GIT-4 Experiments with Plasma Opening Switch of RFNC–VNIITF Design

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Abstract – This report presents the experiments results carried out on the GIT-4 installation with the plasma opening switch designed in RFNC–VNIITF. Flashboards type plasma source is used for plasma injection in the switch. By the switch opening, the stored energy is transferred to the inductive load or to the electron diode. By the conduction switch current ~ 1 MA, the load voltage reaches ~ 1 MV. The energy, dissipated in the diode with the impedance ~ 3 Ohm, reaches ~ 100 kJ. In this report, it is also discussed diode operation variations at the accelerating gap decreasing.

1. Introduction

For the high-current installation SIGMA [1], in RFNC-VNIITF is developed the plasma opening switch with radial plasma injection. For plasma injection in the switch, it is used the flashboard type plasma source with discharge along dielectric surface [2]. The switch electrodes are formed by the cathode of 158 mm or 206 mm diameter, and the anode in the form of squirrel cage (Fig. 1). The anode consists of 18 studs with the 10 mm diameter installed at the 276 mm diameter. In the capacity of a load, the inductance of the coaxial line downstream the switch or the diode with ring blade cathode are used. The diode accelerating gap varies from 2.5 mm to 10 mm. The load current and the load current rise rate are measured by Rogovskii coil and inductive flute (Fig. 4).

The plasma injector consists of six double-sided foil-coated fiber-glass plastic base plates installed at the 440 mm diameter. On each base plate two discharge channels of the 15 mm width with five 1–1.5 mm intervals are made. The base plates are tightly pressed to the switch body by means of six polycarbonate semi-rings of the 13 mm thickness. High voltage pulse is applied to the injector discharge channel from one or two condensers IK50-3 charged up to 40–45 kV. From one condenser, the channels discharge current amplitude reaches ~ 12 kA, from two does ~ 19 kA. The least necessary time delay of the GIT-4 triggering relative to the plasma injector operation is determined according to the fact of current tearing appearance in the shots with the smallest switch conduction time. Hence, the plasma directed velocity is estimated. At the discharge current increasing in the plasma injector in ~ 1.5 times, the plasma velocity grows by 10%: from ~ 4.5 cm/μs to ~ 4.9 cm/μs.

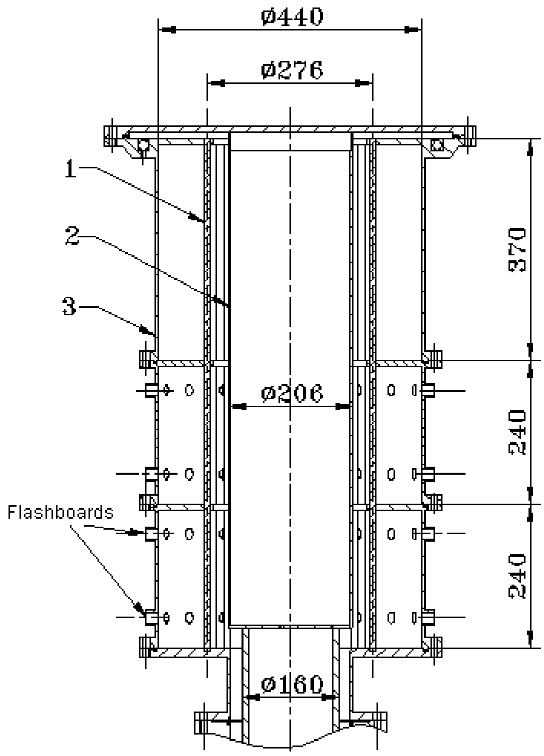

Fig. 1. Plasma opening switch design: anode – 1; cathode – 2; switch body – 3

2. Results with inductive load

In the experiments [3], the switch current increase is reached by means of preliminary plasma injection time increasing or by flashboards discharge current rising. At the delay time growth from ~ 3 to ~ 13 μs, the switch conduction current raises from ~ 0.4 MA to ~ 1.3 MA. At the fixed delay time, the flashboard current increasing yields the switch current increment on ~ 100–150 kA.

The experiments have shown that in the switch with the cathode diameter of 206 mm and the switch conduction current ~ 1 MA, the switch voltage by opening does not exceed ~ 600 kV. Further switch current increasing resulted in the voltage fall up to 200–300 kV. Reduction of the cathode diameter to 158 mm and, accordingly, increasing of the cathode-anode gap in the switch and load region from 22 mm to 46 mm, have provided the doubly switch voltage growth at insignificant drop of the switch conduction current ~ 100 kA. At the delay time ~ 11 μs, the waveforms of the switch and load currents, I_g and I_l, are shown in Fig. 2. The switch current during ~ 900 ns rises to ~ 1.1 MA. The switch voltage, U_s, reaches ~ 1 MV, the load current rise rate does ~12 kA/ns. After switch opening, the load current coincides with the storage inductance current. Current coincidence indicates on current leakage lack in the load coaxial. Hereof it is also testified by constancy of the calculated inductance dependence $L_v(t)$ after switch opening.

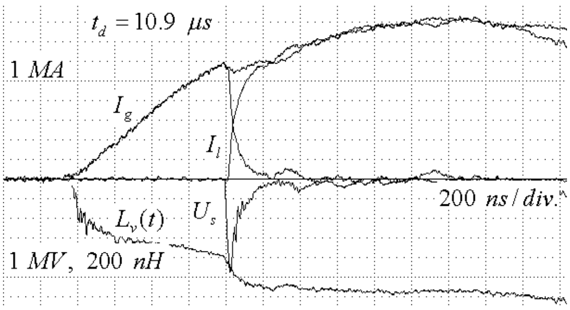

Fig. 2. Waveforms with inductive load 70 nH

3. Results with diode load

The geometry of the diode formed by the ring blade cathode and the flat anode is shown in Fig. 3. In Fig. 3, the calculated electron trajectories are also shown. The cathode diameter is equal to 158 mm, the blade diameter does 140 mm, the distance between the blade edge and the anode plane is 5 mm. The emitting surface is all blade borders. At the accelerating voltage 1 MV, the diode current is equal to 280 kA. The diode current magnetic field leads to considerable electrons trajectory bending. As a result, the electron beam is focused in the anode plane at a diameter of ~140 mm.

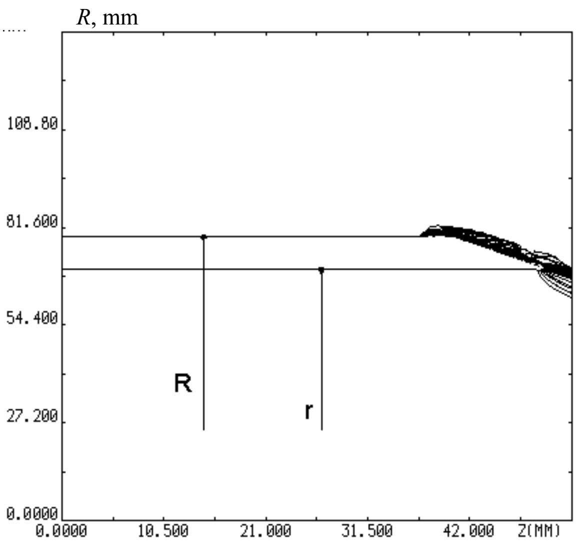

Fig. 3. Diode geometry and electron trajectories

The results of current and diode impedance, R_d, calculations depending on the ratio of the cathode radius, R, to the blade radius, r, at different values of the accelerating gap d, are combined in Table 1. These data are used as initial for experiments with diode load. The simulations are made by means of SSAM code [4].

Table 1. Diode calculated characteristics

d, mm	R/r, mm	I, kA	R_d, Ohm
2.5	100/90	300	3.3
	158/140	550	1.8
	200/180	900	1.1
5	100/90	180	5.6
	158/140	280	3.6
	200/180	400	2.5

The diode design is shown in Fig. 4. Switch operation with diode load is illustrated by Fig. 5. The switch and load current waveforms, I_g and I_d, the load current rise rate, $\dot{I}_d$, and calculated traces of the switch current, I_s, and the switch and diode voltages, U_s and U_d, are shown.

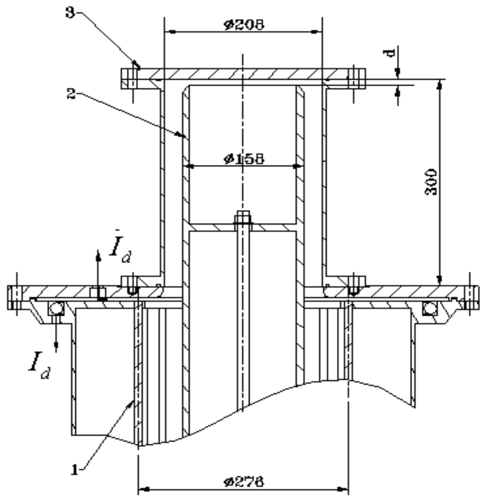

Fig. 4. Diode design: Switch anode – 1; switch and diode cathode – 2; diode anode – 3

The switch conduction current ~ 1.1 MA is approximately equal in all shots; the switch voltage during ~ 30 ns reaches ~ 1 MV. After the switch operates on the diode with the 10 mm gap, the switch and diode voltage traces practically matched during ~ 1 μs. At the peak voltage, the diode impedance is ~ 3 Ohm. The energy dissipated in the diode reaches ~ 100 kJ. After switch opening, the considerable current part continues to close in the switch-load region (Fig. 5, *a*). It means that the switch resistance is small as compared to the diode one.

From Fig. 5, *a* one can see that after ~ 200 ns from the diode voltage onset, some repeated diode voltage growth is observed. Here it ought to notice that the electron beam energy is equal only ~ 16 kJ to the

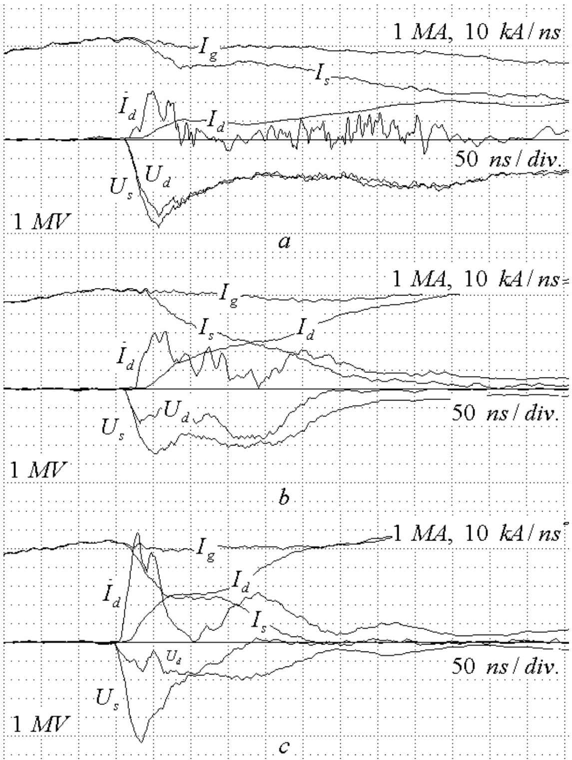

Fig. 5. Waveforms with diode load: $d = 10$ mm (*a*); 5 mm (*b*); and 2.5mm (*c*)

moment of repeated diode voltage growth. This tendency in the most degrees is visualized by accelerating diode gap diminution. This argues about cardinal change of the current passing scenario in the diode. Firstly, gap reduction is accompanied by deflation of the peak diode voltage and the voltage pulse duration. It is visualized the better, wherewith the accelerating gap is less. The diode voltage fall is caused, obviously, by the inductive voltage drop between switch and diode. Actually, at the gap reduction from 10 mm to 2.5 mm, the diode current rise rate is increased more than doubly: from ~ 5 kA/ns to ~ 12 kA/ns. It is obvious also that electrons acceleration in vacuum regime of diode operation takes place only at the voltage pulse onset before repeated voltage growth. At the 2.5 mm gap, the peak diode voltage does not exceed 300 kV, the electron beam pulse duration is about 50 ns. Such pulse duration corresponds to accelerating gap shorting with the velocity of ~ 5 cm/μs. Secondly, after voltage downfall, it is observed repeated voltage growth with subsequent voltage and current stabilization near to some quasi-invariable values. Such current-voltage characteristic is typical for the plasma filled diodes [5]. In such diodes, quasi-invariable current and voltage values are realized due to double layer formation by current passing in the gap filled with preliminary injected plasma. In our experiments, the accelerating gap is shorted by plasma produced on the diode electrodes. In the diode with the 2.5 mm gap, the plasma filled diode impedance grows to ~ 0.7 Ohm. After plasma filled diode reverse closing, the current completely passes through the load. The discussed diode operation regimes are reproduced at all values of the switch conduction current (Table 2). From the table data follows that the switch conduction current increasing is accompanied by the switch voltage fall. In all cases, at the 10 mm accelerating gap, the electron diode is realized with the ~ 2–3 Ohm impedance. At the gap reduction to 2.5 mm, the plasma filled diode is realized with the ~ 0.4–0.7 Ohm impedance.

Table 2. Shots results

t_d, μs	d, mm	I_s, MA	U_s, MV	U_d, MV	R_d, Ohm
3.8	2.5	.95	1.01	.40	.6
	10	.78	.87	.69	2.2
4.8	2.5	1.10	1.10	.42	.7
		1.09	1.07	.34	.7
	10	1.09	.93	.66	3.1
6.8	2.5	1.34	.78	.22	.4
		1.22	.60	.32	.5
	10	1.28	.64	.49	2.2
8.8	2.5	1.20	.58	.30	.6
		1.23	.37	.32	.6
	10	1.15	.61	.60	2.9

The data in Table 2 are obtained for the inductance between switch and diode equal to 86 nH. The experimental results by inductance reduction to $L_l = 42$ nH are illustrated Figs. 6 and 7.

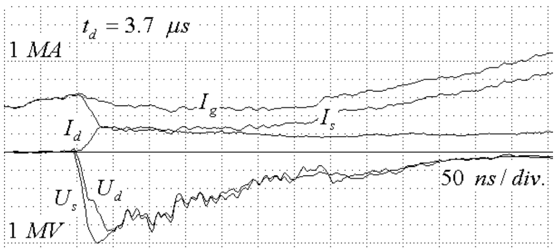

Fig. 6. Waveforms for diode with $d = 10$ mm

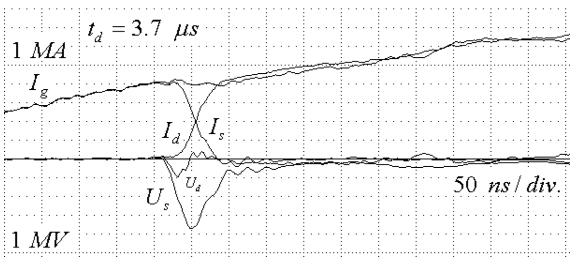

Fig. 7. Waveforms for diode with $d = 2.5$ mm; $L_l = 42$ nH

The smallest possible distance between diode and switch is defined by requirement of influence exception of the plasma streams from the switch region on the diode impedance and the energy transfer to the diode. The experiments have shown that in the diode with the 10 mm accelerating gap such diode voltage pulse lengthening which is shown in Fig. 5, *a* does not occur (Fig. 6). The diode dissipated energy in this shot is equal to 46 kJ only. At the diode gap reduction to

2.5 mm, the current passing regime with the double layer formation is not observed any more. The diode voltage does not exceed 200 kV, the voltage pulse duration is less than 50 ns (Fig. 7). In this case, the current passing regime with the double layer formation is not realized, seemingly, owing to presence of too high density plasma in the diode gap. Actually, the switch-load inductance diminution is accompanied by the load current rise rate increasing. For the shot shown in Fig. 7, the load current rise rate reaches ~ 20 kA/ns. Consequently, the load current growth enhances plasma producing on the diode electrodes. High-density plasma expansion in the diode accelerating gap results in strong gap closing.

4. Conclusion

The experiments have shown that the designed flashboard plasma source provides the switch conduction current ~ 1 MA with microsecond rise time. The developed plasma opening switch ensures the tenfold current rise rate in the ~ 90 nH inductive load. In the diode load, it is obtained the ring electron beam with the current ~ 0.3 MA and the electron energy ~ 1 MeV. The electron beam pulse duration is restricted by the accelerating gap closing due to the cathode and anode plasma expansion. In the described experiments, the impedance of the realized plasma filled diodes reaches ~ 0.4–0.7 Ohm.

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