Opening Stage of Microsecond Megaampere Plasma Opening Switches

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Abstract - This report presents the analysis of opening stage based on the experiments carried out on the GIT-4 and GIT-12 generators with microsecond megaampere plasma opening switches. Switches with axial and radial plasma injection are considered. It is shown, that the experimentally observed switches features can be explained in frame of the modified erosion model of switch opening [1].

1. Introduction

The switch opening stage determines the energy transfer efficiency from an inductive storage to a load. The conduction stage of microsecond switches can be explained in frame of magnetohydrodynamic aproach which gives conduction current dependencies on the switch geometry and plasma density. However, the opening stage depends on specific conditions on the downstream end of plasma bridge that appear to the end of the conduction stage. As soon as the current channel formation and its position to the conduction stage end are not controlled in the experiment, the switch characteristics in opening stage may have large scatter depending on the plasma motion details. This complicates the regularities establishment of the opening stage and the energy switching into the load. In spite of the numerous experimental data there exist no common point of view on how switch opens and what are its real possibilities. Scaling for the switch voltage in the opening stage of microsecond switches obtained in [1]. According to [1] the switch voltage is proportional to the magnetic field penetration velocity through downstream end of the plasma bridge $U_s \propto u = \frac{L\dot{I}}{I_s}$ at high voltage, or to a velocity squared ($U_s \propto u^2$) at low voltage. Here L is the initial plasma bridge length, $\dot{I}$ - the switch current rise rate, I_s - the conduction current. The analysis below investigates the applicability of this scaling to experimental results with switches described in the report [2].

2. Switches with radial plasma injection

In the switches with radial injection the plasma bridge length doesn't depend on preliminary plasma injection time, and so the switch voltage is inversely to the conduction current. The switch current growth is reached due to the plasma density increase by means of more longer time of preliminary plasma injection, by installation of greater quantity of plasma guns or due to the cathode radius increase. However any of these methods leads to the switch voltage reduction (Fig. 1-2). The current increase by the guns quantity (k) increase leads to the voltage reduction $U_s \propto k_s^{-0.25}$ (Fig. 1). As the switch current $I_s \propto k^{0.25}$ [2] then the switch voltage $U_s \propto I_s^{-1}$. The cathode radius increase at the same delay time allows to increase the conduction current, but the switch voltage drops (Fig. 2). The voltage experimental data are in the region limited by the curves $U_s \propto 1/I_s$ and $U_s \propto 1/I_s^2$. When the switch current increases up to ~2.8 MA the voltage falls to 200 kV.

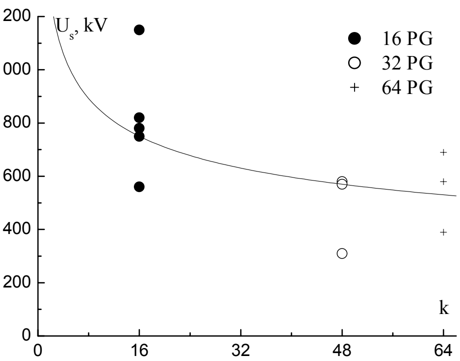

Fig. 1. Switch voltage as a function of guns number

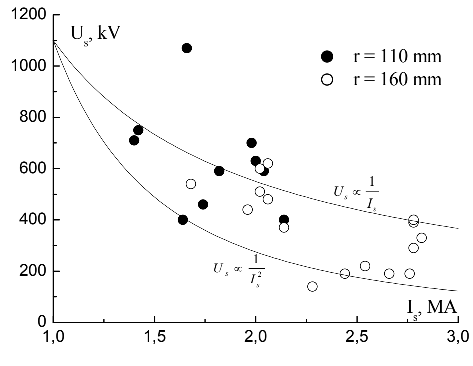

Fig. 2. Switch voltage as a function of conduction current

In switches with radial injection the plasma bridge length increase is reached by the guns installation in several rows with its identical quantity in each one. According to the scaling $U_s \propto u = \dfrac{L\dot{I}}{I_s}$ one should to expect the switch voltage growth as $U_s \propto L^{0.5}$. In fact the linear voltage drop occurs irrespective of the cathode size and the delay time (Fig. 3). The most probable reason of this consists in the plasma density growth on the load end of the plasma bridge due to the magnetohydrodynamic plasma displacement during the conduction stage. As a result the switch opening has deteriorated.

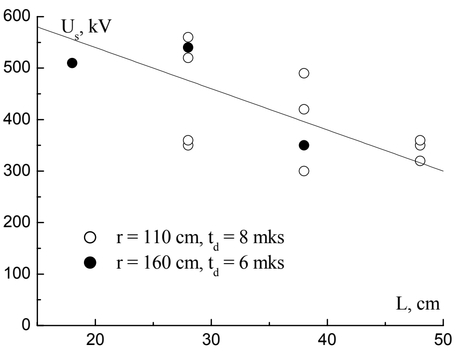

Fig. 3. Switch voltage as a function of initial plasma bridge length

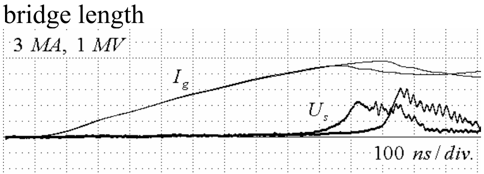

Fig. 4. Two shots waveforms

The switch voltage rise at the plasma bridge length increase is possible only at simultaneous plasma density decreasing. Fig. 4 shows the waveforms of two shots: in the first one 32 guns are established in one row, in the second – in two rows with 16 guns in each one. The plasma injected in coaxial with the cathode diameter 320 mm. The delay time in both shots was the same, so the plasma quantity injected in the switch in both shots was also the same. It means $Ln = const$. The ratio of charge passed through the switch during conduction stage for these two shots equal to 1.25. According to the scaling $Q \propto Ln^{0.5}$ and the term $Ln = const$, the plasma bridge length ratio for these shots coincides with geometrical one and equal to ~1.6. The switch voltage and the current drop speed in the second shot is more than in the first one. The voltage ratio for these two shots is closer to the expected one: $\sim L_2 I_{s1} / L_1 I_{s2} = 1.5$.

The guns quantity variation in rows allows create plasma bridges with inhomogeneous plasma density distribution. According to the magnetohydrodynamic Hall model [3], the current channel propagation in the region with lowered plasma density followed by the switch voltage rise. This was experimentally checked by creation of the plasma bridge with plasma density falling to the load direction. In the initial variant the plasma was injected by one row of guns in quantity of 64 units. Inhomogeneous density distribution was created by additional switching one or two guns rows with 16 units in each one. The table 1 shows the shot results for the switch with the cathode diameter 320 mm. The I variant corresponds to the base one: switch-on only 64 guns in the first row (64+0+0). In the II variant the guns of second row were added (64+16+0) and in the III variant all 3 rows of guns were used (64+16+16). In the table the conduction current marked as I_c, the closed charge - Q, the switch voltage - U_s, the pulse power in the inductive load – P.

Table 1. Shot results

$t_d = 4$ µs				
	I_c,kV	Q, C	U_s,kV	P,TW
I(64+0+0)	2.1	0.9	550	0.2
	2.1	0.9	570	0.2
II(64+16+0)	2.6	1.3	560	0.2
III(64+16+16)	2.6	1.3	490	0.2
	2.7	1.4	570	0.2
$t_d = 6$ µs				
I(64+0+0)	2.9	1.8	560	0.2
	3.0	2.0	610	0.2
II(64+16+0)	3.0	2.2	630	0.2
	3.0	2.0	640	0.3
III(64+16+16)	3.3	2.7	670	0.2

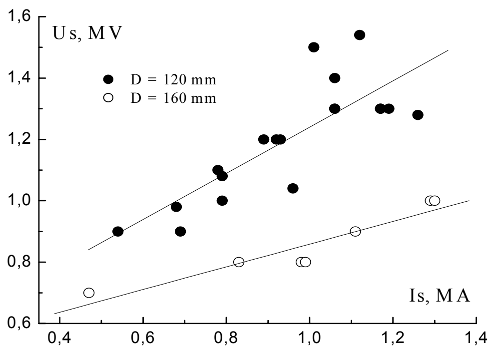

Fig. 5. Switch voltage as a function of conduction current

According to the table data the addition of guns rows leads to the growth both the conduction current and the closed charge. However the current channel propagation in the lowered plasma density region doesn't lead to the switch voltage and the load power growth. It can be consequence of plasma extrusion by the magnetic field pressure to the load end of the plasma bridge. Preliminary formation of the plasma region with low density is so useless for improving of the switch opening parameters.

3. Switches with axial plasma injection

In the switch with axial plasma injection the delay time increase gives the proportional growth of the plasma bridge length. In this case the switch voltage $U_s \propto u = \frac{L\dot{I}}{I_s}$ must increase proportionally to the current because in the magnetohydrodynamic regime the switch current $I_s \propto L^{0.5}$. Fig. 5-6 presents the switch operation characteristics for the high-inductive load (~200 nH). In these GIT-4 experiments the switch is formed by coaxes with 200 mm anode and 120 mm or 160 mm cathode diameters. When the current increases, it is observed the linear growth of the switch voltage and the load pulse power. The cathode diameter increase leads to the switch voltage drop and to the load pulse power decreasing from 400 to 250 GW.

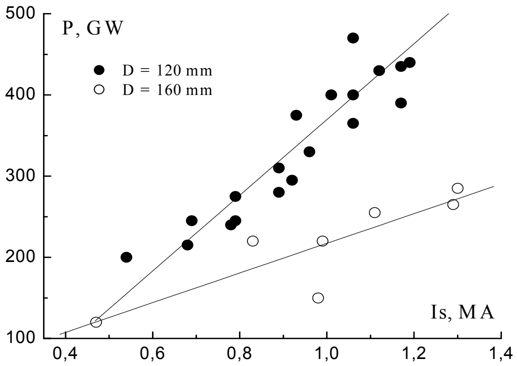

Fig. 6. Load power as a function of conduction current

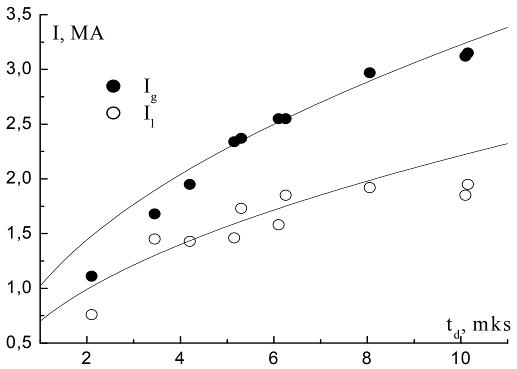

Fig. 7. Switch and load current as a function of delay time. U_{ch} = 40 kV

Fig. 7-8 shows the experimental results with the GIT-12 switches. The data were obtained for the low-inductive load (~50 nH) formed by 90/40 mm coax (Fig. 7) or by 90/60 mm coax (Fig. 8). For the fixed charging voltage the delay time increase up to 10 μs gives the switch current increase ($\propto t_d^{0.5} \propto L^{0.5}$) up to ~3 MA (Fig. 7). But the load current growth stopped at level about ~1.8 MA at the delay time ~6 μs. At the fixed delay time the charging voltage increase up to 55 kV allows to raise the switch current up to ~4.5 MA and the load current up to ~3 MA (Fig. 8). The switch voltage increases from ~400 to ~650 kV.

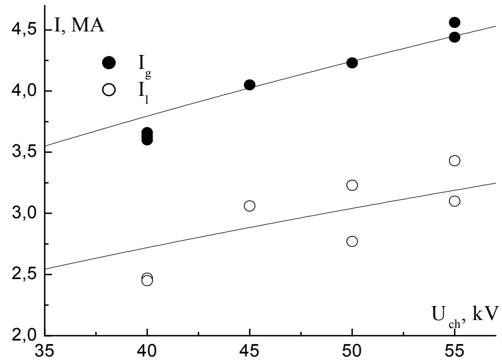

Fig. 8. Switch and load current as a function of charging voltage. t_d = 8 μs

4. Conclusion

In the switches with radial plasma injection the conduction current increase leads to the switch resistance drop by the opening. In the switches with axial plasma injection the voltage linearly depends on the conduction current. It means that the switch resistance doesn't depend on the conduction current, provided that it increases linearly in the conduction stage. These experimentally observed switch characteristics can be explained by the scaling obtained in [1].

References

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[3] A. S. Chuvatin, A. A. Kim, V. A. Kokshenev, and S. V. Loginov, Izv. VUZov. Fisika, 1997, v. 40, №12, p. 56-66.