Conduction Stage of Microsecond Megaampere Plasma Opening Switches

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Abstract - In this paper the analysis of the experiments with microsecond megaampere plasma opening switches is given. The switches with axial and radial plasma injection are considered. It is shown, that the conduction current depending on the switch geometry and plasma density is given by the magnetohydrodynamic scaling.

1. Introduction

The efficiency of the energy transfer from a capacitor into an inductive storage depends on the switch conduction stage. It's main features are the current and the time of switch conduction. The establishment of the current passing regularities in the microsecond switches was a subject of experiments on many installation including GIT-12 [1-2].

In the magnetohydrodynamic approximation [3-4] the switch conduction current, 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 plasma bridge length, m_i and Z are the ion mass and charge number; c is the velocity of light, n is the plasma concentration, $\dot{I}$ – the current rise rate. The charge closed in the switch during conduction stage

$$Q = \left(\frac{3}{2}\pi \frac{m_i c^2}{Z}\frac{n}{g}\right)^{1/2} rL \qquad (2)$$

is proportional to the product of switch geometry dimensions by $n^{0.5}$. Charge dependence on plasma density can serve as validity criterion of various model using for switches description. In the switches with Hall regime of magnetic field penetration $Q \propto n$ [4], in near electrodes diffusion regime $Q \propto n^{4/3}$ [5].

2. Switches with axial plasma injection

In such switches plasma is injected into the electrode coaxial system in the generator direction (Fig. 1). The delay time increase between plasma guns operation and generator switch-on gives the increase of plasma bridge length and correspondingly the switch conduction current. Another way of current variation consists in change of a primary energy store charging voltage. In GIT-12 switches plasma was injected by 64 guns into coaxial with electrode diameter ratio of 370/320 mm or by 32 guns in 208/160 mm coaxial.

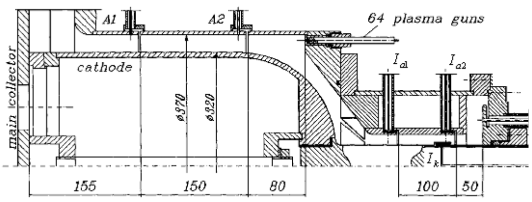

Fig. 1. Switch geometry with axial injection

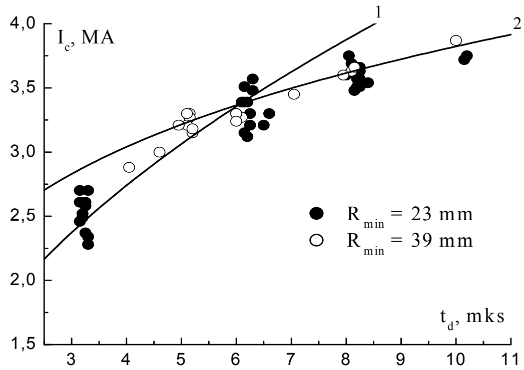

Fig. 2. Conduction current as a function of delay time

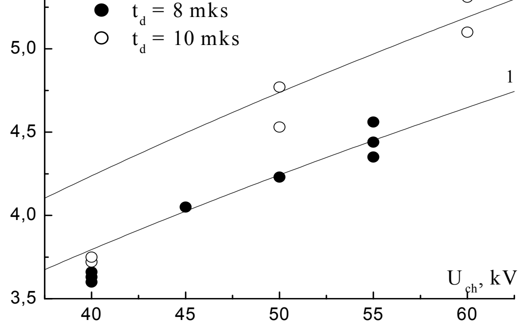

Fig. 3. Conduction current as a function of charging voltage

Experiments showed that by variation of the cathode radius, the plasma bridge length, the current rise rate in the inductive storage, tendencies of current and closed charge change are agree with scaling (1), (2). At 40 kV charging voltage and delay time increase up to ~10 μs the conduction time increased up to ~1.8 μs and the switch current up to ~4 MA (Fig. 2). Deviation of the switch current rise rate from linear for the time delay more than 6 μs leads to current meanings declines from the curve 1 ($\propto t_d^{0.5}$) to the curve 2 ($\propto t_d^{0.25}$). The switch current increased up to ~5.3 MA (Fig. 3), when the charge voltage rose up to 60 kV. Current meanings are close to the curves 1 and 2 ($I_c \propto U_{ch}^{0.5}$). The proportionality coefficient ratio for curves is close to the delay time ratio. Fig. 4 illustrates the radial electrode size influence on the switch current. The guns installation azimuths density was the same, because together with double cathode radius decrease the guns quantity in the plasma injector was a half. For fixed delay time the plasma density and it's axial length was the same in both switches. The current meanings are close to the curves 1 and 2 ($I_c \propto U_{ch}^{0.5}$). The current dependence on the cathode radius corresponds to the scaling (1).

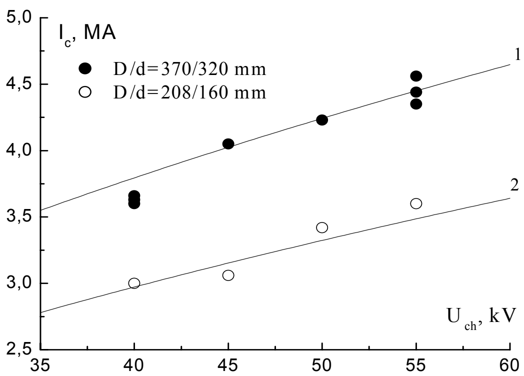

Fig. 4. Conduction current as a function of charging voltage

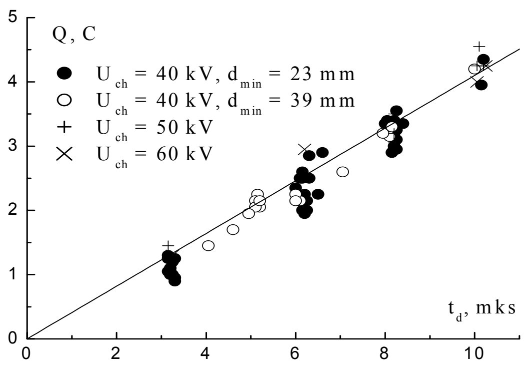

Fig. 5. Closed charge as a function of delay time

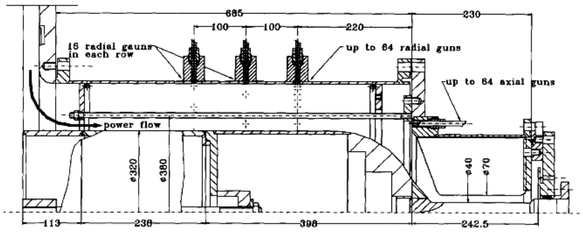

Fig. 6. Switch geometry with radial injection

The current increase at its rise rate increase is accompanied by a simultaneous conduction time decrease. It means that passed through the switch charge during conduction time doesn't depend on the current rise rate. Fig. 5 shows summary experimental results with an axial plasma injection. Passed through the switch charge doesn't depend on the charging voltage and so the current rise rate. The delay time increase and correspondingly plasma bridge length lead to the linear increase of the closed charge. This tendency is adjusted with scaling (2).

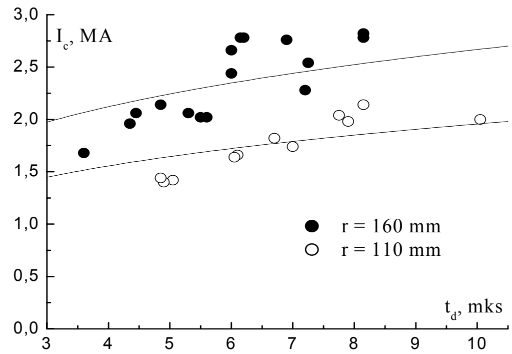

Fig. 7. Conduction current as a function of delay time

3. Switches with radial plasma injection

The switch design is shown in Fig. 6. The anode is made from 32 rods with 10 mm diameter in the form of squirrel cage on the diameter 380 mm. Switch cathode diameter was 320 mm or 220 mm. The radial plasma injection was produced by the guns installed in 3 rows with 100 mm interval on the 500 mm diameter shell. In two rows 16 guns were used and 64 guns were used in the third one. This way of guns set let vary the axial plasma bridge length and create switch with inhomogeneous plasma density distribution in the load or generator direction. Initial axial plasma bridge length on the cathode is determined by an interelectrode gap width and a plasma flying away angle. The delay time increase gives the plasma density growth at practically constant plasma bridge axial length on the cathode.

Fig. 7 and 8 show the conduction current and the closed charge depending on the delay time for the switches with different cathode diameter. Plasma injected into the switch by 64 guns installed in one row. At the same delay time the plasma quantity isn't change so the radius decrease is accompanied by plasma density decrease according to ratio $n(R^2 - r^2) \approx Const$. Total current and charge decrease is adjusted with the scaling (1) and (2) and conditioned both the cathode radius and the plasma density decrease. In contrast to axial injection the charge values on the linear part of the current rise are close to the curves $Q \propto t_d^{1/2}$. This agrees with the scaling (2) by the conditions that the plasma bridge length doesn't depend on the delay time but its increase gives linear plasma density increase.

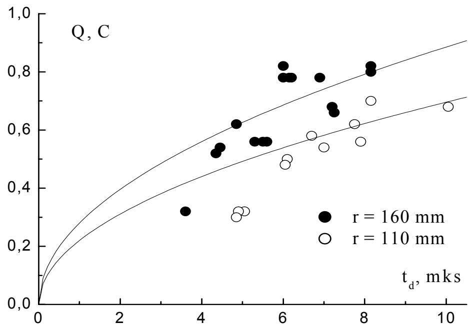

Fig. 8. Closed charge as a function of delay time.

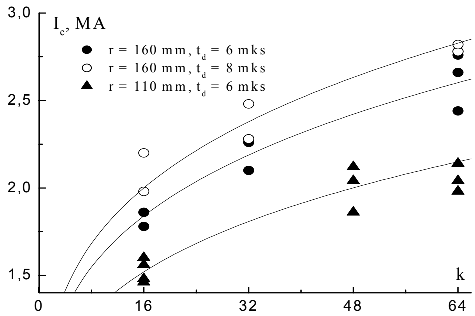

Fig. 9. Conduction current as a function of guns number.

One method of the switch current increase consists in a plasma density increase. This method is realized by installation of a larger plasma guns quantity (k) in one row and leads to the current increase $\propto k^{0.25}$ (Fig. 9). This regularity is realized independently of the cathode radius and the preliminary plasma injection time. The guns quantity increase gives the linear plasma density increase, therefore the conduction current $I_c \propto n^{0.25}$. Another method of the current increase consists in the plasma bridge length increase (Fig. 10). This method is realized by the turning-on several rows with the same guns quantity in each one. The plasma bridge length in Fig. 10 was calculated taking into account that the plasma flight away angle is ~90° and the plasma streams from neighboring rows are overlapped on the cathode. In this method the current values are closed to the curves $\propto L^{1/2}$ independently of the cathode radius and the delay time. The plasma bridge length increase is accompanied by a linear increase of the passed charge (Fig. 11).

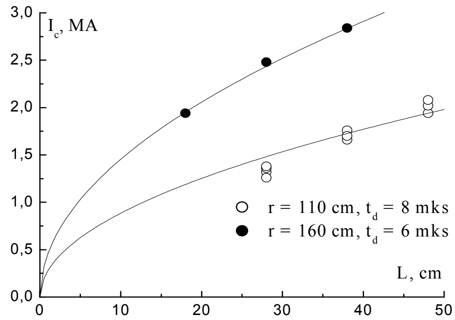

Fig. 10. Conduction current as a function of plasma bridge length.

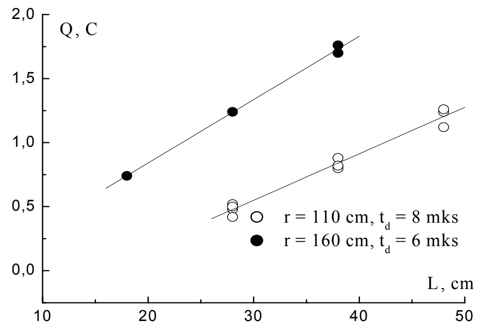

Fig. 11. Closed charge as a function of plasma bridge length..

4. Conclusion

Conduction stage of microsecond megaampere plasma opening switches is determined by magnetohydrodynamic motion of magnetic piston through plasma bridge from generator to load direction. Scaling ratio (1) and (2) are quite suitable for explanation of the change tendencies of the switch conduction current and the charge closed in the switch during conduction stage.

References

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