SUPER FAST 75 ns LTD STAGE *

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Abstract

In this report, a new super fast LTD stage prototype, able to deliver a 75 ns FWHM voltage pulse into a ~(0.5-0.6) Ohm matched load with ~20 GW power, is presented. This stage is designed without peaking capacitors to increase its reliability. It includes 32 GA35436 (8 nF, 100 kV) storage capacitors, 16 multi gap switches, and a magnetic core made with reduced thickness of the ferromagnetic iron tape (50µm) to limit the current losses due to vortical currents. This prototype stage was specifically designed with an ellipsoidal vessel to allow the use of compressed gas (SF6, SF6/dry air mixtures, and pure dry air up to 6 ata pressure), or transformer oil, as the insulating medium.

I. DESIGN OF THE 75 ns LTD STAGE

The design of the 75 ns LTD stage is shown in Fig. 1. As all other fast LTD stages, it consists of sixteen parallel "bricks" locating evenly around the axis. A brick includes a switch type Fast LTD, two serial storage capacitors, and the output connectors. The storage capacitors are 8 nF double ended GA35436 capacitors in plastic case. The ferromagnetic core consists of 6 rings. Each ring is wounded of 50 um thick, 18 mm wide ET3425 iron tape. The turns in the rings are insulated with polyester film and fixed with epoxy. Total effective cross section of the core is ~55 cm^2 which corresponds to a volt second integral of ~17 mV.s in case of passive premagnetization prior to the shot.

The stage was tested with a resistive load which is made as a circular cavity filled with KBr water solution. By changing the amount of KBr in the solution, the resistance of the load was varied in the range ~(0.1-1) Ω.

The stage was tested with both compressed gas and oil insulation. For tests in compressed gas, the stage was inserted between two elliptical flanges allowing to increase the inner pressure up to 6 ata. To allow gas penetration into the stage volume, additional holes were drilled in the top and bottom flat flanges of the stage.

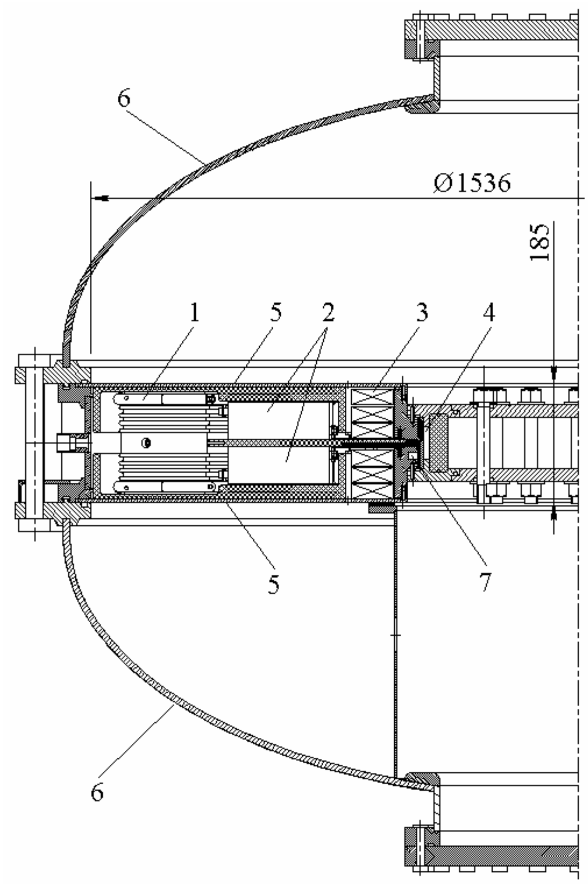

Figure 1. Design of the 75 ns LTD stage: 1 – switch type Fast LTD, 2 – GA 35436 storage capacitors, 3 – ferromagnetic core, 4 – cavity with KBr water solution, 5 – flat flanges of the stage, 6 – elliptical flanges, 7 – circular cavity for Rogovsky coil. Dimensions are in mm.

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In tests, the load voltage was measured with an external resistive voltage divider, the load current by a self integrated Rogovsky coil, and the current around the core by a B-dot probe.

II. TESTS IN COMPRESSED GAS

When the stage is filled with gas instead of oil, the electric field in the triple point at which the switch cover, gas and polyethylene insulator meet increases ~2.5 times because of lower permittivity of gas compared to oil. In preliminary tests with pure SF6 at P=2.2 ata, this increased field resulted in rare flashes along the insulator (initiated at the positive electrodes of the switches only) at maximum charging voltage of ±100 kV. The probability of these flashes was reduced when the pressure was increased to P=3.5 ata, but they did not disappear completely. To suppress these flashes, plasticine O-rings (modelling wax, ε~2.5) were added on positive covers of all the switches (see Fig. 2) in order to close the anode triple points.

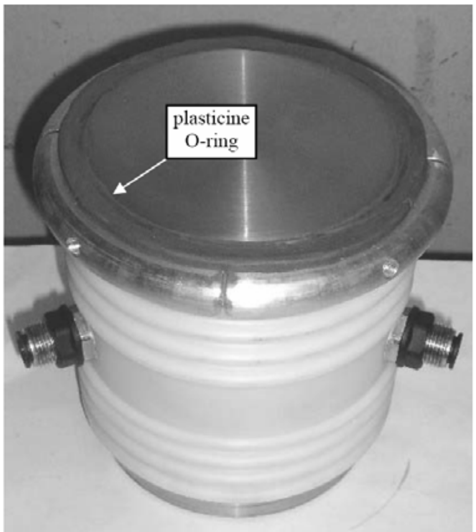

Figure 2. Plasticine O-ring on the positive sides of the switches

After such modification, safe operation of the stage (50 shots at ±100 kV without breakdowns) in pure SF6 was obtained at P=2.5 ata. In the following tests with SF6/dry air mixtures, all the switches were equipped with plasticine O-rings on positive electrodes.

It is well known that relative breakdown field of SF6/dry air mixture reduces with amount of air, and therefore, to keep the breakdown field of the mixture at the same level, its pressure has to be increased when the amount of SF6 reduces, as this is shown in Fig. 3. To fill the stage with SF6/dry air mixture, the ellipsoidal vessel was filled first with dry air, and after, the required amount of SF6 was added from the bottom. No any special mean was applied to mix air with SF6 inside the vessel because, in high electric field, the gas begins to move thus providing homogeneous mixture. The amount of SF6 in the mixture was gradually reduced, and its pressure was increased following approximately the graph in Fig. 3. At each mixture, 50 shots at ±100 kV were made. The final mixture was 20% SF6 + 80% dry air and it has been successfully tested at P =3.9 ata.

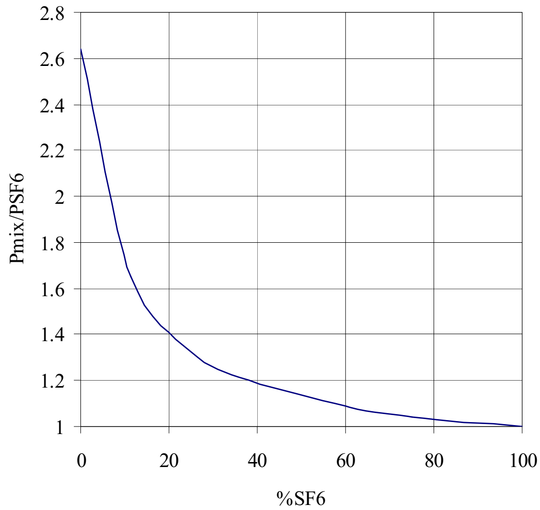

Figure 3. Relative pressure of SF6/dry air mixture providing same insulation as pure SF6.

According to Fig. 3, pure dry air requires ~2.6 higher pressure than pure SF6, or P~6.5 ata which exceeds the maximum operating pressure of the ellipsoidal vessel. Therefore the stage with pure dry air was tested at P=6 ata with a reduced charge voltage of ±95 kV. Fifty shots were made in these conditions with no breakdowns, but when the charge voltage was increased, 3 consecutive breakdowns were observed at ±98 kV charge.

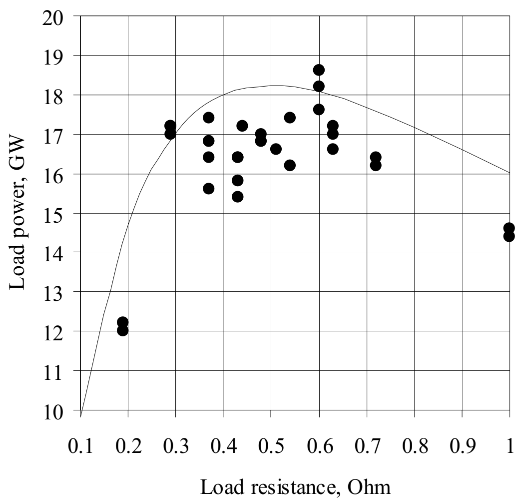

Figure 4. Load power in tests with gas insulation.

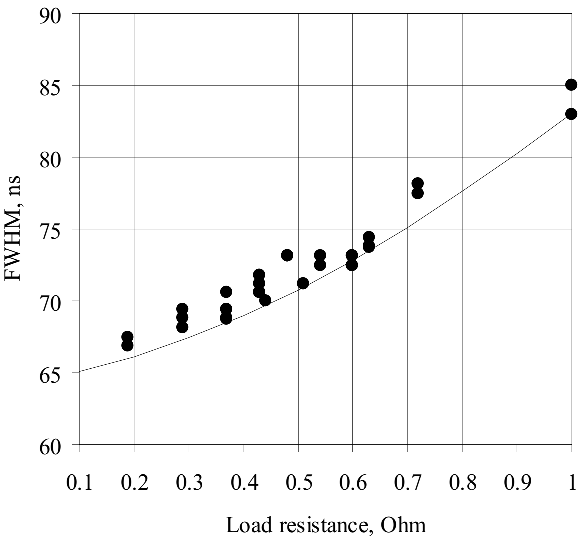

Figure 5. FWHM of the load voltage pulse in tests with gas insulation.

The electric parameters of the stage did not depend very significantly on the gas mixture or pressure. Figures 4 and 5 show peak load power and FWHM of the load voltage pulse versus load resistance R_{LOAD}. At R_{LOAD} ~(0.5-0.6) Ω, the power reaches maximum of ~(17-18) GW, the load voltage is ~100 kV, FWHM of the pulse is ~(70-75) ns. In Figs. 4 and 5, black curves are Pspice simulations described in Section IV.

The compressed gas insulation seems to be convenient for maintenance, but it causes specific problems, for example, to search an air leakage between the insulating pressurized gas volume and the switch hardware. Such a default can indeed generate a penetration of SF6 inside the switches and influence a lot their operating conditions. Also during the tests, some leaking oil was observed in two GA35436 capacitors, each time in vicinity of welded seams close to the output terminals. The exact reason for this leak was not defined, but it seems that because of multiple compressions and releases, cracks may appear in the place where the capacitor case is not as flexible. After disassembly, some vague dark spots were observed on the surface of the ferromagnetic rings. These spots may indicate that though the pressure was enough to isolate the parts for static ±100 kV charge voltage, it might be not enough for perfect insulation of other parts which are influenced by higher pulsed voltage during the shot.

III. TESTS IN TRANSFORMER OIL

The stage was filled with oil after the experiments with compressed gas insulation were completed. More than 1500 shots were performed in total, most of them at peak ±100 kV charge. The overall performance of the stage was very good, no problem requiring opening the cavity for an intervention was observed.

The electrical performance of the stage with oil insulation is illustrated in Figs. 6 and 7. The load power is in that case somewhat higher than in gas. The peak load power reaches ~19.5 GW at R_{LOAD} ~(0.5-0.55) Ω. With this load, the voltage is ~104 kV, FWHM is almost the same as in tests with gas. In Figs. 6 and 7, black curves show again for comparison same Pspice simulations as in Figs. 4 and 5.

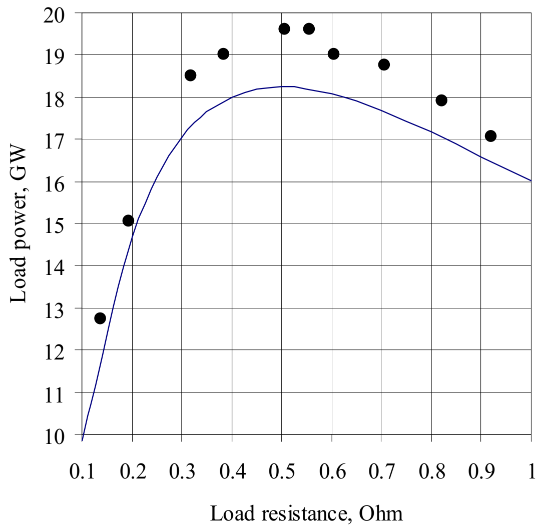

Figure 6. Load power in tests with oil insulation.

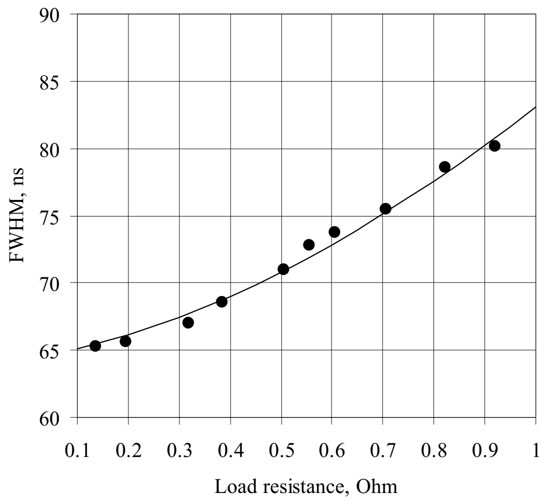

Figure 7. FWHM of the load voltage pulse in tests with oil insulation.

IV. DISCUSSION

Figures 4-7 show that in matched mode at R_{LOAD}~0.5 Ω the width of the pulse is below the required 75 ns. But in critical mode, at R_{LOAD}~1 Ohm, it increases to ~85 ns. In RLC circuit which is essentially the equivalent scheme of the fast LTD stage, such increase of the pulse width may be related to an increase of the equivalent inductance of the circuit, L_{EQ}. In [1] we have shown that L_{EQ} is a function of current flowing through the switch, but this dependence is apparent and can be explained in frame of the basic physics of gas discharge which deals with *resistance of the spark channel only*.

In [1], the parameters of a single brick similar to those in the 75 ns LTD stage prototype were investigated. The resistive load of the brick was varied from ~5 to ~20 Ω, which are equivalent to (0.3-1.25) Ω for a stage consisting of 16 bricks. The charge voltage was varied from ±60 to ±100 kV. Excluding the inductance of the capacitors and the load (defined in specific experiments or with geometrical estimations), the equivalent inductance of the switch and its connections in a simple RLC equivalent scheme was found to be ~60-180 nH, depending on current. In more detailed simulations, the inductance of the switch was assumed to be constant, L_{SW}=60 nH, and the resistance of the switch R(t) was calculated as:

$$R(t) = 1.126 \cdot 10^{-5} \frac{p^{1/3} d}{\int_0^t I^{\alpha} d\tau}, \text{ Ohms} \qquad (1)$$

where p is gas pressure in ata, d is total length of the switch gaps in cm, I is current in the switch in A, time is in s, and α=0.85 (α=0.67 transforms Eq. (1) into Braginsky's resistance of the spark channel in air [2]). It was found in that case that, as in [1], the simulated voltage perfectly fits the recorded traces at any charge voltage and load resistance, demonstrating that the simulated increase of the equivalent inductance of a single brick appears just because of the specific dependence of the switch resistance on the conducted current.

The performance of the 75 ns LTD stage prototype was then simulated by using the equivalent circuit presented in Fig. 8. Here C, RC and LC are equivalent capacitance, resistance and inductance of GA35436 capacitors in the stage, Rcore simulates the loss in the core, the values of Lbus and Lout are calculated from the geometry of the stage, Ldiv and Rdiv are inductance and resistance of the external voltage divider used to measure the load voltage, RL is the load.

The inductance Lswx and resistance swxBR simulate the switch parameters. The value of Lswx=6.5 nH corresponds to L_{SW}=16Lswx=104 nH, which is higher than L_{SW}=60 nH obtained in [1]. This increase appears because of two reasons. First, the switch in the stage is moved away from the capacitors for 13 mm compared to its position in the brick tested in [1]. This increases the inductance of the loop with the switch by ~25 nH to L_{SW}~85 nH. Second reason is the interference of the magnetic fields of neighboring bricks. The assembly of the switches in the stage represents a coaxial structure similar to coaxial line which is formed by numerous rod-strip pairs locating evenly on same radius around the axis. If the number of rod-strip pairs in such structure increases, the total inductance of the structure reduces but less than linearly with the number of rods. So the equivalent inductance of each pair increases due to the interference of the magnetic fields of neighboring pairs. Estimations show that for given dimensions of the switch assembly in the stage, the equivalent inductance of each switch increases for ~17% and reaches L_{SW}~100 nH.

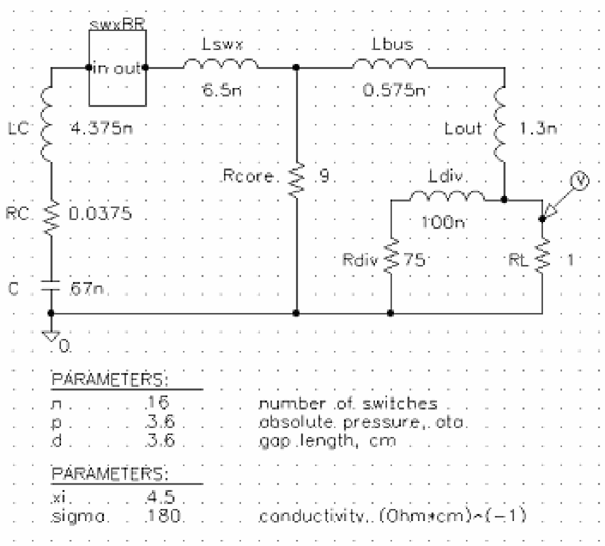

Figure 8. Equivalent circuit of the 75 ns LTD stage.

The block swxBR calculates the resistance of the switch according to Eq. (1). The best agreement between the experimental data and simulations, as this is shown in Figs. 4-7, was obtained at α=0.8, which is close to α=0.85 defined in [1]. This indicates that the width of the output pulse of the 75 ns LTD stage prototype increases with R_{LOAD} because of the dependence of the switch resistance with the conducted current.

Somewhat higher output power in tests with oil compared to compressed gas (compare Figs. 4 and 6) could be due to partial discharges in the gas as it was mentioned at the end of Section II.

V. REFERENCES

[1] A. A. Kim, V. G. Durakov, S. N. Volkov, etc, "Gas switch performance depending on current in the switch", in Proc. 14th Symp. High Current Electronics, 2006, p. 297.

[2] S. I. Braginsky, "Theory of the development of the spark channel", Rus. J. Exp. Tech. Physics, vol. 34, No. 6, pp. 1548-1557, 1958.