Determination of the Parameters of Opening Switches with Axial Plasma Injection

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Abstact – This paper presents the results of experiments carried out on the GIT-4 and GIT-8 systems with microsecond megaampere plasma opening switches with axial plasma injection. The conduction phase duration for a switch with an axial dimension L is determined by the magnetic field penetration velocity $u \propto L^{1/2}$. As the conduction current and, hence, the magnetic field at the cathode, B, increase, the velocity u rises proportional to B. Measurement and calculation results are given for the plasma density in opening switches of different geometry.

The energy storage capability of an inductive system with a plasma opening switch is determined by the conduction phase duration of the switch, t_c, which is limited to the time of the magnetic field penetration through the previously created plasma bridge. Depending on the parameters of the plasma and on the switch current, the field penetration may occur by various mechanisms. The question of the field penetration mechanism into the plasma of a microsecond megaampere opening switch still remains open. This has been the subject of numerous experimental and theoretical studies. In the hydrodynamic approximation [1, 2] of a plasma pushed up by a magnetic piston, the magnetic field penetration velocity is of the order of the Alfven velocity, and the conduction current of the switch, provided that it increases linearly, is limited to

$$I_s = \left(6\pi m_i c^2 n / Z\right)^{1/4} (\dot{I}^2 r^2 L^2 / g)^{1/4}, \qquad (1)$$

where $g = \dfrac{\ln R/r}{(R/r)^2 - 1}$, R and r are the anode and cathode radii, respectively; L is the switch length; m_i and Z are the ion mass and charge number; c is the velocity of light, and n is the plasma concentration. The current (1) corresponds to the field penetration velocity $u = L/t_c$, which, for $I_s = \dot{I}t_c$, is given by

$$u = L\dot{I}/I_s. \qquad (2)$$

The most wide-spread opening switches are devices with radial plasma injection. In this case, plasma is injected into a coaxial electrode system on the anode side toward the cathode. The initial axial switch length at the cathode is determined by the electrode gap spacing and by the angle of plasma expansion from the guns. An increase in plasma density in the switch at a practically constant axial length is attained by increasing the delay t_d between the operation of the plasma guns and the switch-on of the generator. In another case plasma is injected along the axis of the system toward the current pulse generator (Fig. 1).

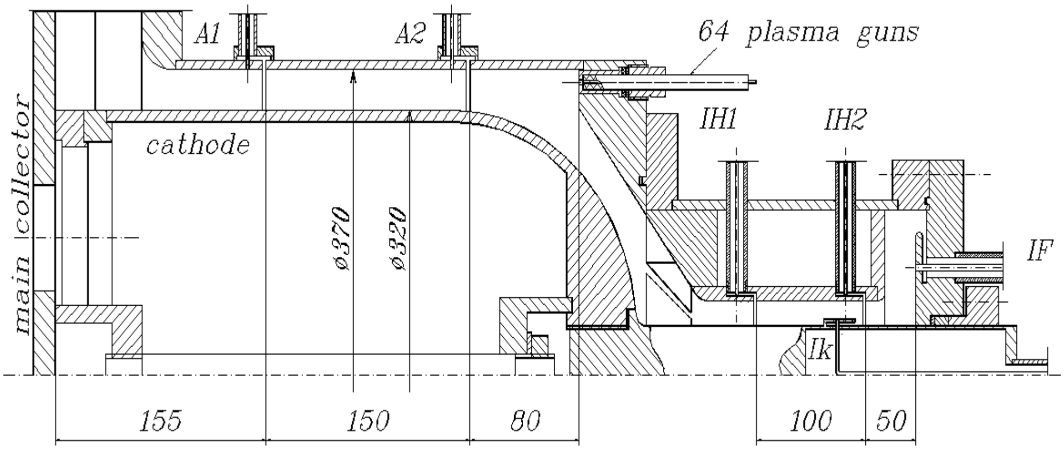

Fig. 1. Geometry of GIT–8 opening switch with axial plasma injection [3]

An increase in t_d increases in the main the switch length. According to (1), the switch current is proportional to nL^2. The amount of plasma injected into a switch along the axis is equal to that injected in a radius for the same t_d, and, hence, $n_a L_a \delta r = n_r L_r \delta R$, where the electrode gap spacing $\delta r \ll r$. In opening switches with radial plasma injection, the necessary length is attained by placing the guns in a circle whose diameter is greater than the anode diameter, and, as a rule, with $\delta R > \delta r$. If the angle of plasma expansion from the guns is ~90°, $L_r \approx 2\delta R$ and then $\frac{n_a L_a^2}{n_r L_r^2} = \frac{L_a}{2\delta r}$. From here it follows that for $L_a > 2\delta r$ a greater current can be achieved in a switch with axial plasma injection. Since the axial switch length, $L_a \approx v_d t_d$, is determined by the directional plasma velocity and by the delay time, the above condition is fulfilled for $t_d > 2\delta r / v_d$. For typical $\delta r \sim 3$ cm and $v_d \sim 3$ cm/μs, this condition is fulfilled even for delays longer than 2 μs.

Experiments with axial plasma injection were carried out on the GIT-4 and GIT-8 generators [3–5]. For plasma injection, cable spark guns were used, each producing a plasma flow within a solid angle of about 80–90°. In the experiments on GIT-4, 32 guns were used to inject plasma into coaxial opening switches with the anode radius $R = 10$ cm and cathode radius $r = 5.1$, 6, and 8 cm. The distance d from the base of the cathode hemisphere to the plane of the guns was 59, 89, and 75 mm. In the latter case, a reflecting electrode was used to confine the plasma expanding from the guns [5]. In experiments on the GIT-8 generator, the cathode and anode diameters were increased, respectively, to 320 and 370 mm. The distance d was 39 mm. The plasma injected into the switch was generated by 64 guns.

Figure 2 shows the switch conduction current as a function of its length for the case of axial plasma injection with the anode-to-cathode diameter ratio 200/160, 200/120, 370/320 [mm]. The switch length was defined as $L = v_d t_d$, and the average directional plasma flow velocity, v_d, was assumed equal to 3 cm/μs. This is an approximate definition of the switch length, since actually the plasma expands along the axis for a much larger distance because of the presence of light hydrogen plasma whose velocity can reach ~10 cm/μs. The actual length of the plasma bridge can exceed L by L_0, the length of the region filled with low-density plasma. However, this definition of L can be justified for the main switch component, dense carbon plasma, that is responsible for the conduction current. The experimental points are approximated by the relation $I_s \approx \alpha L^{1/2}$, and this, according to (1), testifies to the fact that the plasma density remains almost unchanged with increasing t_d.

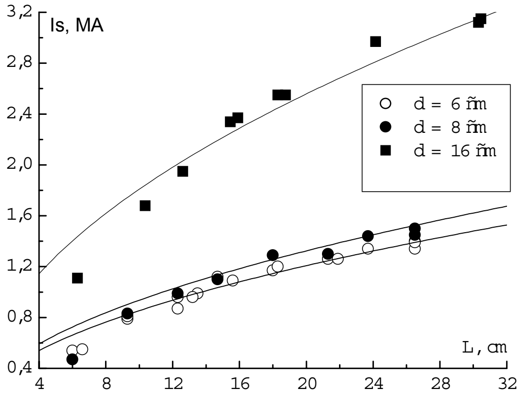

Fig. 2. Opening switch current versus length. GIT–4: r = 6 and 8 cm, d = 59 mm. GIT–8: r = 16 cm, d = 39 mm

The velocity of the magnetic field penetration into a switch (2) as a function of the switch length is given for different cathode diameters in Fig. 3. The solid curves are plots of the approximating relation $u = u_0 + \alpha L^{1/2}$. These curves differ only by the values of u_0; the coefficient α for all the three curves is equal to 0.3. The velocity u_0 is gained by the current channel probably early in the pulse during its passage through the low-density region of length L_0 ahead the region of length L. The same trend also shows up in the dependence of u on the magnetic field at the cathode (Fig. 4). The experimental data are approximated by the linear function $u = u_0 + \beta B$ with the same values of u_0 as in Fig. 3. The velocity difference $u - u_0$ is directly proportional to the magnetic field strength. The deviation of the points from the straight lines depending on the switch current testifies to rather little variations in plasma density. Similar dependences of u on the switch length and on the magnetic field at the cathode are obtained for a switch with other geometric dimensions.

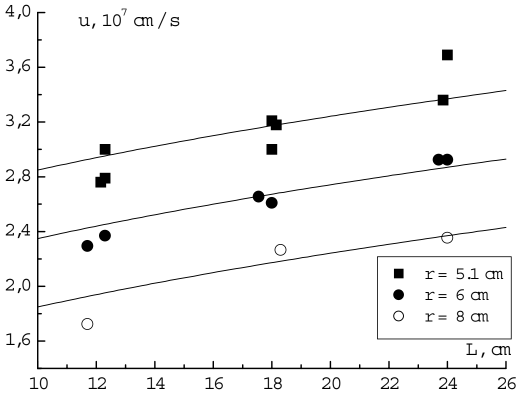

Fig. 3. Dependence $u(L)$. $d = 75$ mm

The experimental dependence of the switch current on its geometric dimensions confirms the validity of formula (1). Proofs of its applicability for various

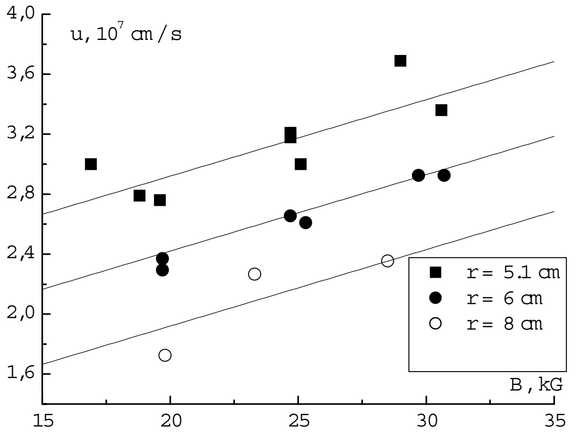

Fig. 4. Dependence $u(B)$. d = 75 mm

geometric dimensions and current rise rates in an opening switch are also given in [2, 4, 7]. However, the relationships revealed does not enable one to give preference to any particular mechanism of the field penetration. The same dependences of the switch current on the switch length and on the magnetic field at the cathode are also obtained in the approximation of electronic magnetohydrodynamics [2, 8]. A criterion for the validity of one or another approximation might be the dependence of the switch current on plasma density. This dependence was established, for example, in [2, 7] and, in particular, in experiments on GIT-8 [6]. With the help of a laser interferometer, the line plasma density nl, equal to the product of the plasma density by the axial length of the switch, was measured. Experiments have shown that for the same delay time t_d the switch current varies as $(nl)^{0.2}$. For a constant delay, we have $l \cong$ const and, hence, $I_s \propto n^{0.2}$. As t_d was increased, the switch current varied as $(nl)^{0.55}$. Since in the case of axial plasma injection the average plasma density n does not depend on l, then $I_s \propto l^{0.55}$. These dependencies of the current on n and L also agree with (1). The values of nl calculated by (1) correspond to those measured experimentally to within ~50%. Thus, for t_d = 4.4 μs, the calculated value of nl and its measured value averaged over the electrode gap spacing are, respectively, ~$5.2 \cdot 10^{16}$ cm^{-2} and ~$3.5 \cdot 10^{16}$ cm^{-2}. The fact that the calculated and measured values of nl are close to each other justifies the choice of the velocity of directional plasma motion equal to 3 cm/μs. With another choice of the plasma velocity, these values will be substantially different. Actually, from (1) it follows that nl^2 = const for some value of the switch current and, hence, $nl \propto l^{-1}$. The calculated value of n averaged over 17 shots was ($3.9 \cdot 10^{15}$ ± 50%) cm^{-3}.

The agreement between the measured and calculated values of n allows one to use (1) not only for qualitative, but also for quantitative estimations. The result of calculations of the plasma density for t_d ~ 8 μs is presented in Table 1. Given in brackets are values of the switch mass rise rate $\dot{M} = \pi(R^2 - r^2)v_d m_i n / Z$ calculated for the carbon ion component of the plasma.

Table 1. The plasma density n, 10^{15} cm^{-3}, and the switch mass rise rate $\dot{M}$, μg/μs

R, mm	r, mm	d, mm			
		39	59	75	89
100	51	–		.3 (1.1)	–
-.-	60	–	1.5 (4.4)	.4 (1.2)	1.3 (3.8)
-.-	80	–	1.8 (3.1)	.8 (1.3)	1.3 (2.1)
185	160	1.5 (6.0)	–	–	–

From the data above it can be seen that in the case where a reflecting electrode is placed in a switch with d = 75 mm, the plasma density in the switch noticeably drops. Conversion of n from one geometry to another in accordance with the relation $\pi(R^2 - r^2)Ln \approx$ const gives coincidence with the values listed in the table to within ~10%. The increase in distance d from 59 to 89 mm is also accompanied by a decrease in plasma density in the switch. For the case of no reflecting electrode, the agreement between the values of n calculated by (2) and those converted from one geometry to another is impaired. Such a conversion gives a difference of ~ 1.5 times against the calculated values. For the case of a reflecting electrode present in a switch, the accuracy of conversion is higher. This seems to be due to the fact that the indeterminacy of the geometry of the switch region adjacent to the injection plane is eliminated since this region is the same for any diameter of the cathode.

The axial density of guns is the same for the plasma injectors of GIT-4 and GIT-8. As a consequence, the plasma density is also practically the same. The increase in $\dot{M}$ is due to the fact that the number of guns used for GIT-8 is twice that used for GIT-4. The spread in $\dot{M}$ values about an average value for the case with a plasma reflector is 25%, and as the reflector is removed, it increases to 40% for d = 59 mm and to 70% for d = 89 mm. It should, however, be noted that the change in $\dot{M}$ and, hence, in n, for example, two times will change the conduction current only by ~ 20%.

The values of the plasma density and velocity of its inflow into a switch calculated by the above method can also be used in calculations for opening switches with radial plasma injection. These calculations predict an expected conduction switch current which agrees with its experimental value.

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