{\infty} n_i v_{iT} \exp\left[\frac{m_i(v_{iT} - v_p)^2}{2kT_i}\right] dv_{iT}$$

for $v_p < 0$ in the direction of the anode. The further development of the double layer depends on the rate of growth of the total current in the circuit. If $dI_i/dt \gg v_{is} n_i ZeS\omega_{pe}$, then a supersonic nonstationary regime is realized, while if the opposite inequality holds a quasistationary regime occurs. In the first case, the plasma gap of the diode can be divided into three zones: the zone of undisturbed plasma near the anode, a transition zone, and the double layer. During this phase, the electric field penetrates into the plasma to the depth of the transition zone, accelerating the plasma electrons to the anode and enabling the ions to escape from this region to the cathode. The duration of this process depends on the parameters of the external circuit, which restricts the rate of delivery of energy to the diode, thus leading to a steady subsonic regime of evolution of the double layer with velocity v_{iT} and thermal emission of ions from the boundary of the anode plasma. In the subsonic regime, the erosion of plasma at the boundary of the double layer is accompanied by escape of a rarefaction wave to the anode with velocity v_{is}, so that in this case there is no region of undisturbed plasma.

The ion beam formed in the plasma erosion phase undergoes space–time bunching, and in the phase of nonstationary expansion significant bunching occurs in the double layer itself, thus increasing the electron stream from the cathode.

This model does not take into account the self-magnetic field of the current, which has a significant influence on the switching characteristics. The self-magnetic field was taken into account in the model of a coaxial POS in Ref. 63, most conclusions of which were confirmed by operation of a switch in the nanosecond range. In this model, the conduction and switching processes are divided into four phases: conduction, erosion, enhanced erosion, and magnetic insulation. In two phases, the phenomena are described in the same way as in Ref. 62, with allowance for the coaxial geometry. The erosion phase continues until the gap of the double layer becomes comparable with the electron Lamor radius in the magnetic field of the current flowing through the cathode. The bending of the electron trajectories has the consequence that the electrons remain in the double layer for a longer time and increases their space charge. To neutralize the increased negative charge, a greater ion charge is needed, and the rate of ion removal from the anode boundary of the double layer is increased. This leads to an appreciable increase in the rate of expansion of the double layer; the impedance of the switch and the voltage across it increase sharply; and switching of the current to the load commences. This phase is called the enhanced-erosion phase; in it, the contribution of the ion component to the total current is determined by the relation

$$I_i/I_e \cong [2m_e Z(\gamma_{DL} - 1)/m_i]^{1/2} l/x_{DL}.$$

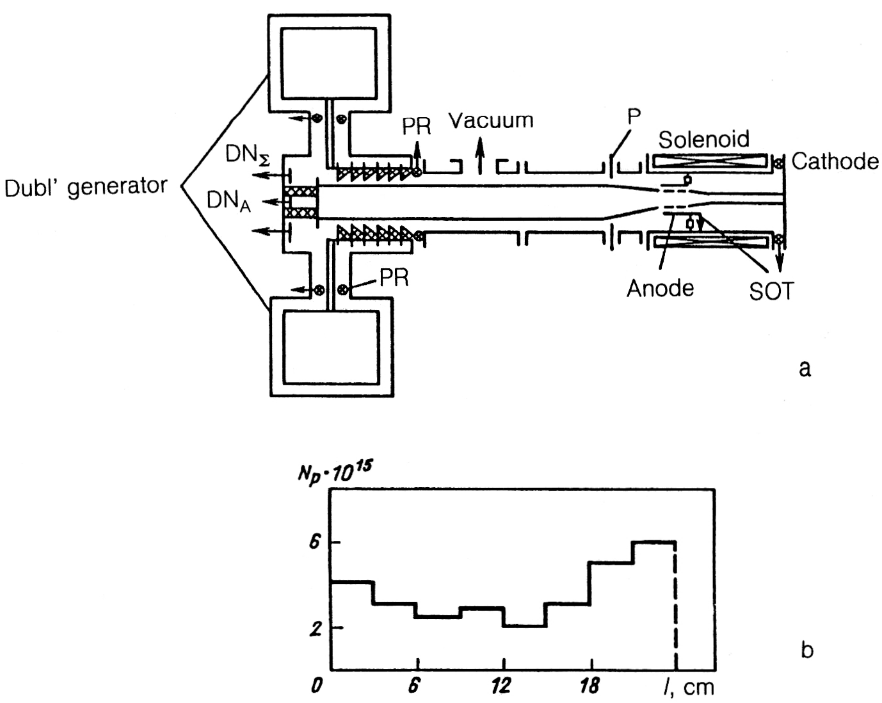

FIG. 11. Arrangement of an experiment to generate a high-power ion beam in a magnetically insulated diode placed after the MPOS in the generator Dubl' (a) and distribution of the high-energy proton fraction over the length of the ion diode (b).

In the event of rapid expansion of the double layer during the enhanced-erosion phase, this phase goes over into the magnetic-insulation phase, when the following condition begins to hold:

$$I_s > I_c \cong (m_e c^3/e)[\ln(R/r)]^{-1}(\gamma_{\rm DL}^2 - 1)^{1/2}.$$

The cutoff of the electron component of the current is accompanied by a sharp decrease of the total current in the circuit and the generation of an eddy emf.

As noted above, the conclusions of the model of Ref. 63 found experimental confirmation for a POS of the nanosecond range. However, in the case of operation with a MPOS deviations from the model of Ref. 63 were noted. Characteristic features of the MPOS operation were: a) a lower value of the limiting current I_s in operation of a MPOS having an identical construction to the nanosecond analog; b) a dependence on the plasma concentration n_i different from the one in the nanosecond range (in the nanosecond regime, the current I_s is proportional to n_i, while in the microsecond regime I_s is proportional to $n_i^{0.25}$); c) the absence of a clearly expressed concept of critical current; d) a significantly lower value of the impedance (R_s) for opening of the switch at the same currents I_s.

Some of these MPOS properties can be explained by the model of Ref. 64, which is a modification of the model of Ref. 63. In accordance with this modification, near the cathode during the conduction phase a double layer is formed with width such that the magnetic field of the current flowing in the switch is sufficient to bend the trajectories of the electrons within the width of this layer already before a shortage of ions for current transport in the bipolar regime occurs. Thus, the conduction phase is replaced by a phase of enhanced erosion. It follows from the model that the maximum current I_s in the switch at plasma concentrations $\leqslant 10^{12}$ cm^{-3} is above the maximum current of the model of Ref. 63, so that at low concentrations the model of Ref. 63 is valid. However, in the region of high concentrations ($\geqslant 10^{13}$ cm^{-3}) the new model is valid, since here $I_s < I_{Bp}$, where I_{Bp} is the Child–Langmuir bipolar current. Analysis shows that the model of Ref. 64 explains the maximum currents obtained in the POP, PAWN, and EYESS experiments, and the dependence of I_s on n_i has the form $I_s \sim n_i^{0.25}$.

A further consequence of the model is that the limiting current in the POS decreases with increasing l of the switch: $I_s \sim l^{-0.5}$. This dependence could explain the growth of the limiting current with increasing rate of delivery of the current to the POS if at the same time the width of the current layer were to decrease, but this has not been confirmed experimentally. In the same way, the model does not explain the appreciably higher limiting current in the switch in the GAMBLE I experiments compared with the POP experiment, since the same switch was used in these experiments.

We note that the dependence $I_s \sim n^{0.25}$ also follows from the assumption that a break arises in the plasma following displacement of the center of mass of the plasma under the influence of the magnetic-pressure forces through a certain fixed (compared with the length of the switch) distance.[65]

The models described here do not in fact consider the process of penetration of current into the plasma during the conduction phase and cannot explain experimentally observed phenomena such as current switching when $dI_s/dT \leqslant 0$. Models of the process of penetration of the magnetic field of the current into the plasma were proposed in Refs. 66–70. Common features of these studies are allowance for the Hall effect, the development of plasma instabilities, and a change of the plasma density during the conduction phase.

In the model of Ref. 66, the initial stage of the conduction phase is treated as in Ref. 62, since the depth of the collisionless skin layer is $\delta_s \gg x_{\rm DL}$, and a one-dimensional approximation is valid. Subsequently, the trajectories of the electrons entering the plasma from the double layer are bent by the self-magnetic field ($r_{ce} \cong \delta_s$), and they are displaced in the direction of the load, forming two adjacent layers—an axial cathode layer and a radial current layer, the latter being constituted by electrons from the cathode layer and electrons emitted from the cathode. In the cathode layer, there is a regime of magnetic self-insulation of an electron stream neutralized by ions. Growth of the current in the circuit is ensured by advance of the current channel into the plasma until it emerges on its boundary with simultaneous expansion of the cathode layer. The speed of the current channel is determined by the "sweeping up" of the plasma as in the "snowplow" model. On the arrival of the current channel at the load side of the plasma, there is an inductive voltage $-L(dI/dt)$ due to the decrease of the current and the magnetic pressure on the current channel, and this leads to its heating and expansion with formation of a tail. This facilitates even greater acceleration of the current channel and magnetization of the electrons in the part of it in which $\nu_{ef} > \omega_{ce}$. This leads to escape of electrons from the plasma, acceleration of ions under the influence of their field, and the formation of an electron–ion stream propagating toward the load. A shortcoming of this model is that it applies only for the case when the layer of electrons drifting in the axial direction occupies the entire cathode layer, and the model does not take into account the contribution of the ion space charge. In addition, the mechanisms responsible for the anomalous growth of the resistance of the current channel are not considered. Nevertheless, experimentally observed phenomena such as the bending of the current lines, the current switching at $dI_s/dt \leqslant 0$, and the formation of an electron–ion stream on opening of the POS are explained in this model.

A study of undoubted interest is the paper of Ref. 67, in which, in contrast to the model of Ref. 63, the processes taking place in a POS are a consequence of the motion and compression of the plasma as a result of interaction of the current flowing through the POS with the self-magnetic field. To describe the penetration of the current into the plasma, an effective frequency of electron–ion collisions is introduced, representing a superposition of Coulomb collisions and collective effects associated with the development of microinstabilities in the plasma. The analysis of the variation of the density $n_i \cong f(x,t)$ as a result of the "sweeping up" of plasma shows that a divergence of the density occurs after $\tau \cong 2/(\omega_{ce}\omega_{ci})^{1/2}$, this leading to the appearance in the current channel of an electric potential $\varphi_0 \cong B_0^2/8\pi n_0 e^2$, which is responsible for generation of a reflected ion stream. A consequence of this is friction between the ions entering and leaving the current channel. Assuming a decrease of the plasma density from the anode to the cathode, the authors obtain a high rate of "sweeping up" of plasma, $v = B_0/(8\pi n_0 m_i)^{1/2}$ near the electrodes, and this leads to the formation of vacuum gaps in these regions. Interruption of the electron current through the plasma occurs when the forming gaps increase to a size at which the boundary conditions for the existence of an equilibrium two-dimensional electron flow cease to hold. An important conclusion is that not only a cathode layer but also an anode layer is formed. However, the assumption of a lower plasma density near the cathode is hardly correct for the real experimental situation.

In Refs. 68–70, the penetration of the magnetic field into the plasma is considered from the point of view of electron magnetohydrodynamics, in which one ignores the motion of the ions and considers times $t \gg \omega_{ce}^{-1}$ and plasma dimensions satisfying $c/\omega_{pi} \gg a \gg c/\omega_{pe}$. The most important consequence of this theory is the possibility of penetration of the magnetic field into the plasma not only through diffusion processes but also by transport of the magnetic field by the current flowing through the plasma. Convective transport of the current is realized in the presence of a gradient of the plasma density and curvature of the lines of force of the magnetic field and even in the case of perfect conduction of the plasma.

Analysis of the equations of the evolution of the magnetic field with allowance for the Hall effect shows that there is a decrease of the time of its penetration to the depth of the skin layer compared with the classical value by a factor $\beta = \sigma H/(enc)$ (β is the Hall parameter); at the same time, the value of the Hall potential in the plasma reaches $\varphi_H = H^2/8\pi en$, and the ion velocity is $v_i = H/(4\pi n_i m_i)^{1/2}$.

Considering the case with $\sigma \to \infty$ and flow of current along the lines $n_i r^2 = \text{const}$ in a cylindrical geometry, the authors of Ref. 70 concluded that because of the strong density gradient at the plasma–electrode boundaries enhanced diffusion $D = \beta^2 c^2/4\pi\sigma \gg c^2/4\pi\sigma$ of the magnetic field with the formation of current layers with $\delta = a/(\omega_{ce}\tau_e)$ occurs. The rate of penetration of the magnetic field is greater near the anode because of the vanishing of the component of the electric field tangential to the electrode (vanishing of the Hall emf), the angle of entry of the electrodes to the anode tending at the same time to zero: $\theta = (\omega_{ce}\tau_e)^{-1} \to 0$. In addition, because of the $\mathbf{j} \times \mathbf{B}$ force there is a separation of the plasma boundary from the anode surface with dissipation of magnetic field energy in the layer that is formed.

Consequences of the rapid penetration of the magnetic field into the plasma are magnetization of the electrons and the formation of narrow electrode layers on which the total voltage applied to the plasma is concentrated. As we have already noted, the appearance of a Hall voltage leads to acceleration of the ions, a change of the density with Alfvén velocity, and, accordingly, an increase of the voltage. The resistance of the plasma can be estimated as $R = \varphi_H/I$. The decrease of the plasma density in the current layer can cause the development of current instabilities (ion–acoustic and then Buneman), which will have an important influence on the opening process. At low densities of the plasma, it ceases to be quasineutral, and a vacuum gap $d \sim c/\omega_{pe}$ is formed. Because of the further flow of the ion current, there is an increase of this gap and of the voltage across it. On the basis of charge-limited ion emission, the rate of expansion of the vacuum gap can be estimated in accordance with the formula $v = v_A c(\gamma - 1)(d\omega_{pe} i_{\min})^{-1}$, and the duration of the conduction phase until the formation of the vacuum gap is estimated at $\tau_c = (ar_c c/I)(\pi n_i m_i)^{1/2}$. Thus, in the current switching phase, the POS behaves like an ion diode with magnetic self-insulation of the electron stream, this corresponding to the experimental data. It should be noted that this model predicts a slope of the current lines and a more rapid penetration of the magnetic field near the anode, and these are also confirmed by experiment.

Besides the analytical models that we have described, there have been several numerical calculations of processes in MPOS. In the study of Ref. 58, which did not include calculations of the conduction phases, there is a description of the results of calculations in accordance with a model taking into account factors such as the finite length of the switch, the distribution of electron losses over its length, the development of secondary plasma near the cathode, and motion of the dense cathode plasma into the coaxial gap of the POS. The calculations showed that when the current flowing through the POS reaches a critical value, expansion of the double layer with $v \cong 10^8$ cm/sec commences; at the same time, a magnetic-insulation wave propagates along its length, already covering after $t < 10^{-8}$ sec up to 80% of the complete length of the switch. The electron losses are concentrated on a finite section of the POS until the magnetic field of the current switched to the load exceeds the critical value. The duration of the phase of enhanced erosion increases along the length of the POS, as a consequence of which the double layer acquires the shape of a funnel that expands in the direction of the load, this resulting in nonuniformity of its wave impedance and the occurrence of electron losses even when $B > B_c$. The calculations also showed that it is preferable to use high-velocity streams of a light (hydrogen) plasma to obtain better switching characteristics and that the characteristics are downgraded when formation of secondary plasma is taken into account.

The influence of the impedance, load current, and aspect ratio l/d, where l and d are the length and width of the vacuum gap in the POS, on the amplitude of the switching current was investigated in Ref. 71, which was devoted to numerical modeling of the electron orbits in the framework of a two-dimensional hydrodynamic model in the vacuum cathode gap formed by plasma erosion or the influence of

$\mathbf{j}\times\mathbf{B}$ forces. It was shown that there exists a critical value of the load current necessary for interruption of the current (the electron component) through the POS. The nature of the electron trajectories in the gap determined the distribution of the potential, the magnetic field, and the electron density in the field.

Numerical experiments including calculations of the conduction phase of a POS were made in Refs. 72–76. A simple model of the POS conduction phase, including one-dimensional hydrodynamics and two-dimensional electron orbits, was considered in Ref. 72 under the assumption of constancy of the velocity of the current channel (determined by the electron current from the cathode in the regime of charge-limited emission). The resulting transverse electric field $[\varepsilon\sim d(LI)/dt]$ and the azimuthal self-magnetic field ensure drift of the electrons, and this leads to polarization of the plasma (Hall effect) and radial drift in the $\mathbf{E}_z\times\mathbf{B}_\theta$ fields; as a consequence, conduction of the plasma across the gap is restored. The model leads to the conclusion that the width of the current channel is determined by the combination of hydrodynamic compression of the plasma and magnetic insulation of the electrons on the side of the generator near the cathode.

Numerical investigation of the conduction phase by means of a 1.5-dimensional hydrodynamic code[73] confirmed the main conclusions of the analysis, namely, the decisive role of charge-limited emission from the cathode and of the Hall effect in the flow of current through the POS and the shaper of the current channel in the plasma. At the same time, the calculated thicknesses of the current channel were found to be appreciably less than the experimentally observed values. The introduction of additional mechanisms of scattering and energy loss of the electrons near the cathode led to breakdown of the magnetic insulation, deflection of electrons to the anode, and expansion of the current channel, improving the agreement with the experiments.

As possible mechanisms of penetration of the magnetic field of the current into the plasma and broadening of the current channel, the ion–acoustic and lower-hybrid instabilities were considered in the two-dimensional model of Ref. 74. The presence of anomalous electron collisions led to the appearance in the plasma of microturbulence fields, which are additional scattering centers for the electrons. The calculations also showed that whereas ohmic current transport by the electrons is realized at the beginning of the conduction phase, it subsequently becomes convective in nature.

The most complete numerical investigation of plasma opening switches was made in Ref. 75 by a self-consistent solution of Maxwell's equations for a three-fluid model—an electron stream from the cathode and electron–ion streams from the plasma. The calculations revealed the presence in the conduction phase in the plasma of diagonal streams of electrons emitted by the cathode, the existence of which came to an end with the onset of magnetic insulation, and also the formation of layers at not only the cathode but also the anode surface. The penetration of the magnetic field was convective in nature but more complicated than the behavior found from the model of Ref. 70 considered above. A gap formed near the cathode on the side of the generator expands mainly in the direction of the anode, across the POS, and a gap on the side of the anode is formed along it, growing in the direction to the load. Flow of current along the anode leads to the appearance of a gradient of the magnetic pressure, which repels ions from the anode, thereby accelerating the penetration of the magnetic field in this region. The calculations showed that in the case of breakdown of conductivity of the anode the anode penetration of the magnetic field becomes minimal relative to the cathode penetration, leading to more rapid interruption of the current, in agreement with the experimental results.[76] The decisive process is penetration of the magnetic field near the cathode, this also agreeing with the results of experimental studies.[38] The calculations show a gradual evolution of the cathode gap with a magnetized electron stream within it. The rapid phase of the current switching occurs only when the cathode gap reaches the load side of the plasma. The further evolution of this gap occurs as in the description in Ref. 62. The numerical experiments with POS geometry analogous to that of the GIT-4 generator[76] established a correspondence of the dependence of the gap size and the limiting current in the POS on the rate of delivery of current to the MPOS. Improvement of the characteristics of the POS with decreasing axial extension of it was demonstrated.

Thus, it may be noted that the existing models and numerical experiments make it possible to explain qualitatively many phenomena observed in the experimental operation of MPOSs. However, there is no unified theory capable not only of explaining existing data but also of predicting the operation of planned generators.

CONCLUSIONS

Efforts over five years to develop the concept of high-power pulsed generators with inductive energy storage based on MPOSs have made it possible to develop working facilities, gather significant experimental data on the processes that take place in MPOSs, and analyze some of them theoretically. Taken together, the results enable us to view the work that has been done as the first stage in the development of the concept, the formulation of its main features, and the identification of tasks for the future.

The main result has been the demonstration of the viability of MPOSs for the creation of generators with power at a level of a few terawatts. These generators have primary energy stores in the form of fast Marx generators and inductive stores of mixed type, using the inductance of the Marx generators themselves as well as a vacuum coaxial load shorted by the plasma of the MPOS. It has been shown that MPOSs can maintain a low-resistance state during the phase of energy delivery to the inductive store during 1 μsec, making it possible to transform electric field energy into magnetic field energy with practically no loss. It has been shown that MPOSs can increase their resistance by 3–4 orders of magnitude during a time $\cong 10^{-7}$ sec, making possible switching of an energy flux to a load with a power several times larger than the power of the primary store. As in the case of the nanosecond analog, the possibility of reliable control of the time of actuation of the MPOS by variation of the parameters of the created plasma has been demonstrated. The principle of synchronization of individual MPOSs by the introduction of current feedback has been formulated and has been shown to be experimentally feasible. Promising results have been obtained on the generation of high-power ion beams, electron beams, and hard and soft x rays in experiments on the compression of liners in generators with MPOSs.

The efforts of various groups have yielded data on the details of the current flow in MPOSs in the conduction and switching phases that in part confirm and in part complement one another. Thus, in a coaxial MPOS a current channel moves during the conduction phase from the generator to the load with an increasing velocity, which reaches 10^8 cm/sec. At the time when the current is switched to the load, the current channel is at a distance of more than 20 cm from the plane containing the guns, outside the region of the initially produced plasma. The width of the current channel (several centimeters) indicates a lowering of the plasma conductivity by 10^2–10^3 times and the development of collision processes.

Analysis of the electron–ion losses to the electrodes of the MPOS indicates that at the time of current switching the current in the MPOS is mainly carried by the ions. The sharp increase of the MPOS impedance is due to processes taking place near the negative central conductor. On reversal of polarity ("plus" regime) the MPOS parameters are significantly downgraded. The use of an external axial magnetic field makes it possible to improve the parameters in the "plus" regime but leads to a lowering of the MPOS parameters in the "minus" regime. The direction of injection of the plasma into the MPOS does not have a significant influence on its operation.

The most important factor governing the characteristics of a MPOS in the "minus" regime is the diameter of the central conductor. A decrease of this diameter leads to upgrading of the switching characteristics but simultaneously lowers the maximum current amplitude at which the switching occurs. This conflict is the main hindrance to the creation of generators at the multi-tera-watt power level.

At the present time, we can indicate several possible ways of overcoming this difficulty.

The first is to use a second stage of power multiplication; this will make it possible almost to double the power of generators with MPOSs.

The second is to use an additional pulsed insulating azimuthal magnetic field. The viability of this idea was demonstrated in experiments using the generator Taĭna, in which the voltage across the switch could be increased from 1.5 to 2.6 MV.

The third is to select an optimum composition of the initially produced plasma. In this connection, a significant experiment was made using the generator Dubl', for which the MPOS impedance for hydrogen and deuterium plasmas was twice that for argon or krypton plasmas.

Finally, a more careful investigation must be made of the fact of decrease of energy expenditure on operation in the "minus" regime and plasma injection from the inner electrode to achieve the same current amplitudes in the MPOS as for the opposite direction of injection. This may make it possible to raise the level of the current in the MPOS without increasing the diameter of the inner conductor or downgrading the switching characteristics.

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