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PLASMA DYNAMICS

Outlook for the Use of Microsecond Plasma Opening Switches to Generate High-Power Nanosecond Current Pulses

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Abstract—An analysis is made of the current break process in microsecond plasma opening switches and their possible application in high-current generators. Necessary conditions are determined for generating megavolt pulses in the erosion mode of a plasma opening switch with the gap insulated by an external magnetic field. Under these conditions, efficient sharpening of high-power submegampere current pulses can be achieved. The possibility of using plasma opening switches operating at voltages of 5–6 MV to generate X-ray and gamma emission is discussed. The main operating and design parameters of a six-module plasma opening switch with a current pulse amplitude of 3.7 MA and voltage of 4–6 MV for use in the MOL generator, which is the prototype of one of the 24 modules of the projected Baikal multimegajoule generator, are estimated by using the available scalings.

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1. OPERATING PRINCIPLES OF THE PLASMA OPENING SWITCHES AND THEIR APPLICATION

Progress achieved during the past two decades in studying physical processes in the pulsed plasma of high-current discharges made it possible to create plasma opening switches (POSs). The POSs have found application as vacuum switches of megampere currents in solving the problems of inertial confinement fusion (ICF) [1] and for generating megavolt nanosecond pulses in high-power X-ray sources [2, 3].

During the past decades, a large number of theoretical and experimental papers were devoted to studying the physics of POSs and their possible application. In Russia, important results on the physics and technology of POSs were achieved with the GIT-4 and GIT-16 high-power generators at the Institute of High-Current Electronics (Siberian Division, Russian Academy of Sciences) [4, 5] and, in the United States, on the ACE-4 facility at Maxwell Laboratories [6] and on the Hawk facility at the Naval Research Laboratory [7]. At the Kurchatov Institute, POS-based generators operating in the repetitive mode have been developed [8].

In studying POSs, a number of specific phenomena occurring in a current-carrying plasma were revealed. This gave rise to the theory describing the so-called plasma opening (or current break) phenomenon—an abrupt increase in the plasma resistance, which makes it possible to generate a high-voltage pulse $U \propto -L\frac{dI}{dt}$ with an amplitude of up to several megavolts and to switch the generator current to a parallel load during a time on the order of 1 ns.

In [9], a scheme was developed in which a POS was used to sharpen the power of an inductive energy storage with a microsecond energy input (Fig. 1). An advantage of such a scheme is the simpler design of the generator, which is directly connected to the primary capacitive energy storage (Marx generator), rather than through an intermediate water storage. This scheme (Marx generator–inductive energy storage–power sharpener–load) proved to be convenient for creating compact devices, e.g., apparatuses for radiation treatment with a high peak dose rate [10]. At the same time, practical application of POSs in high-power facilities was hampered by the limited energy density that can be transferred through a POS in the conduction phase [11].

POSs used to switch the current from the inductive storage to the load (an electron or ion diode) are usually designed as a segment of a vacuum coaxial line that is filled with a plasma supplied from several plasma sources (Fig. 1). When the gap of the coaxial line is closed by the plasma, the current flows through the plasma bridge so formed. The bridge impedance has an active component and an inductive component, which is proportional to the magnetohydrodynamic (MHD) propagation velocity of the plasma bridge along the electrodes. In the conduction phase, the POS voltage is relatively low.

In the opening phase, the active resistance of the plasma bridge increases substantially, a vacuum gap with a reduced plasma density forms, and the current is switched to a load connected in parallel to the POS. In this phase, a nanosecond voltage pulse is generated,

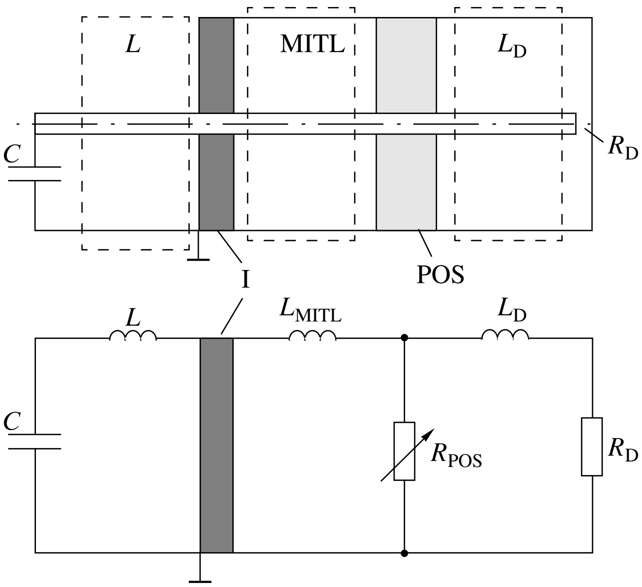

Fig. 1. Electric circuit of a high-power pulsed generator with a POS for the sharpening of the power of the inductive energy storage: (C) primary capacitive energy storage (Marx generator), (L) inductance of the input circuit, (I) high-voltage vacuum insulator, (L_{MITL}) inductance of the MITL, (R_{POS}) plasma bridge of the POS with a nonlinear impedance, (L_D) inductance of the line transferring energy into the load, and (R_D) load (e.g., an electron diode).

which is characterized by the voltage multiplication factor $k = \frac{U_{POS}}{U_{MG}}$, where U_{POS} is the POS voltage at the instant of opening and U_{MG} is the output voltage of the Marx generator (the primary capacitive energy storage).

There are different models describing the dynamics of the current-carrying POS plasma [12–21]. In the MHD model [13, 14], the magnetic field is frozen in the plasma, which drifts toward the load. This model is capable of describing POSs with a duration of the conduction phase of about 1 μs, plasma densities as high as 10^{15}–10^{16} cm^{-3}, and currents of 600–700 kA and more.

The approach based on electron magnetohydrodynamics (EMHD) with allowance for the Hall effect [12, 15–18] accounts for the penetration of a fast magnetic-field wave into the plasma with the velocity $v_H = B/(2\mu_0 e n_e L)$, where B is the current-induced magnetic field, n_e is the electron density, and L is the POS inductance. Taking into account the ion motion in this model can result in the formation of local density minima. In this case, the fronts of the current and the magnetic field penetrate into the plasma in the form of the so-called Kingsep–Mokhov–Chukbar (KMS) wave [15] with the velocity $V_{KMS} = V_A \frac{c}{\omega_{pi}\delta} \gg V_A$, where V_A is the Alfvén velocity, ω_{pi} is the ion plasma frequency, and δ is the skin depth. Since the wave propagation velocity is inversely proportional to the plasma density, the wave accelerates as the density decreases. Such a penetration of the magnetic field into the coaxial plasma bridge was observed experimentally in [19]. The applicability of the fluid model in the conduction phase was confirmed experimentally. At high generator currents and, accordingly, high plasma densities, this model adequately describes the values of the plasma parameters at which the plasma bridge breaks. However, the model fails to predict the instant of breaking at densities of 10^{12}–10^{14} cm^{-3} typical of low-current devices (with a current below 500 kA), which are characterized by a large voltage multiplication factor in the opening phase. At plasma densities of 10^{14} cm^{-3} in the conduction phase (note that, in the opening phase, the plasma density decreases significantly), the time during which the magnetic-field wave penetrates into the plasma bridge is ≈100 ns, which is almost one order of magnitude shorter that the duration of the POS conduction phase.

In the vacuum bipolar (VB) model [20, 21], which considers the electron and ion flows propagating in opposite directions, the concept of plasma erosion is introduced and the vacuum stage of magnetic insulation of the POS gap is distinguished. This stage corresponds to the instant of current break and is characterized by the appearance of a vacuum gap when the critical current is reached.

In the modified bipolar (MB) model, the skin depth in the conduction phase is compared with the radius of the electron orbit and the critical current is defined as $I_{MB} = 1.02 \times 10^{-2} r\sqrt{n}$, where r is the gap radius and n is the plasma density. It is assumed that, when the current exceeds this critical value, the plasma erosion intensifies, which leads to the current break. The VB model was initially proposed for POSs with a conduction phase as short as 50–100 ns, plasma densities of 10^{12}–10^{13} cm^{-3}, and currents of 1 MA. However, such plasma densities can also occur in lower current POSs with a microsecond duration of the conduction phase if we assume that, in the opening phase, the vacuum–plasma gap of the POS is magnetically insulated.

A transition from the EMHD effects to the plasma erosion can occur via the development of plasma instabilities, e.g., Rayleigh–Taylor instability, which is related to density fluctuations caused by the presence of different ion species [22], or Buneman instability [23]. The applicability ranges of different models of POSs with a microsecond duration of the conduction phase were considered in more detail in [11].

In the above models, the relation between the characteristics of the opening phase and the macroscopic parameters of the problem (such as the voltage and power) was usually discarded; therefore, there is a necessity of finding means for controlling the process of current break. A number of important characteristics of the POS operation were inferred from experiments.

Thus, the limiting charge transferred per unit length of the perimeter of the outer POS electrode in the conduction phase was found to be [24]

$$Q/r \le 0.5 \text{ C/m}, \quad (1)$$

where Q is the total charge transferred in the conduction phase and r is the radius of the outer electrode. If the linear charge density transferred during the current pulse through the plasma bridge is less than or equal to Q/r, then the current can be efficiently broken and the voltage multiplication factor can reach a value of 3–10. At the same time, the necessity of satisfying this condition leads to an increase in the POS dimensions at high currents.

Another method for increasing the POS voltage in the opening phase is to apply an additional external magnetic field in order to improve magnetic insulation of the gap. For an axisymmetric POS at currents of 100–300 kA, it is convenient to apply an axial magnetic field B_z. Such a field improves magnetic insulation of the gap and decelerates plasma drift in the azimuthal magnetic self-field toward the load. An important point is that, in this case, the longitudinal size of the POS can be reduced. The magnitude of the axial field should be chosen such that

$$B_z = A\max(B_c; B_g), \quad (2)$$

where $A > 1$ is an empirical factor and B_c is the magnetic field corresponding to the critical current predicted by the erosion model,

$$I_c[\text{A}] = \frac{2\pi m_e c}{e\mu_0}(\gamma^2-1)^{1/2}\frac{r}{D_c} \cong 8500(\gamma^2-1)^{1/2}\frac{r}{D_c}, \quad B_c \propto \frac{1}{D}(\gamma^2-1)^{1/2}, \quad (3)$$

where $\gamma = 1 + \frac{eU}{mc^2} \cong 1 + 2U\,[\text{MV}]$ is the relativistic factor, with U being the voltage applied to the gap; r is the cathode radius; D_c is the width of the vacuum gap; and B_g is the magnetic field corresponding to the maximum generator current, $B_g \propto \frac{I_g}{r}$. In the bipolar model, the gap width increases with the velocity

$$\frac{dD}{dt} = \frac{I_i}{2\pi r l}\frac{1}{n_i e} - v_d, \quad (4)$$

where I_i is the ion current, r is the gap radius, n_i is the ion density, and v_d is the plasma drift velocity.

When estimating the magnetic field, an important factor (in addition to the average value of the magnetic field strength in the gap) is the field configuration; specifically, there must not be magnetic field lines that connect explosive emission regions at the cathode with the anode and whose length is on the order of several interelectrode gap lengths. Therefore, configurations in which the anode is the high-voltage inner electrode are of primary interest.

The POS voltage is determined by the energy density spent on the acceleration of ions (plasma erosion) and can be expressed through the voltage of the Marx generator as

$$U_{\text{POS}} = \alpha U_{\text{MG}}^{4/7}, \quad k = \alpha/U_{\text{MG}}^{3/7}, \quad (5)$$

where U_{POS} and U_{MG} are expressed in megavolts, $\alpha = 2.5$ for conventional POSs without an external magnetic field for magnetic insulation of the gap, and $\alpha = 3.6$ for POSs with an external magnetic field. The opening voltages observed in devices with microsecond submegampere POSs [11, 25, 26] are well described by the above scaling.

An important factor that relates the POS characteristics to the plasma density and the limiting charge transferred through the POS is the configuration of the plasma injectors and the feasibility of plasma injection across the field lines of the external magnetic field [27]. When there are several high-power plasma injectors, condition (1) can be rewritten as [24]

$$q \le (6 \pm 1) \times 10^{-3} \text{ C/gun}. \quad (6)$$

In coaxial POSs, the axial plasma dynamics and the penetration of the magnetic field (which are adequately described by the EMHD model) play an important role even when conditions (1) or (6) are satisfied. Applying an external magnetic field under these conditions makes it possible to achieve an efficient current break, while the plasma bridge is displaced only slightly. Such a situation takes place in experiments with two-sided feeding [28], when the current is input symmetrically from two identical generators located on the opposite sides the POS—the case corresponding to the so-called "disk pinch" geometry.

The development of new devices based on the effect of current break was stimulated by the need to solve practical problems of high-power pulsed technology, in which the device geometry plays an important role. In solving these problems, it was necessary to generate powerful high-voltage pulses in a system of limited volume, including in the repetitive mode. In this context, the following main requirements, common to many projects, were formulated.

(i) The capability of achieving current breaks in the repetitive mode, the repeated generation of the plasma and its removal before the next pulse, and control over heat removal and gas release.

(ii) Combining the switch and the load (an electron or ion diode) for increasing the utilization efficiency of the generator current.

(iii) Applying an external magnetic field for increasing the efficiency of magnetic insulation and, hence, for achieving the maximum possible voltage in the opening phase.

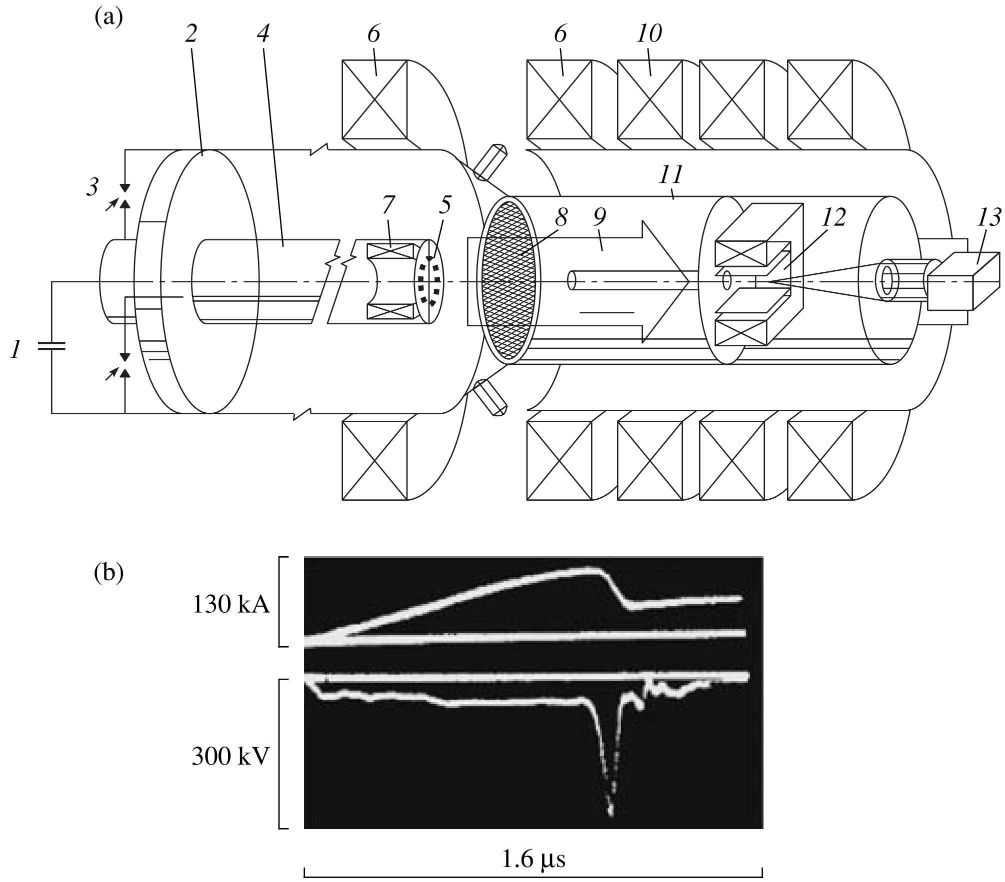

Fig. 2. (a) Schematic of a POS in the form of an ion diode with an external magnetic insulation and (b) waveforms of the generator current and voltage: (*1*) capacitive energy storage, (*2*) high-voltage insulator, (*3*) multichannel current switch, (*4*) capacitive energy storage, (*5*) plasma injectors, (*6*, *7*) coils producing the external magnetic field, (*8*) grid diode, (*9*) direction of the ion flux, (*10*) coils of the ion-transportation chamber, (*11*) ion-transportation chamber, (*12*) mass–energy analyzer of the ion flux, and (*13*) open planar image tube with an MCP at the input.

Several projects with the use of POSs satisfying the above requirements were accomplished. These projects included the development and creation of a fast ion source for technological purposes [29], studies of the feasibility of creating a high-aperture ion source, and the creation of an X-ray bremsstrahlung (XRB) generator for sterilization (RS-20 facility) [30, 31]. The results obtained allowed one to employ POSs in new higher-power pulsed systems, e.g., the UIN-10 model device [32].

A new direction in developing POSs for high-power pulsed generators is the use of a multimodule POS in a megampere MOL generator with a current pulse amplitude of 3.7 MA and voltage of 2 μs, which is now under construction within the Baĭkal program [33].

2. POS AS A MAGNETICALLY INSULATED ION DIODE

Experiments with high-impedance POSs having a microsecond conduction time have shown that the POS in the opening phase may be considered as a magnetically insulated ion diode [29]. Such experiments were conducted, e.g., in the Tigr-2 generator. The experiments were aimed at creating a pulsed ion source with a voltage amplitude of 200–300 kV, current of 100 A/cm^2, and pulse duration of 150 ns. The experimental setup was an inductive energy storage in the form of a segment of a vacuum coaxial line 50 cm in length and 18 cm in diameter. The primary energy storage was a capacitor with a charging voltage of 40 kV and stored energy of 3 kJ, which was switched through a multichannel spark gap to a plasma-filled diode placed in the extension of the vacuum line (Fig. 2). The parameters of the plasma and the pulsed magnetic field were chosen according to limiting-charge criterion (1) and magnetic-insulation condition (2), so the plasma bridge in the diode operated as a POS. The amplitude of the output current pulse was 130 kA, the output voltage was 300 kV, and the current pulse duration was 150 ns. The diode gap was filled with a plasma produced by plasma injectors mounted at the end of the diode anode. A steel grid mounted at a distance of 120 mm from the anode served as a cathode. Magnetic insulation was provided by an external magnetic field produced by several groups of solenoids. The peak value of the magnetic field strength near the anode was 7 kOe. As a result, an axial ion beam with a current density near the anode of 100 ± 30 A/cm^2 and a divergence of 15° was generated. The beam was transported over a distance of 80 cm by using an axial magnetic field produced by magnetic coils. At the output from the system, a 300-keV beam of C^{2+}, C^{3+}, and C^{4+} ions with a current density of 50 A/cm^2 was obtained. The beam parameters were measured by Faraday cups and a mass–energy analyzer based on Thomson's method of parabolas. The ion energy corresponded to the voltage generated by the POS plasma, whose main components were hydrogen (H^+), carbon (C^{2+}, C^{3+}, C^{4+}), and oxygen (O^{2+}, O^{3+}). The conclusion was made that the POS in the opening phase operated as a magnetically insulated diode.

In the experiments performed in the Taĭna facility, the energy was supplied symmetrically from two Marx generators (with an output voltage of 450 kV, a current of 200 kA, and a stored energy of 140 kJ), installed on both sides of the system [28]. The current rise time was 2.5 μs. The plasma was produced inside a vacuum coaxial line with diameters of the outer and inner electrodes of 36 and 7 cm, respectively. The axial length of the plasma source composed of 128 injectors was 25 cm. The ion-current density was measured by Faraday cups and was 200 A/cm^2 at a voltage of 1.0–1.5 MV (Fig. 3). The ion energy also corresponded to the POS voltage. The outer solenoids produced a magnetic field with a longitudinal component of 0.7–0.8 T. An appreciable ion current was observed 1 μs before current break. It was assumed that the phase of enhanced erosion began just at this instant, i.e., well before the opening phase, whereas in the rest of the conduction phase, the ions escaped from the plasma bridge.

The POSs used in the above experiments were designed in accordance with condition (1). The opening voltages observed in the above and many other experiments [19, 26, 28–31] agree with scaling (5), which was deduced independently of those experiments. This allows one to compare the parameters of the experimental facilities operating at different currents by analyzing their opening efficiencies.

An analysis of the effect of an external magnetic field on the POS operation allowed one to draw the following conclusions, which were then used when designing new generators.

First, the external magnetic field with a required strength and configuration increases the opening voltage to the value predicted by scaling (6).

Second, in our opinion, the ion current densities below 50 A/cm^2 observed in the conduction phase and 100–200 A/cm^2 in the opening phase are related to the formation of a vacuum gap in the erosion mode of the POS operation. Assuming that the POS does operate in this mode, the critical values of the gap width and magnetic field can then be estimated from these measurements. The high opening efficiency can be achieved by applying a supercritical magnetic field. It should be noted that, within the range of admissible plasma densities (10^{13}–10^{15} cm^{-3}), the Hall EMHD scenario can also be used. However, for our nonstandard configuration (with a high-voltage inner electrode), no quantitative estimates can be made using the EMHD approach.

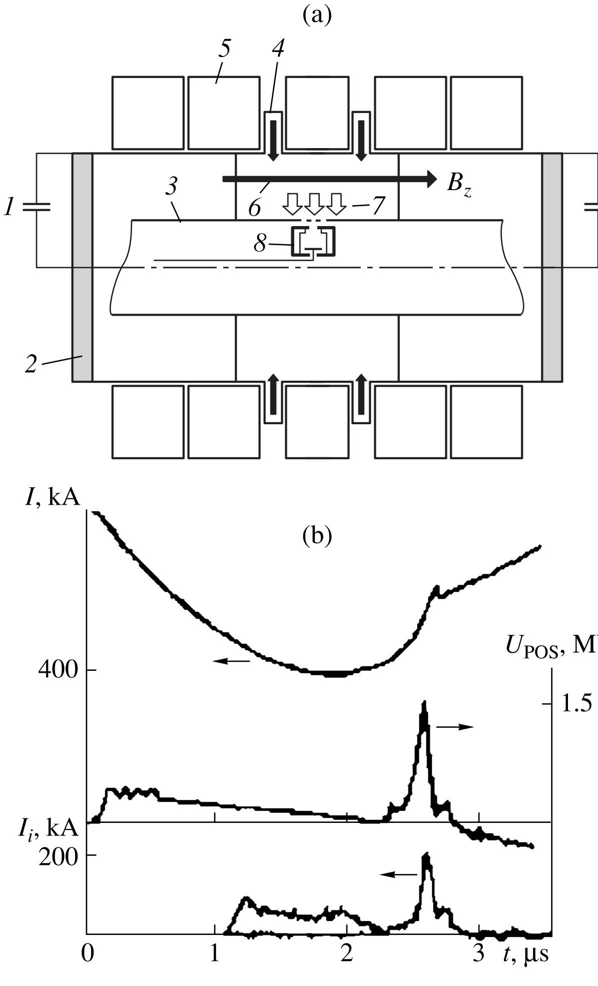

Fig. 3. (a) Scheme of the experiment with energy input from both sides of the POS and (b) waveforms of the total ion current of two generators, I; the voltage at the high-voltage divider, U_{POS}; and the ion-probe signal I_i: (*1*) capacitive energy storage, (*2*) high-voltage insulator, (*3*) anode of the vacuum inductive energy storage (inner electrode), (*4*) plasma injectors, (*5*) coils producing the external magnetic field, (*6*) direction of the longitudinal magnetic field, (*7*) direction of the ion flux, and (*8*) ion-current probe.

3. INVESTIGATION OF NEW MAGNETIC CONFIGURATIONS IN POSs OPERATING IN THE REPETITIVE MODE

Besides creating a magnetically insulated vacuum gap in the opening phase, it is also necessary to optimize the configuration of the POS electrodes. A scheme in which the power of an inductive energy storage was sharpen by a POS and an electron diode served as a load was previously used in [34] to generate high-power XRB pulses. In [10], 80- to 100-kA XRB generators operating in the repetitive mode and allowing one to produce megavolt pulses in POSs were designed. These devices were devised in connection with the development of new radiotechnologies for sterilization of medical instrumentation and materials of large volume and high average density, safe processing of industrial and domestic wastes, and water treatment. The employment of the acceleration devices in radiotechnology was thoroughly analyzed in [35]. The capability of POS-based sources to generate X-ray pulses with a high peak power is also promising for radiotechnology [36, 37].

When designing repetitive XRB generators based on the Marx generator–inductive energy storage–POS scheme, the parameters of the Marx generator turn out to be limited by the lower (by about one order of magnitude) energy capacity of capacitors operating in the repetitive mode as compared to that of dc capacitors. This does not allow one to achieve the current required for magnetic self-insulation of the vacuum–plasma gap in the POS. Estimates of the critical current in the VB and MB models [38] give a value of a few hundred kiloamperes for a plasma density of $n = 5 \times 10^{12}$ cm^{-3} and gap radius of $r = 10$ cm. The gap width was determined from condition (2) for the minimum value of the current rise time (0.5–0.7 μs) of the Marx generator–inductive energy storage circuit. This time is in turn limited by the minimum possible inductance of the circuit. The energy provided by such a device at a current of a few hundred kiloamperes was estimated to be 100–300 kJ per pulse, which considerably complicates its design. Therefore, a conventional POS cannot be used in a generator operating in the repetitive mode.

To overcome the above limitations, new methods for generating high-voltage pulses and preventing electron leakage in POSs were developed. All these methods turned out to be efficient only in the case of the positive polarity of the high-voltage electrode.

Another problem in designing a generator operating in the repetitive mode is related to creating a plasma source capable of generating a short-lived plasma bridge that would not close the diode and the POS during subsequent pulses and would not provoke an uncontrolled gas release in the structural components of the device. The problems concerning the development of the components of POS-based generators operating in the repetitive mode were discussed in [35, 39].

Several possible POS schemes were used in the RS-20 facility [10, 40] (Fig. 4). One of these schemes included a high-voltage anode; a grounded cathode, on which plasma injectors were installed; and an electron diode with a high-voltage emitting anode. The POS anode was a 25-cm-diameter, 30-cm-long cylinder with an extension in the form of a squirrel wheel made of rods that were arranged on a circle and whose diameter decreased from 12 to 6 mm over the length 35 cm. The plasma bridge was produced in the radial gap between the cathode and the cylindrical part of the anode. This scheme was capable of generating up to one million 2.5-MV pulses at a diode current of 10 kA, pulse duration of 150 ns, and repetition rate of 2 Hz.

The further experiments aimed at achieving higher voltages were performed with a POS in an external magnetic field that was produced by a solenoidal coil [10, 41] and had a substantial longitudinal component B_z. The magnetic coil was installed on the grounded cathode. The magnetic-field topology was such that there were no magnetic field lines connecting the anode with the regions of the cathode or the vacuum chamber where explosive electron emission could occur. This ensured magnetic insulation of the POS gap.

The strength of the quasi-steady (with a rise time of ~1 ms) magnetic field in the radial section of the gap was 5–8 kOe. The energy expended on the generation of this magnetic field did not exceed 5% of the energy consumed by the Marx generator and, hence, insignificantly affected the total efficiency of the system. The use of an external magnetic field made it possible to reduce the electron component of the current in the POS and to increase the fraction of the ion component. The energy of the inductive energy storage was expended on the removal of ions from the gap, which led to a reduction in the plasma density. With this configuration, a voltage pulse amplitude of 3 MV and a complete break (down to zero) of the current were achieved.

Experiments with repetitive POS-based generators in which the high-voltage electrode is the anode and magnetic insulation is provided by an external magnetic field have shown that such a scheme is capable of generating high-voltage pulses in the opening phase of the POS. Thus, the RS-20 facility operating in the repetitive mode at a current of 80 kA produced voltage pulses with an amplitude of 3 MV, as well as 3-MeV electron beams with a duration of 100–150 ns, at the initial Marx generator voltage of 0.8 MV [10]. The experiments were also performed at 240 kA. The radial gap of the POS was 4 cm wide, and the anode and cathode diameters were 18 and 10 cm, respectively. The axial length was 12 cm, the applied longitudinal magnetic field was 1.6 T [42], and the voltage in the opening phase was 3.0–3.3 MV.

The above schemes have demonstrated the high efficiency of current break. A disadvantage of these schemes is that a fraction of energy is lost when the POS current is switched to the load. In this case, the conversion efficiency of the Marx generator energy into the electron-beam energy does not exceed 25–30%. In order to increase the conversion efficiency, a scheme was proposed in which the plasma bridge is produced in the cut of the outer electrode of the POS. In this case, the extension of the inner electrode can be used as an X-ray target of a high-current electron beam [43].

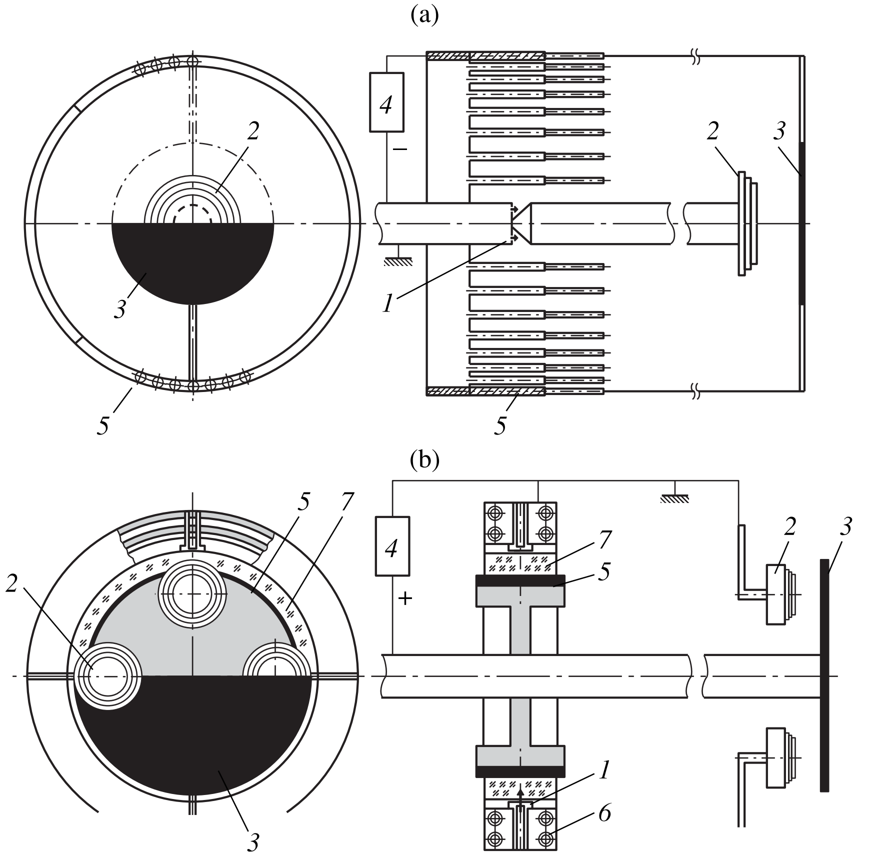

Fig. 4. (a) Schematic of a POS and an electron diode in the RS-20 facility: (*1*) plasma injectors, (*2*) cathode of the electron diode, (*3*) anode-converter of the electron diode, (*4*) Marx generator, and (*5*) rod anode of the POS with variable transmittance for the electron flux in the azimuthal direction. (b) Schematic of a POS with an external magnetic field in the RS-20 facility: (*1*) plasma injectors; (*2*) cathode of the electron diode, consisting of four disks; (*3*) anode-converter of the electron diode; (*4*) Marx generator; (*5*) cathode insert made of pyrolyzed graphite; (*6*) magnetic-field coil; and (*7*) anode–cathode gap of the POS.

Experiments with POSs in which the inner electrode is the anode and magnetic insulation of the gap is provided by an external magnetic field have shown the high efficiency of current break in the plasma bridge of the POS. Repetitive generators of submegampere current pulses that were discussed in this section have become useful test-beds for demonstrating the efficiency of many engineering approaches to generating maximum possible voltages in the opening phase of a POS in an external magnetic field. These approaches were then used in designing new schemes of higher-power generators.

4. USE OF A POS IN A MODIFIED UIN-10 MEGAVOLT GENERATOR

Applying an external magnetic field to a POS makes it possible to increase the amplitude of the voltage pulse generated in the opening phase of the POS. This circumstance is promising for generating XRB pulses during the deceleration of a high-energy electron beam in a high-*Z* target.

In some generators of XRB pulses, electrically exploded wires (EEWs) are used to switch the generator current to the electron diode. The use of a POS instead of an EEW makes it possible to increase the amplitude of the generated voltage pulse, to enhance the generation efficiency, and to integrate the POS into an existing device with a given configuration of the output unit.

Let us consider how a POS was integrated into the UIN-10 accelerator at the Research Institute of Scientific Instruments (Lytkarino) [32, 44]. The UIN-10 facility (Fig. 5) is a direct-action accelerator with an intermediate inductive energy storage in which the accelerating voltage pulse is generated due to the electric explosion of parallel copper wires. The intermediate inductive energy storage is supplied from a Marx generator. The voltage pulse generated with the use of EEWs is fed through a gas-discharge switch to the input of a magnetically insulated transmission line (MITL), which is ended with an electron diode, whose anode serves as a radiation converter. A characteristic feature of the MITL of the UIN-10 accelerator is its fairly great

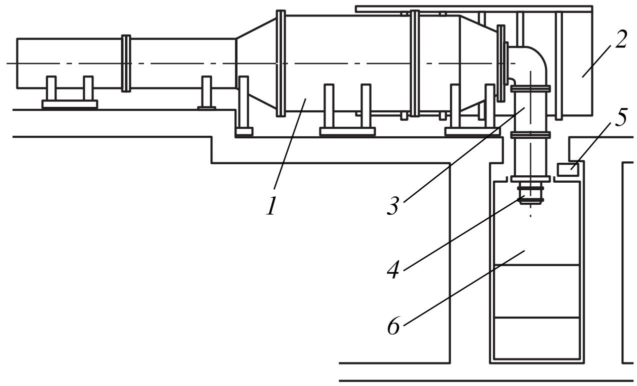

Fig. 5. Schematic of the UIN-10 accelerator with a POS: (*1*) capacitive energy storage (Marx generator), (*2*) protective screen, (*3*) MITL, (*4*) POS, (*5*) capacitor bank for powering the plasma injectors of the POS, and (*6*) research chamber.

length (~6 m). The parameters of the accelerator are listed in the table.

The use of EEWs as a current switch in the accelerator with an inductive energy storage has disadvantages. These are the necessity of replacing the EEWs after each shot, a substantial energy spent by the Marx generator on the explosion of the wires, and the loading of the transmission vacuum insulator of the MITL by the high voltage generated during the wire explosion. Installing a POS at the MITL output makes it is possible to improve the operating characteristics and output parameters of the accelerator.

The POS can operate in either a single- or two-stage mode of generating the accelerating voltage pulse (Fig. 6). In the single-stage mode, the POS is used instead of EEWs to output the magnetic energy accumulated in the inductive energy storage. In the two-stage mode, the POS is used to sharpen the power of the pulse generated with the help of the EEWs and the switching gap. Replacing EEWs with a POS allows one to increase the repetition rate of the generated pulses; to lower the voltage at the insulator and to improve its reliability and resource; and to reduce energy losses in the MITL, which, in the case of EEWs, serves as an additional load shunting the electron diode. The use of a POS also requires the modification of the anode-converter of the electron diode, which is used to generate XRB pulses. In the modified accelerator, a multilayer converter was employed that was previously tested in the RS-20 facility [45].

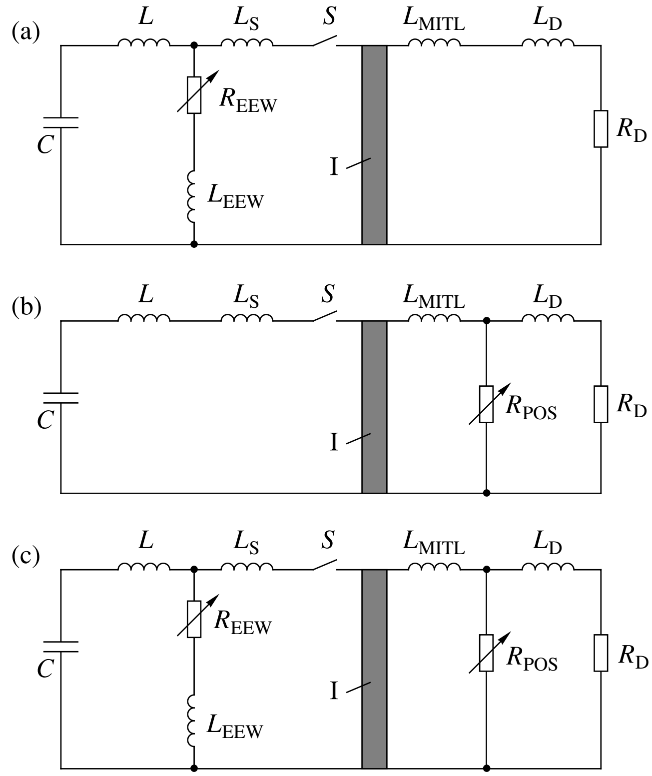

Fig. 6. Electric circuit of the modified UIN-10 accelerator with a POS: (a) version with EEWs, (b) version with a POS, and (c) version with a simultaneous use of EEWs and a POS: C = 0.1 μF; L = 15 μH is the total inductance of the Marx generator; L_{EEW} = 2 μH is the inductance of the EEWs; R_{EEW} is the variable resistance of the EEWs; L_{MITL} = 3 μH is the inductance of the MITL; R_D = 80 Ω is the diode resistance; S is the switch, with L_S being the inductance and active resistance of the switch; L_D = 230 nH is the load inductance; and R_{POS} is the POS resistance.

To enhance the generator efficiency, it was proposed to use a POS with an external magnetic field produced by magnetic coils surrounding the system of plasma

Expected characteristics of the UIN-10 accelerator

Marx generator energy, kJ	Marx generator voltage, MV	Operating mode	EEW	POS	Insulator voltage, MV	Diode voltage, MV	Amplitude of the diode current, kA	Duration of the diode current pulse, ns
216	2	EEW	Present	Absent	7–7.5	4	60	70–100
216	2	One-stage	Absent	Present	3	5.4	75	100
216	2	Two-stage	Present	Present	7–7.5	6	75	50

injectors. Applying an external magnetic field allows one to increase the POS voltage by a factor of 1.5. A distinctive feature of the proposed POS is that the inner high-voltage electrode serves as a cathode (Fig. 7). In this case, the magnetic field produced by the coils arranged on the outer anode is skinned by the copper cathode of the POS. On the one hand, this enhances the field in the POS gap and, on the other, ensures that electrons emitted from the cathode cannot arrive at the anode along the magnetic field lines of the external magnetic field, because the electric field prevents them from moving along these lines.

5. USE OF A POS TO SHARPEN MEGAMPERE CURRENT PULSES

Due to its capability of efficiently switching the current to the load, a POS can be used as a final sharpening stage of a high-power pulsed generator that is now under construction within the Baĭkal program. In the modified RS-20 facility [46], special experiments were carried out with the aim of verifying voltage scaling (5) and achieving the maximum possible voltages. At a Marx generator voltage of 0.84 MV and currents of 150–300 kA, the voltage U_{POS} = 3–3.5 MV was obtained, which agrees with scaling (5). At a charge density transferred through the plasma of ≈0.45 mC/cm, such a voltage pulse was generated in more than 50% of shots. As the charge density was increased to 0.9 mC/cm, which could only be achieved by increasing the plasma density, the POS voltage decreased by a factor of 1.5–2. Attempts were made to compensate for plasma erosion by additional plasma injection; in particular, experiments were performed on programmable filling of the POS gap with plasma. Although it was extremely difficult to do this on so short time scales, these experiments allowed one to achieve a voltage of 3–3.2 MV in four (of one hundred) shots. This confirms our assumption that, while operating in the erosion mode (i.e., at a limited value of the plasma density), it is possible to increase the charge density transferred through the plasma and to achieve the maximum possible voltages. Since scaling (5) is fairly important for practical applications of POSs, independent measurements were performed in addition to electric measurements, specifically, the high-frequency boundary of the γ spectrum of the XRB of electrons decelerated in the anode was determined by the photoneutron activation method. For this purpose, the ^{9}Be(γ, n)^{8}Be and ^{2}D(γ, n)p reactions with thresholds E_{Be} = 1.65 MeV and E_D = 2.25 MeV, respectively, were used. The results obtained corresponded to an electron energy of 3.2 MeV [47] for a POS with an external magnetic field.

It should be noted that the concept of a POS with an external magnetic field that was proposed at the Kurchatov institute in order to increase the POS voltage is quite different from that of a magnetically controlled POS used at the Sandia National Laboratories [48]. In the latter, the axial magnetic field is generated by the

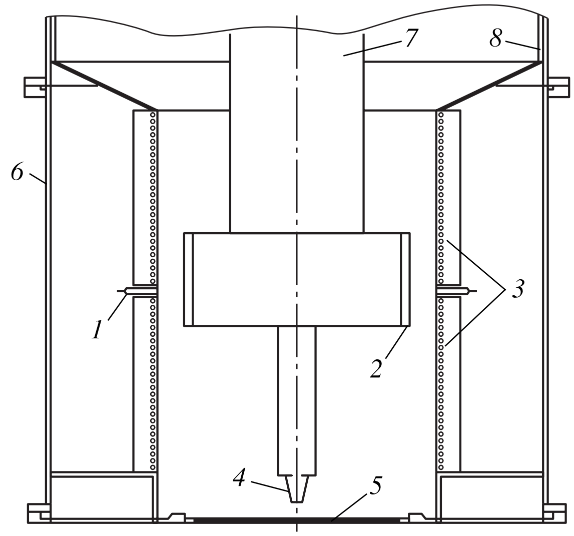

Fig. 7. Schematic of the POS of the UIN-10 accelerator: (*1*) one of 48 plasma injectors, (*2*) POS cathode, (*3*) 600-mm-diameter 380-mm-long magnetic-field coils, (*4*) cathode of the electron diode, (*5*) X-ray anode-converter of the electron diode, (*6*) outer surface of the vacuum chamber, (*7*) MITL cathode, and (*8*) MITL anode.

POS current flowing through a multiturn coil. In this case, the process of current break is governed by the magnetic pressure rather than by plasma erosion. The plasma is injected along the magnetic field generated by a pulsed coil that is used to control of the instant of break. The voltages achieved in a magnetically controlled POS are by 50–70% lower than those predicted by formula (5) for a POS with an external magnetic field.

In the Baĭkal program, it is suggested that the high-voltage pulse produced at the POS output (10 MV, 50 MA, 100–300 ns) be used to compress a fast liner in order to generate an X-ray pulse with an energy on the order of several tens of megajoules [49].

To model the conditions of the Baĭkal generator and to examine the possibility of transmitting such a pulse, the MOL facility is presently being under design. It is planned that the amplitude of a 100-ns voltage pulse generated in this facility with the help of a POS will be 4–6 MV at a current of 3.7 MA [1]. A characteristic feature of the MOL and Baĭkal generators is the presence of a relatively long (≈38 μs) current prepulse and a subsequent main current pulse with a rise time of ≈2 μs at the input to the POS. This presents a severe engineering problem, because the POS should pass the entire prepulse and switch the main current over 100–200 ns at the instant of maximum.

The MOL device [1] is intended to investigate and test the entire power sharpening scheme, including the POS. The liner load is simulated by the second POS, whose impedance, similarly to that of the liner, is initially low and then increases with time. A detailed analysis of the circuit of the MOL facility is beyond the

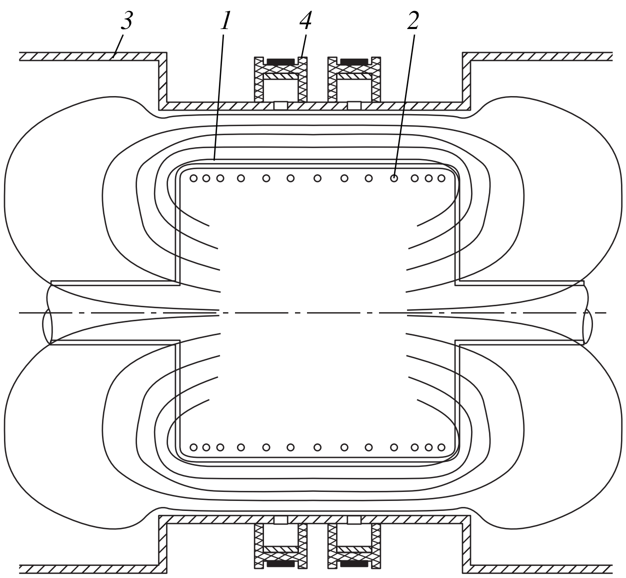

Fig. 8. Configuration of the magnetic field in one of the six units of the MOL facility: (*1*) POS anode with magnetic-field coils inside it, (*2*) one turn of the magnetic-field coil, (*3*) POS cathode, and (*4*) plasma injectors.

scope of this paper. Below, we will consider the basic characteristics of a POS capable of transmitting the main pulse (3.7 MA, 2 μs) in the erosion mode. These characteristics can be determined using the criteria formulated in the previous sections.

We propose a new scheme of a POS (Fig. 8) in which the external magnetic field was produced by a solenoid installed at the high-voltage inner anode. This field was screened by the outer electrode (cathode). In this case, the field is concentrated inside the anode–cathode gap of the POS. In this configuration, the modules can be placed close to one another without distorting the magnetic field. The feasibility of such a scheme with a synchronized instant of current break was tested for two identical POSs and was found to operate satisfactorily well [50].

To increase the current flowing through the POS and, at the same time, to retain the linear charge density, it is necessary to increase the POS dimensions according to condition (1). This is an obvious disadvantage because the problem arises of concentrating the current within a small-size fusion load, which seems to be practically unfeasible. As the POS diameter increases, both the charge density and the plasma density in the POS increase. The magnetic field produced by the current flowing through the POS increases as well. In this case, the POS operates according to the MHD scenario in both the conduction and opening phases. For a microsecond duration of the conduction phase, this implies that the POS should be sufficiently long, which complicates the synchronization and matching of the loaded modules.

The limitation related to an increase in the volume and caused by the limiting charge condition can be overcome by using a multimodule POS, provided that all the modules operate synchronously. The diameter of such a multimodule POS can be reduced by a factor of $n^{1/2}$, where n is the number of modules. The use of small-size modules each of which satisfies condition (1) allows one to reduce the dimensions of the POS unit.

The current pulse at the input of a six-module POS can be conventionally divided into two parts: the prepulse of duration ≈38 μs, which comprises ≈80% of the charge and ≈20% of energy, and the main pulse of duration ≈2 μs, which comprises 20% of the charge and 80% of energy. To overcome the problem related to the prepulse, it was proposed that the process of plasma erosion be compensated for by a programmable filling of the gap with plasma [51]. The POS remains operable even when the charge density per unit length reaches 20 mC/cm. According to condition (1) with allowance for only the main pulse, the diameter of the POS modules of the MOL generator was chosen to be ≈40 cm.

The width of the interelectrode gap was chosen to be 4 cm in accordance with the experimental results obtained in the RS-20 facility [8, 26], in which the 4-cm-wide gap was quite sufficient to achieve a voltage of 3.0–3.5 MV. Therefore, six parallel modules, each carrying a current of 0.6 MA, can be arranged inside a vacuum chamber 150 cm in diameter, which is an external technological limitation.

For each submegampere module, the voltage can be estimated from formula (5). Although there is no Marx generator in the MOL scheme, we may introduce the effective voltage of the source U_{eff} as

$$U_{\text{eff}} = W/Q, \tag{7}$$

where $W = 3.4$ MJ is the energy in the inductive energy storage of the MOL and Q is the charge transferred by the main pulse. We then find from formula (5) that the voltage in the opening phase will be ≈4 MV.

The exponential growth of the current in the main pulse can result in a substantially higher generated voltage. Calculations [52, 53] show that, when an explosion magnetic generator producing a pulse with nearly the same shape as in the MOL scheme is used as a primary energy storage, the POS voltage can reach 2.25 MV for $U_{\text{eff}} = 0.1$ MV. Thus, the exponential growth of the current indeed leads to a higher generated voltage in comparison with that in the case of a sinusoidal current pulse.

The required magnetic field in the POS can be estimated from condition (2) by comparing B_c and B_z. For one module with a maximum current of about 600 kA and an average radius of 18 cm, the azimuthal magnetic field is nearly equal to 0.7 T. The value of B_c corre-

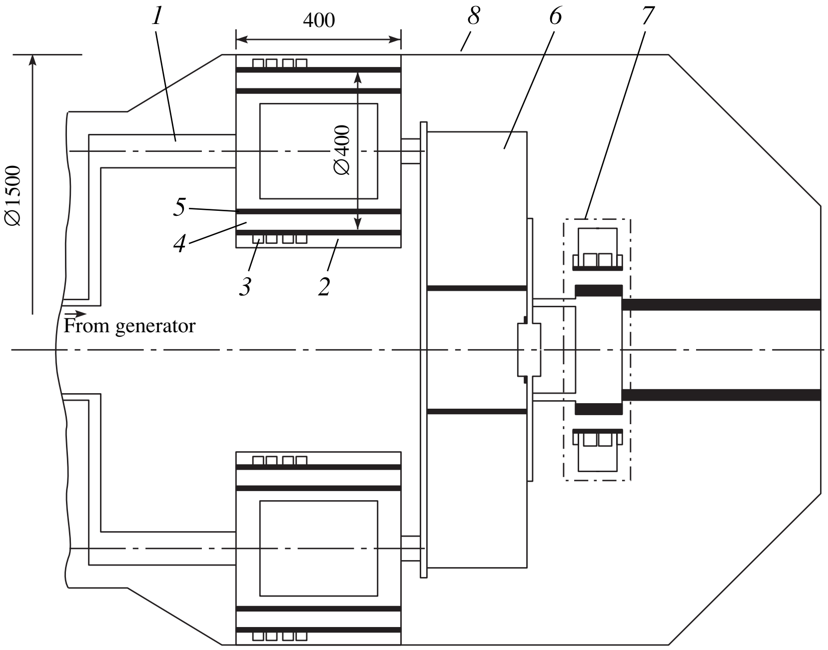

Fig. 9. Axial cross section of the load of the MOL facility with six POSs connected in parallel: (*1*) current lead (anode), (*2*) POS cathode, (*3*) plasma injectors, (*4*) anode–cathode gap of the POS, (*5*) POS anode with magnetic-field coils, (*6*) spark gap, (*7*) POS (plasma bridge) for simulating a load with a nonlinear impedance, and (*8*) vacuum chamber.

sponds to the critical current and is determined by the formula

$$B_c\ [\mathrm{T}] = 3.36 \times 10^2(\gamma^2 - 1)^{1/2}/d_{\mathrm{eff}}\ [\mathrm{cm}], \qquad (8)$$

in which $d_{\mathrm{eff}} = (r_c^2 - r_a^2)/2r_a$ and $\gamma = 1 + 1.96 \times 10^{-6}U_{\mathrm{POS}}$. According to this formula, we have $B_c = 0.5$ T. However, d_{eff} can be determined more exactly because the opening is associated with the formation of a narrow vacuum gap in the POS plasma.

In experiments described above, the ion current density at the cathode in the opening phase was found to be as high as 100 A/cm^2. If the current break occurs according to the erosion model, then the distance corresponding to this current density is determined from the Child–Langmuir law. At a POS voltage of 4 MV, the gap width is about 1 cm. This corresponds to a magnetic field of about 2 T.

We calculated the main parameters of the POS for the MOL facility by using an approach based on the limited charge. For the outer and inner POS diameters of 40 and 32 cm, respectively, and an external field of 2 T, a voltage of ~4 MV can be achieved in each of the six synchronized modules conducting a 600-kA current pulse with a duration of 2 μs. In this case, the total current is 3.6–3.7 MA. A more detailed modeling of the POS in this stage is hardly possible, because we did not specify the shape of the current pulse generated by the inductive energy storage. However, the above analysis of the POS geometry allows us to propose a POS scheme that will be tested in the MOL generator.

Besides the choice of the POS dimensions, it is necessary to solve problems related to the synchronization of several modules and to the possibility of repeatedly closing the modules by the plasma after switching the current to the load. When the plasma gaps of the POS modules are magnetically insulated, it is also necessary to prevent a distortion of the magnetic fields of the modules, which are placed close to one another. The possibility of using several synchronously operating POS modules was demonstrated previously in [54, 55]. The feasibility of a scheme with a synchronized POSs was investigated experimentally by using a scheme consisting of two parallel modules, each of which transmitted 150-kA current pulses with a duration of 2 μs. The results of these experiments showed that the redistribution of 10% of the current or 1% of the charge substantially improved the synchronization characteristics [50].

A specific feature of a multimodule POS is that a multielectrode spark gap is used to shorten the front of the current pulse transferred to the load and to prevent the closure of the POS by the plasma during at least 3 μs after the current is switched to the load. The vacuum spark gap consists of a set of small vacuum gaps, which are separated by insulators and assembled into one section, and is placed between the six-module POS of the MOL and the load. The efficiency with which the spark gap prevents the closure of the POS was tested in a separate experiment in [56].

6. CONCLUSIONS

The above analysis of the operation of microsecond POSs in an external magnetic field has allowed us to determine the prospects of utilizing them for the generation of high-power nanosecond megavolt pulses, including in the repetitive mode.

We have reviewed the experimental studies of POSs operating at currents of 40–300 kA, output voltages of 0.5–3.5 MV, and plasma densities of 10^{12}–10^{14} cm^{-3}, the duration of the conduction phase being 0.7–2.5 μs. It has been shown that, under these conditions, the current break is governed by plasma erosion. The experimental results have allowed us to reveal the main mechanisms and constants determining the operation of an erosion POS: the linear charge density transferred through the POS, $q_{\text{lin}} \approx 5$ mC/cm, the ion current density $j_i \approx 100$ A/cm^2, the requirements for the strength and configuration of the external magnetic field, the voltage scaling $U_{\text{POS}} \propto U_{\text{MG}}^{4/7}$, etc. Based on these data, a method for calculating a POS with specified parameters has been proposed.

Thus, the design features of the POS scheme for the modified UIN-10 accelerator in which EEWs are replaced with a POS have been analyzed, the parameters of the external magnetic field have been determined, and the output voltage has been estimated to be at a level of ~5 MV.

A multimodule POS scheme has been proposed for the newly designed megampere MOL generator. The parameters of the modules were calculated by the method proposed in this paper. The results of calculations are confirmed by numerical simulations and model tests.

Methods for increasing the current switched to the load, the duration of the conduction phase, and the efficiency of energy transfer from the inductive energy storage to a liner load whose impedance is initially low and increases with time have been considered.

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