Solid-State Marx Generator for the Compact Linear Collider Breakdown Studies

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***Abstract*— A high repetition rate, semiconductor based, Marx generator has been designed and developed for a spark gap system: this system will allow the study of breakdown rate phenomena for different materials and surface finishes, for RF structures for the proposed Compact Linear Collider (CLIC). The Marx circuit is based on new SiC MOSFETs (Metal Oxide Semiconductor Field Effect Transistors), with 15 compact stages, capable of running with capacitive type loads during normal operation and also short-circuit mode at reduced repletion rate. Experimental tests with 150 pF to 650 pF dummy capacitances and also the actual spark gap system are presented: these tests and measurements prove the performance of the Marx generator to generate pulses from 200 ns to 100 µs pulse width, up to 10kV, with frequencies up to 1 kHz and pulse voltage rise times less than 100 ns with a load capacitance of not more than 150 pF. In addition, first breakdown results validating the operation of the Marx generator during breakdown are presented.**

Keywords—component; formatting; style; styling; insert

I. Introduction

A new semiconductor based Marx generator, using SiC discrete MOSFETs (Metal Oxide Semiconductor Field Effect Transistors), has been designed to meet the specifications for carrying out high field vacuum breakdown research for the Compact Linear Collider (CLIC) study: CLIC is an international collaboration working on the design for a machine to collide electrons and positrons (antielectrons) head-on at energies up to several TeraelectronVolts (TeV), under study at the European Laboratory for Particle Physics (CERN) [1]. One of the issues concerning CLIC's feasibility is the capability of the Radio Frequency (RF) structures to sustain high surface electric fields: a field superior to 200 MV/m, with a breakdown (BD) rate below 3×10^{-7} breakdowns/pulse/m is required [1].

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To investigate breakdown rate phenomena for different materials, a d.c. spark system, which creates similar surface electric field as in a RF structure, was designed and built at CERN [2]. This spark gap system will be connected to the output of the Marx generator. The spark gap load can generally be considered to be capacitive in nature: normally the load will not conduct, however it will occasionally breakdown (i.e. when there is high voltage across it, it can transition into an electrically conducting state). The purpose of the high-gradient breakdown studies is to determine the breakdown characteristics of metal surfaces in the high surface field and low breakdown rate regime. The pulsed dc system described here allows investigation under a range of test conditions including different pulse lengths, materials and operational scenarios and to investigate long-term behaviour. Thus the Marx generator must be designed to operate reliably with both a capacitive load and following an electrical breakdown of the load.

This new generator aims to replace the existing one, which utilizes a single commercial MOSFET stack switch and a Pulsed Forming Line, PFL, for the energy storage system [3]. The objective for new pulse generator is to gain operation flexibility: the present system does not have an active pull-down, but rather uses a bleed resistor. The new system has both active pull-up and pull-down hence the pulse width will be variable allowing study of breakdown rate as a function of pulse width, to closer reproduce the time structure of the RF pulses in CLIC.

The requirements for the Marx generator include applying positive voltage pulses to loads whose capacitance can be in the range from 150 pF to 650 pF, at a repetition rate from 1 Hz to 1 kHz, with a flattop of up to 10 kV pulse amplitude and a pulse width in the range from 500 ns to 100 µs. In addition, rise and fall times of 100 ns, measured from 5% to 95%, are required for the effective load capacitance of 150 pF. Ideally there will be no ripple during the flattop: the equipment is used for breakdown studies and, for a given geometry of the sample under test (i.e. the load), the breakdown rate is approximately proportional to Voltageˆ30 (i.e. a small ripple can give a large change in breakdown rate) [2]. To minimize ripple the circuit inductance must be kept to a reasonable minimum.

Preliminary results with the connection of the Marx generator to various dummy capacitive loads, in normal operation and under short-circuit conditions, are presented in this paper. Also, results from the connection to the real d.c. spark-gap system are shown and discussed.

II. Experimental Apparatus

A. Spark gap load

The d.c. spark system comprises two separated, galvanically isolated, copper (Cu) electrodes: the anode is connected to HV and the cathode is connected to ground, inside a vacuum chamber, as shown in Fig. 1, [2].

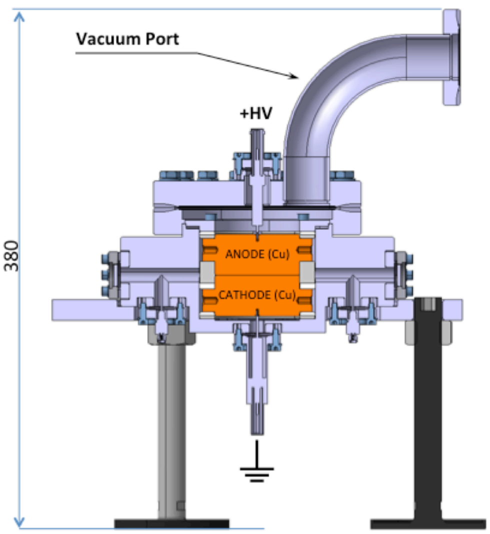

Fig. 1. Schematic mechanical drawing of the d.c. spark systems, with distance in mm.

Fig. 2 shows, in more detail, the structure that holds the electrodes and maintains their spacing. The spacers can be replaced to change distance, which affects the load capacitance. The cathode Cu electrode is connected to the metal vacuum chamber while the anode Cu electrode is connected to the pulse generator via a coaxial, 50 Ω, vacuum feedthrough (SHV-20). The same feedthrough also connects the outer of the coaxial cable to the body of the vacuum chamber.

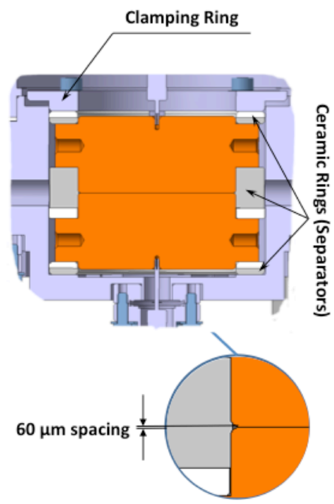

Fig. 2. Detailed view of the holding structure and the spacing between the electrodes.

Fig. 3 shows a photograph layout of the experimental apparatus: the d.c. spark structure is housed inside the vacuum chamber.

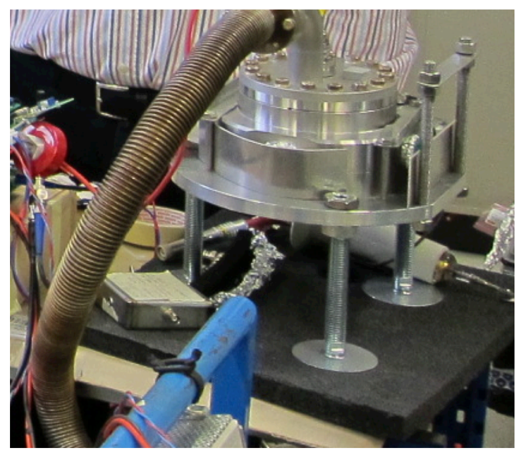

Fig. 3. Photograph of the d.c. spark gap mechanical enclosure.

B. Marx generator

In order to generate high voltage rectangular, repetitive, pulses into different load conditions, a semiconductor based Marx generator seems a reasonable choice [4]. In effect, improvements in discrete semiconductor technology led to a new generation of discrete semiconductor devices with switching properties very close to the ideal switch, making possible the use of traditional topologies, but with improved performance. One example of these are the new SiC switching MOSFETs with lower on-state losses for kV range operation, reasonable current pulse capability and fast switching speed.

Considering the above, a Marx pulse generator was developed, reference EPULSUS®-FPM1-10, from EnergyPulse Systems, with a general schematics shown in Fig. 4. The heart of this is a 15 stages solid-state Marx generator, which is supplied by an external dc power supply, type FuG MCP 140-1250. Three auxiliary d.c. 5 V, 24 V and 48 V power supplies feed the control and protection circuits. The generator is controlled from a microcontroller that is programmed via a RS-232 connection from a PC. An input high frequency filter (Ca/L1L2/Cb) attenuates high frequency transients, in order to minimize interference between the two systems. Also, a RiCi network provides protection by limiting the input voltage/current, and an auxiliary switch Taux disconnects the dc power supply from the Marx generator during pulsing, via an auxiliary signal Vaux.

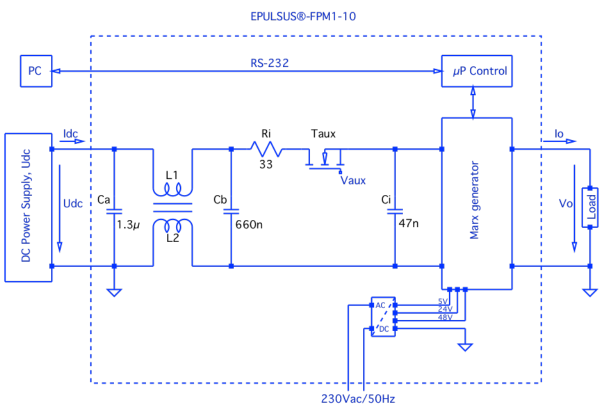

Fig. 4. General schematics of the Marx pulse generator equipment.

The Marx generator simplified circuit is shown in Fig. 5, where each stage comprises a 330 nF energy storing capacitor Ci, two sets of diodes Dai and Dbi, reference BYG23T-M3, and a half-bridge with two SiC MOSFETS switches, reference C2M0280120D: MOSFETs labelled Tpi ("i" is an integer in the schematic), at the top of the half-bridge, apply pulses to the load, and the bottom MOSFETs, labelled Tci, are for charging capacitors Ci between pulses and for discharging the load capacitances after the pulse [4]. Because of the switch half-bridge topology, there must be a dead time between a switch turning-off and the other turning-on, which, due to the capacitive nature of the load, will impose a minimum pulse width equal to the dead time. For safety reasons a 100 ns dead time was imposed in the trigger signal of the Tpi and Tci switches.

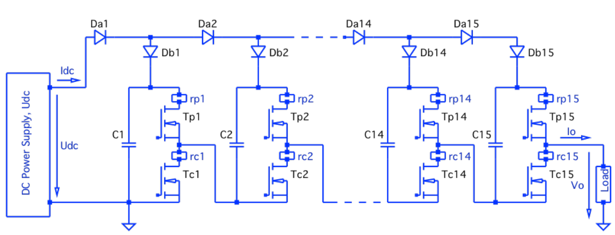

Fig. 5. Schematic of the Marx generator.

Capacitors Ci are charged in parallel from power supply Udc (external to the generator enclosure) by diodes Dai and Dbi and Tci MOSFETs: during this period the load capacitances is discharged to 0 V. The pulse is applied to the load by connecting in series the Ci capacitors with the Tpi MOSFETs [4]. The Dbi diodes are included for safety reasons, as they limit the discharge of each Ci capacitor into the Ci+1 onwards capacitors, reducing the damage, if a Ci+1 capacitor fails.

In addition, a 3.3Ω, rci, and 6.6Ω, rpi, non-inductive resistors are placed in series, respectively, with each charging and pulse MOSFET, resulting in a total series resistance of, respectively, 49.5 Ω and 99 Ω. These resistors limit the current peak during short circuit operation and damp the voltage in order to limit the voltage overshoot and oscillation. These two sets of resistors impose, also, a minimum time constant for the pulse and load discharge paths, depending of the load capacitance. As an example, for a 150 pF load, the times constants are $99 \times 150 \times 10^{-12} = 15$ ns and $49.5 \times 150 \times 10^{-12} = 7.5$ ns, respectively.

Considering the 15 stages used for the Marx generator, a power supply voltage of ~670 V is required to achieve the 10 kV output: this gives both redundancy and a reasonable voltage safety margin, for the 1.2 kV devices used. In addition, depending upon the redundancy requirement, it allows for future increase of the output voltage.

Fig. 6 shows a photograph of the EPULSUS®-FPM1-10 unit, 19 inch rack, 4U, 425x425x172 mm^3, including the 15 stage Marx generator (A), the input filtering board (B), the control microcontroller based board (C), the output HV connector LEMO ERA.3Y.430.CLL (D), and the two Bergoz CT-D0.5-B current transformer sensors (E) for measuring the current and sending this information both to the CERN control systems and to the internal short-circuit protection circuit.

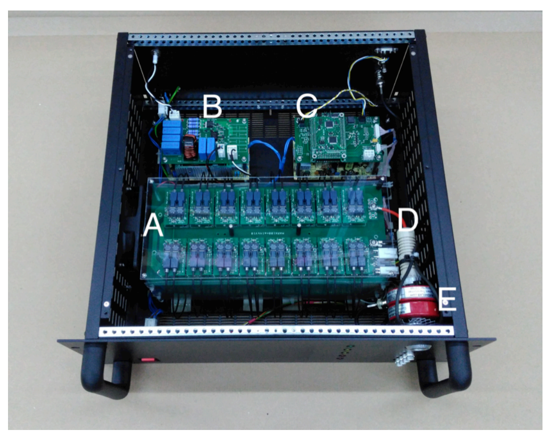

Fig. 6. Photo of the inside of the EPULSUS®-FPM1-10 unit.

It is important to take into consideration the circuit losses in order to specify the input power supply, as well as to investigate the dissipation in the switches and distributed passive elements.

In effect, due to the capacitive nature of the load, and the fact that the Marx is a capacitive type discharge generator, the overall efficiency of the Marx generator connected to this load is about 50%, this means that the power supply Udc must deliver a power *Pdc*, at least twice that delivered to the load capacitance,

$$Pdc \geq 2fEo, \tag{1}$$

where *Eo* is the energy stored on the load capacitance, and *f* the pulse frequency.

Hence, during the pulse mode half the energy delivered by the Marx is supplied to the load and half is dissipated in the Tpi and rpi devices, afterwards during the charging mode of Marx capacitors Ci, two situation occur, the discharge of the load capacitance, where the energy of the load is dissipated in the Marx Tci and rci devices, and the charging of Marx capacitors Ci through Tci and rci, which dissipates also some energy, although lower, because this charging current is much lower. Consequently, the power supply Udc must deliver a power higher than twice that delivered, by the Marx, to the load.

Considering the worst operating condition, for a 650 pF load charged to 10 kV, 1 kHz repetition rate, the energy stored in the load is 32.5 mJ per pulse, corresponding to a power of 32.5 W dissipated in the Tpi and rpi, during pulse to the load, and 32.5 W dissipated in Tci and rci, during load discharge. Therefore, the power supply must provide at least 65 W, considering also the losses during charging of capacitors Ci. The chosen dc input power supply can source up to 125 W at 1.25 kV and 70 W at 700 V, which is sufficient for this application.

III. Generator Test on Dummy Capacitive Loads

Prior to connecting the generator into the spark gap structure of Fig. 3, several tests were performed with dummy capacitive loads in order to verify the performance of the generator during normal, as well as on short-circuit operating conditions.

First, the generator was connected to a 150 pF capacitance, results shown in Fig. 7, with a 10 kV, 500 ns pulse, 10 Hz. The observed 5 % to 95 % rise and fall times are about 80 ns.

It is seen on Fig. 7 an almost equal positive and negative 24 A peak pulse, during the rise and fall times of the pulse. The measured voltage pulse shows a small overshoot, however calculating the critical damping operating condition, R=2√(L/C), the critical resistance is 115 Ω and 58 Ω, respectively, for 150pF and 600pF, assuming an approximate parasitic 0.5 µH Marx inductance. In reality the actual series resistance in the Marx during pulse is higher than 99 Ω, mainly due to the distributed 6.6 Ω in each stage, plus the on-resistance in the Tpi MOSFETs.

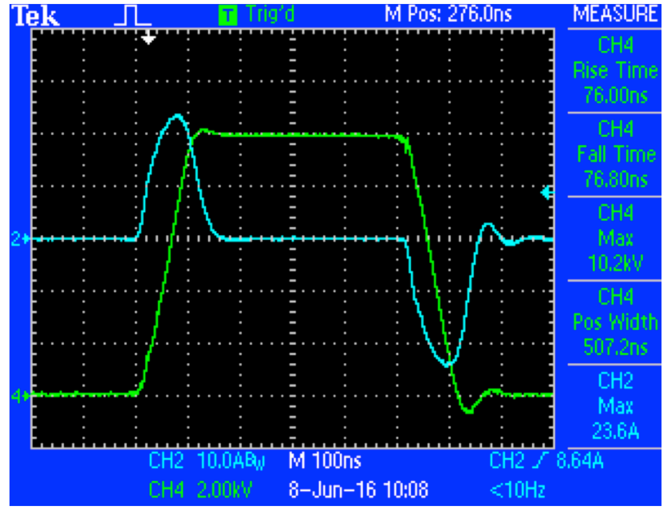

Fig. 7. Generator pulse into a 150pF load, voltage (green) and curent (blue): 2kV/div, 10A/div, 100ns/div.

In order to confirm that there is no overshoot, in Fig. 8 and Fig. 9 it is shown the output voltage pulse, respectively, rise and fall times, with 1200 V pulse amplitude, using two different calibrated probes for 150 pF load. In effect, the result in Fig. 8 supports the theoretical estimation that there is no overshoot for 150 pF, using 99 Ω, series resistance.

Fig. 8. Generator 1200V pulse into a 150pF, rise time: 200V/div, 20ns/div.

The result in Fig. 9 supports, also, an undershoot of about 15%, which is not critical in this application.

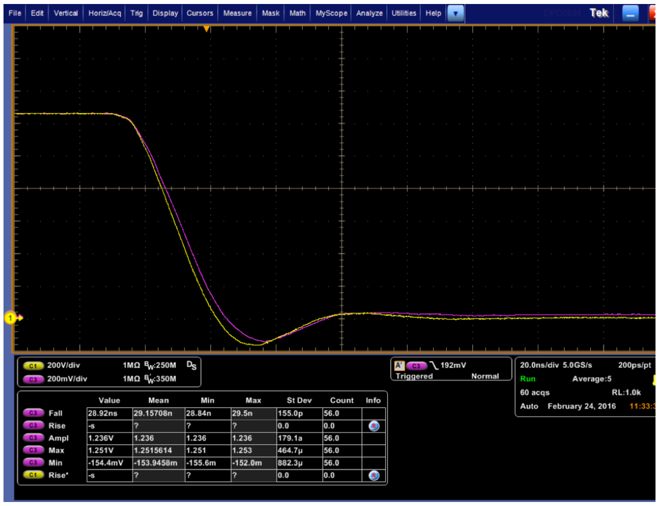

Fig. 9. Generator 1200V pulse into a 150pF, fall time: 200V/div, 20ns/div.

It is important to note that the measurements of rise and fall times, respectively, Fig. 8 and Fig. 9, performed at 1200 V output pulse have more accuracy and take into account a worst operating condition than at 10 kV.

Considering the same 10 kV pulse protocol, Fig. 10 shows the results of increasing the load capacitance from 150 pF to 600 pF, where the most obvious difference, in relation to the 150 pF Fig. 7 result, is the increase of the 5% to 95% rise and fall times from 80 ns to about 200 ns, and the corresponding peak currents to approximately 32A.

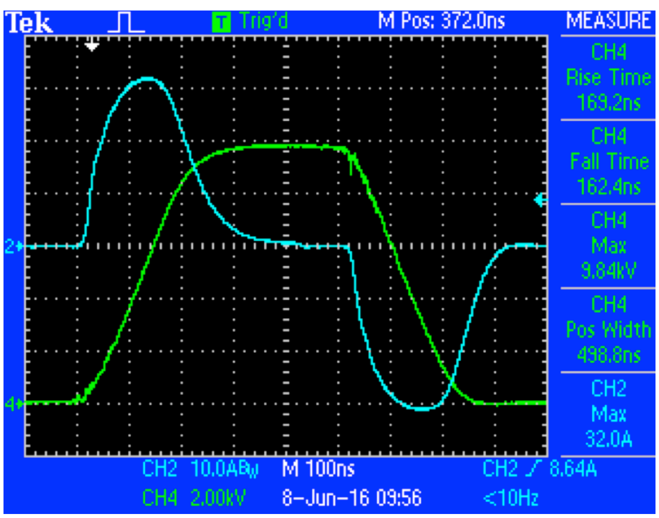

Fig. 10. Generator pulse into a 600pF load, voltage (green) and curent (blue): 2kV/div, 10A/div, 100ns/div.

Afterwards, the generator was tested with short-circuited output, or hard short-circuit condition, for two input voltages, 400 V and 700 V, and a 5 µs pulse, the results are shown, respectively, in Fig. 11 and Fig. 12.

Fig. 11. Generator output short-circuited, with 400V input, first capacitor voltage (green) and output curent (yellow): 50V/div, 8A/div, 200ns/div.

In Fig. 11, with a 400 V input voltage, one can see the droop in the Marx's first capacitor voltage during the pulse, and the current on the short-circuit that reached approximately 50 A, and then decreases due to the droop on the Marx capacitors voltage.

In comparison with Fig. 11, in Fig. 12 the input voltage was 700 V, but the maximum current is about the same, 56 A. This means that the intrinsic Marx dynamic behaviour is limiting the output current.

Fig. 12. Generator output short-circuited, with 700V input, first capacitor voltage (green) and output curent (yellow): 80V/div, 8A/div, 500ns/div.

In effect, when the current is low the main voltage droop in the Marx is across the distributed series 99 Ω resistors, but when the current increases, and due to the current limitation of this MOSFET (i.e. 20 A Pulsed Drain Current), the impedance of the MOSFET increases and the voltage droop inside the Marx is distributed between the resistors and MOSFETs, which thus limits the output current to a value of less than 60 A. One has to take into account that in this operating mode, the frequency much be reduced to a minimum of a few Hz in order to lower the power dissipation in the devices.

From the above results, it reasonable to say that the Marx generator of Fig. 6 is ready to be connected to the Fig. 3 spark gap structure for high-gradient breakdown studies at CERN, considering the requirement described in the Introduction.

IV. Generator Test on Spark Gap System

The Marx generator was connected to the d.c. spark system described in Fig. 3, section II, through a 50 Ω coaxial cable. Fig. 13 shows the pulse voltage and current outputs for a 4000 V pulse with 800 ns pulse width, at approximately 10 Hz.

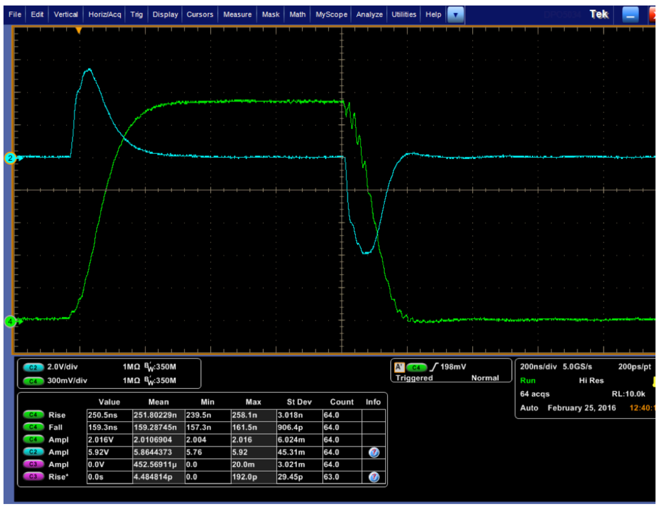

Fig. 13. Generator output connected to spark gap, 650pF, with 4kV output, pulse voltage (green) and current (blue): 600V/div, 5A/div, 200ns/div.

The measured voltage rise and fall times (5 % - 95 %) are, respectively, 200 ns and 130 ns, and peak current amplitude during each period, respectively, 14 A and 15 A. The total effective load capacitance, calculated from the current integral, and confirmed by direct capacitance measurement, is 650 pF.

Fig. 14 shows an example of a preliminary breakdown experiment, during operation at 4.8 kV, for the d.c. spark system.

The main goal of these preliminary breakdown experiments in the d.c. spark system was to evaluate the behaviour of the new Marx generator when connected to this type of load, as well as, to assesse its reliability in short-circuit operation.

Further measurement were made with the Marx generator to investigate the power dissipation at 1 kHz with 650 pF load, with normal operation, and at 2 Hz in short circuit mode, which proved the equipment ready to enter a new phase of commissioning.

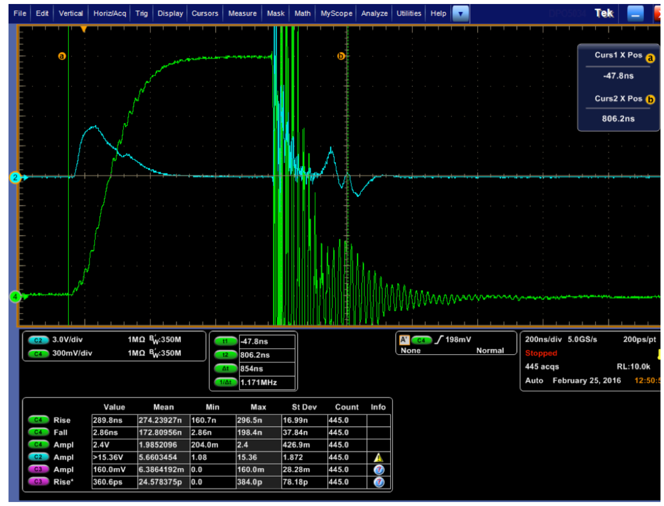

Fig. 14. Generator output connected to spark gap, 650pF, with 4.8kV output, pulse voltage (green) and current (blue): 600V/div, 5A/div, 200ns/div.

V. Conclusions

The new Marx generator is now being commissioned in exhaustive tests in the CERN d.c. spark gap system. These tests will demonstrate its flexibility and hence value for use in breakdown rate phenomena experiments, which create similar electric field as in a RF structure, of the future CLIC. During the first tests on capacitive dummy loads and on the real spark gap system, both during normal and short circuit operation, the generator reached the expected requirements. Possible future upgrades include an increase of the voltage and frequency.

Acknowledgment

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