2019 International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil, 30th September – 4th October 2019.

Laboratory Facilities for Fulgurite and Lightning-Induced Volcanic Spherules (LIVS) Generation

Camara, A.S.B.; Heidler, F.
University of the Armed Forces Munich (UniBw)
Institute of Energy Systems
Munich, Germany
alessandra.camara@unibw.de; fridolin.heidler@unibw.de

Cimarelli, C.; Teixeira, L.M.F.
Ludwig-Maximilians University (LMU)
Institute of Geology
Munich, Germany
cimarelli@min.uni-muenchen.de; ludmilateixeira@icloud.com

***Abstract*—The following work presents the activities performed by the University of the Federal Armed Forces in Munich (UniBw) in cooperation with the Ludwig-Maximilians-University (LMU) in research about fulgurite and LIVS (lightning-induced volcanic spherules) generation in laboratory. Fulgurites are basically tubular glassy structures produced by lightning strike, from thunder or volcanic storms, in sediments, soil or hard rock. The task to UniBw was to create an experimental setup in the high voltage laboratory to reproduce the effects of lightning by producing sand fulgurite and/or LIVS. At the LMU, the samples are analyzed in the composition, internal texture and chemical modification. Different pieces could be successfully created, with lengths from 5 till 75 mm and diameter between 0.5 and 15 mm, from small spheres till ramified structures.**

Keywords—fulgurites; lightning; lightning-induced volcanic spherules; LIVS; volcanic lightning

I. Introduction

Fulgurites can be defined as tubular glassy structures generated basically by a large amount of energy provided in a very short time over a surface of sand or rock. The source of such energy is lightning, that can be from thunder or volcanic storms. These last ones can also produce the so called LIVS (lightning-induced volcanic spherules).

By its origin, fulgurites are considered as “fossilized lightning”, condition that attracts the attention of different scientific fields. It registers lightning transient effects, providing like a printed information about the environment conditions and processes in that very moment of the phenomena.

In a similar way to thunderstorm lightning, volcanic lightning generated during volcanic explosive eruptions may play a very special role on the evolution and changing of the earth’s surface and its atmosphere [1]. The effect of lightning bolts on the volcanic ash in the eruptive cloud and eventually on the rocks at ground is still to be fully understood. Experimentally reproducing and studying the so called fulgurites and lightning-induced volcanic spherules (LIVS), about their chemical and morphological modifications, helps constraining the processes involved during their formation. So, the work presented in this paper can be considered a derivative from the one presented in [1]. In short words, this work is part of a study with synthetic fulgurites and LIVS generated in high voltage and high current laboratory at different experimental conditions (Fig.1).

Fig. 1. LIVS and fulgurites generated at the UniBw with “Laacher See” ash

II. Fulgurites and LIVS Naturally Generated

A. *Fulgurites naturally generated*

Natural glass on earth mostly occurs due to meteorites impact - the so called Tektite - or due to lightning strike, the so called Fulgurites. Fulgurites are very resistant to weathering and hence the study of properties of fulgurites may be helpful in understanding the ultra-high temperature natural phenomena during lightning [2]. There are two major types: sand fulgurites and rock fulgurites. Sand fulgurites are usually hollow, glass-lined tubes with sand adhering to the outside. Rock fulgurites are formed when lightning strikes the bare surface of rocks. Rock fulgurites are relatively low in silica and exhibit a wide variety of colors, depending on the composition of the rock. The process of lightning strike in rock and sand is chemically similar to the micrometeorite impacts [2]. In both cases, there is a rapid rise of temperature followed by a rapid cooling.

Fulgurites are classified generically as a variety of the mineraloid lechatelierite, although their absolute chemical composition is dependent on the physical and chemical properties of the target material affected by the lightning discharge. They are formed when lightning melts silica or other common conductive or semi-conductive minerals and substrates, fusing, vitrifying, oxidizing and reducing mineral grains and organic compounds. They are natural, commonly hollow assemblages of glassy, protocrystalline, and heterogeneously-microcrystalline tubes, crusts, vesicular masses and clusters of dielectric and refractory materials. It is assumed that the process of fulgurite generation occurs over a timespan of the order of a single second and leaves direct evidence of the dissipation path and its dispersion over the surface or into the earth [3]. Pseudo-fulgurites can also be produced when, for example, the cables of a high voltage electrical distribution network are severed, discharging alternating current into a conductive surface beneath. It produces a linear trace structurally distinct from natural fulgurite due to the alternating polarity and duration of the discharge.

B. LIVS naturally generated

Experimental studies and investigation of volcanic deposits have shown that volcanic lightning can create besides fulgurite the so called “lightning-induced volcanic spherules” (LIVS). These tiny glass spherules are formed during high-temperature processes such as cloud-to-ground lightning strikes, analogously to fulgurites. The temperature of a bolt of lightning can reach 30000 K. When this bolt contacts ash particles within the plume it may do one of two things: (1) completely vaporize the ash particles, or (2) cause them to melt and then quickly solidify as they cool, forming orb shapes. The presence of lightning-induced volcanic spherules may provide geological evidence for volcanic lightning when the lightning itself was not observed directly.

In [1], it is presented that volcanic lightning occurs in regions of the eruptive column and plume that have widely variable ash particle concentrations, what would suggest that millions of ash particles should be morphologically transformed by the occurrence of lightning discharge. Numerical models indicate that both the timescale of lightning discharge and the size of exposed ash particles determine the likelihood of forming LIVS. Observations of natural ash falls from several volcanoes where lightning has been documented reveal very few LIVS, typically comprising 1% or less of grains.

III. Fulgurites and LIVS by Artifitial Generation

In [1], it was observed that features of volcanic lightning are similar to thunderstorm lightning, and the physical characteristics show that volcanic lightning can be treated as a miniature version of thunderstorm lightning in many respects (see Fig. 2). The overall duration, length, inter-stroke interval, peak current, and charge transfer exhibit values 1 – 2 orders of magnitude smaller than those of thunderstorm lightning, thus suggesting a scaling relation between volcanic and thunderstorm lightning parameters. The laboratory setups were build up considering this similarity and the study procedure was based on the waveforms so adopted for lightning standards tests and research. Lightning currents are essentially unidirectional and are studied as a sum of different components effects. The main current components are the first return stroke, the subsequent return stroke and the long-duration continuing current. First return strokes have the highest current amplitudes, typically of some 10 kA up to a few 100 kA, lasting up to several 100 µs. Subsequent return strokes are lower in amplitude and duration, but often with a significantly higher current steepness di/dt of up to a few 100 kA/µs. Long-duration continuing currents exhibit much lower current amplitudes of just a few 100 A, but last much longer (up to several 100 ms). As the waveforms of these three basic current components are quite different, different generator designs are usually necessary to simulate each one effect.

By the physics involved and the information already available, in case of fulgurites, the continuous current is the most important one, although the other component effects are not negligible. For the LIVS generation, one may say that the first and the second components are the most important ones. The tests were performed with different types of sand, namely “Laacher See” ash, Fiber Glass, Olivine and Quartz. The “Laacher See” is a volcanic caldera lake located in Germany. Different circuit setups were also tried, as presented in the following subsections, where main elements of the experiments are described.

Thunder Storm Lightning:

Length: 10^3-10^4 m
Peak current: $3x10^3$ A
Channel temperature: Up to 30,000 K

(Rakov and Uman, 2006)

Volcanic Storm Lightning:

Length: 1-10^3 m
Peak current: 10-10^3 A
Channel temperature: Up to 1,000 K

(Cimarelli and Aizawa, 2016)

Fig. 2. Thunder storm and volcanic storm lightning comparison

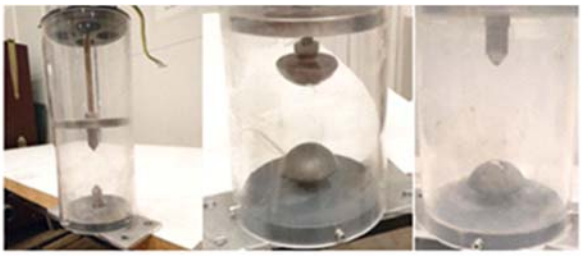
A. Sand Samples and Object under Test

The setup allowed for variations on type and amount of material, the type and distance between electrodes, the proportion of air space and the use or not of air circulation. The following type of sands were used:

- “Laacher See” ash, a natural sand from a volcanic region, with a granulation of 90 µm;
- Industrial E-type glass fibers, with a granulation of 180 µm;

- Olivine sand, with granulation of 5 , 75, 200 and 500 µm;
- Quartz sand, with granulation between 40 and 150 µm.

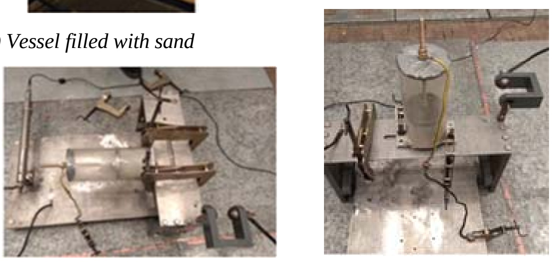
The test object consists of a cylindrical polymeric (plexiglas) tube, to hold the material in a controlled volume (Fig. 3). The tube has a height of 28.5 cm, with a diameter of 11 cm. The electrodes are made of tungsten-copper and are located centrally, having a uniform distance to the edge of the vessel. As the vessel, the bottom and the top are made of very stable and electrically non-conductive polymer compounds (insulator material). The bottom electrode is fixed, while the top electrode is attached to a movable plate, which allows to adjust the distance between the electrodes.



a) Object under test, with different combinations of electrodes

b) First electrodes used

c) Vessel filled with sand



d) Horizontal and vertical tests

Fig. 3. Object under test

B. *First Setup: LIVS and Small Fulgurites (High Current Generator with RLC-Circuit)*

The first tests were considered "pre-tests". The aim was to find out which could be the best circuit configuration to be used. These tests were performed with "Laacher See" ash, using a high-current impulse generator based on RLC-circuit. High-current impulse generators usually consist of a variety of high-voltage capacitors connected in parallel to a capacitor bank (C_S). The capacitor bank is charged from a D.C. source up to a voltage U_{ch} and then rapidly discharged via a starting switch S (usually a spark gap) through the external "wave-forming" elements R_{ext} and L_{ext} into the object under test given by R_{load} and L_{load}. The equivalent circuit is presented in Fig. 4. At the UniBw, a tandem generator is used consisting of two high-current impulse generators, each one with 12 surge capacitors of 2.5 µF (total: 60 µF), with a maximum charging voltage of 100 kV. They are disposed in a "U" shape, making possible to locate the object under test in the middle (Fig. 5).

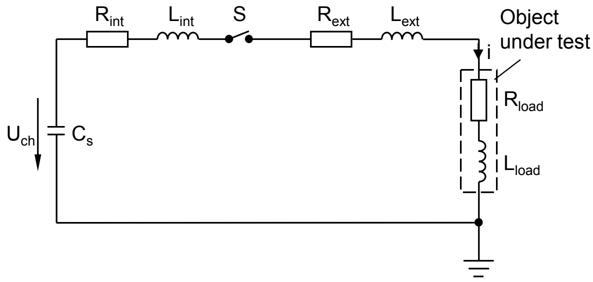


Fig. 4. RLC-circuit of the high-current impulse enerator

Fig. 5. Tandem impulse current generator at the UniBw

During the tests, the capacitors were charged with 60 kV using different "wave-forming" elements R_{ext} and L_{ext}. We had circuits with R_{ext} and L_{ext} of 600 Ω and 0 mH or 0,26 Ω and 5 mH. Tests performed without L_{ext} (0 mH) and using the total capacitor bank (60 uF) were successful on producing LIVS but no fulgurite. With 0.26 Ω and 5 mH we could produce the first fulgurites larger than 2 cm (Fig. 6). The "load" consisted of natural "Laacher See" ash.

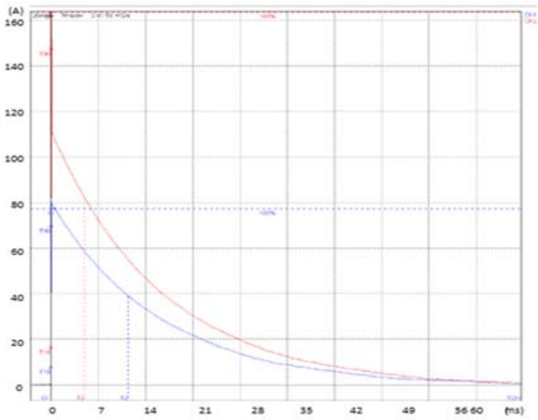
Although with such circuit (Fig. 4) we could generate fulgurite and LIVS, it was clear the need to improve the continuous current to improve the results. Basically, with the setup of *RLC-circuit type with High-Current Generator*, we could reproduce mainly effects of the first and the return stroke. Some results from these tests are presented in Fig. 6. As they were considered only "pre-tests" for setup adjustment, the material produced was not used for further analyses.

C. *Second Setup: All Sort of Fulgurites Generation (DC Source with Trigger-Pulse by High-Voltage Generator)*

In glass formation, melting is a fundamental process and melting with lightning attachment are predominantly related to continuous currents. Their comparatively long duration of several hundreds of milliseconds enables a deep penetration of the "melting front" into the material, whereas for first return stroke currents, the finite thermal conductivity of the material prevents the "melting front" from penetrating deep into the material during its shorter duration of a few hundreds of microseconds.

Long-duration currents are characterized by average currents of 100 A lasting up to 500 ms and resulting in a charge transfer of a few hundreds of coulombs. There are standards, in which the tests for continuous currents are defined by a rectangular waveform, whereas other standards also mention unidirectional waveforms with exponential or linear decay. So, the first type of circuit tested and presented previously was based on this last assumption. As we decided to move to another construction, we changed to a setup that could produce rectangular wave shapes.

(a) Fulgurites generated in the pre-tests



(b) Pre-tests wave forms examples

Fig. 6. Pre-tests results (Setup with High Current Generator)

Rectangular waveforms are generated using a D.C. voltage source, which is applied to the object under test via a resistor (R_{ext}) to adjust the required current amplitude. The D.C. voltage source used was a set of 60 batteries of 12 V, connected in series. This provides 720 V, a voltage that is not enough to start the arc, or, in other words, to promote the dielectric disruption for the planned gaps (from 1 till 7 cm) between the electrodes in sand. For a poorly conductive target material that does not vary significantly in composition in aerial extent, the electric field must exceed the breakdown field strength of the material to propagate a spark. For sand, although this varies according to the composition, its dielectric strength is higher than the air. In numbers, air has a breakdown strength around 3 MV/m (at sea level), while quartz has 30 MV/m. It is expected that the breakdown strength of sand will be much less than the one of quartz alone.

The long-duration current flow was initiated by a voltage impulse, using 3 steps of a Marx-Generator partially charged (35 kV/stage) as the trigger impulse to the spark gap (SG). An inductance L_{ext} (5 mH) was used to decouple the trigger generator from the D.C. source and to smooth the current, as also a resistance between 0.5 and 0.7 Ω. After around 500 ms, the current flow was interrupted by the circuit breakers. Fig. 7 presents the electrical equivalent circuit.

Under this construction, the tests were performed with the different types of material, in different amounts and proportions, considering or not air circulation, with or without argon in the replacement of normal air and some other variations.

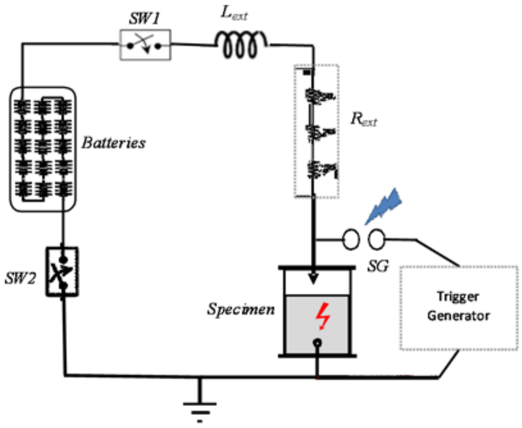


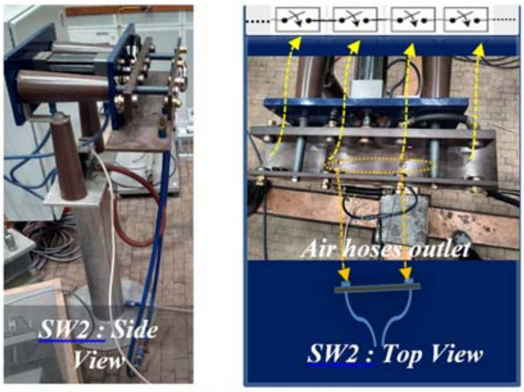
Fig. 7. DC Source (batteries) with trigger-pulse set up

D. Description of the main elements of the set up with the battery system and the trigger generator

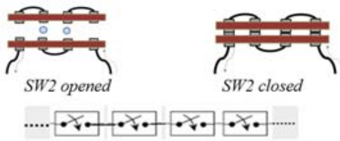
1) Circuit breakers and Switches

SW1: The circuit breaker identified in Fig.7 as SW1 has three chambers for arc extinction, which increases the chance for a successfully arc interruption. The switching control is made by a *Switching Control Box (Timer)* that is connected to the *Safety Loop Circuit* of the laboratory through a *Safety Extender Box*.

SW2: In Fig. 7, the circuit breaker identified as SW2 is a electro-pneumatic circuit breaker (see Fig. 8), with multiple contacts, that work like four switches in series to increase the chances of a successful and fast current interruption. In order to help the arc extinction, it is also used air blowing over the central contacts. As the normal state of SW2 is opened, if the power supply for its magnetic drive coil is interrupted, no matter if manually or by the safety circuit action, it opens immediately.



(a) SW2 Front and Top View

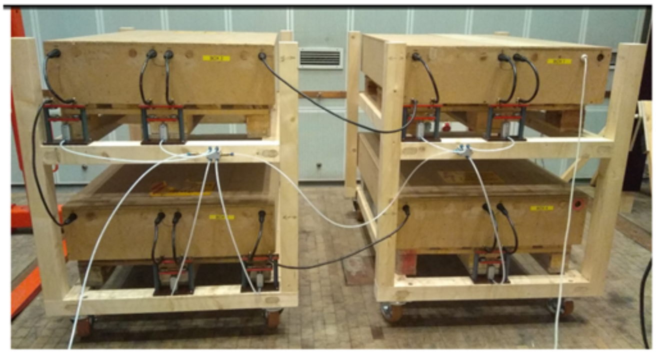


(b) SW2 *Switching Scheme*

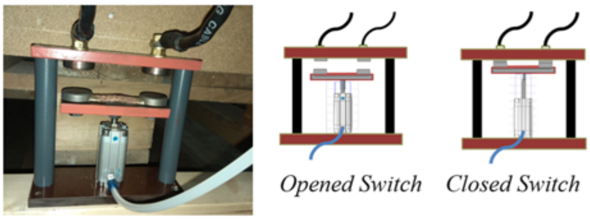
Fig. 8. Electro-pneumatic circuit breaker (SW2)

2) DC Source: Battery System

To simulate the effects of the continuous current, we use as D.C. source a system of batteries. This system is composed of 60 silver-lead-acid batteries of 12 V (61 Ah, 600 A) connected in series. For safety reasons, in a sequence of tests, when specimens must be removed or installed, the batteries are kept in 7 lines of only 8 units connected in series, which means 96 V at the terminals of each line (8 x 12 V) and one row with 4 batteries (4 x 12 V = 48 V). These lines of batteries are all connected in series for the tests by pneumatic switches, presented in Fig. 9. Such switches have exclusively pneumatic actuation and the air supply goes through the *Extender Safety Box* (see Fig. 10) that is connected to the *Safety Loop* of the laboratory.

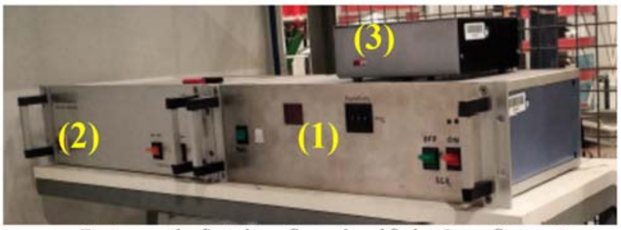


(a) Battery System Front View

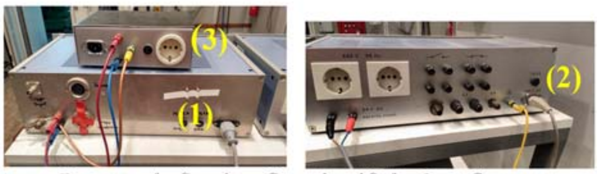


(b) Front View of a Pneumatic Switch

Fig. 9. Front view of the battery system and its pneumatics switches



Equipment for Switching Control and Safety Loop Connection (Front View)



Equipment for Switching Control and Safety Loop Connection (Back View)

Fig. 10. Equipment for the switching control and safety loop connection

3) Switching Controller and Extender Safety Circuit

After the impulse is initiated by the spark gap disruption, the DC current from the batteries starts to flow, providing the continuous current square impulse. Although most of the currents were adjusted to stop after 500 ms, we tested also with different times, from 300 ms up to 900 ms. Figure 10 presents the equipment used to control and to connect to the safety loop.

The equipment is described below and illustrated in Fig.11:

(1) *Switching Control Box:* Besides to be used to open and close manually the circuit breakers (SW1 and SW2), it has also the timer function, where the duration of the impulse is selected and automatically controlled by it.

(2) *Extender Safety Box*: Used to connect the test circuit to the safety loop circuit of the laboratory. Not only the current for the circuit breakers actuation can be automatically interrupted but also the air supply for the pneumatic switches can be switched off by it.

(3) *Auxiliary Box:* Through this box, the current that feeds the switching control of both circuit breakers (SW1 and SW2) is properly connected to (1) and (2).

The sensor for current monitoring is installed direct in the battery box, as presented in Fig.12. At one terminal, after the last battery, one copper wire is used as a fuse - also an extra protection, in case of too long currents. Behind it, a Pearson Coil is installed, sending the information of the current through the batteries for the *Switching Control Box (Timer)*.

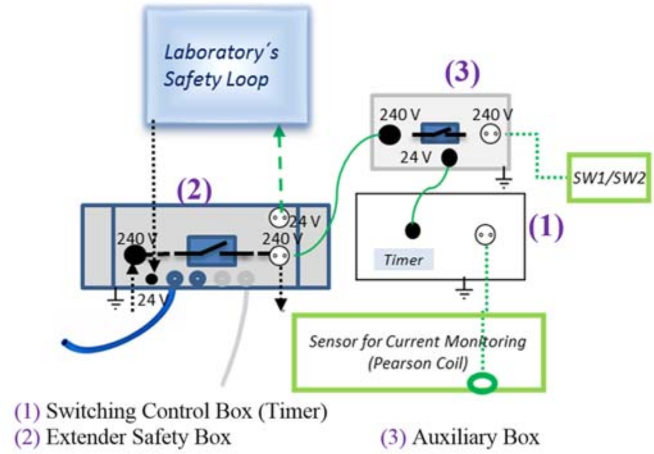


Fig. 11. Safety loop connections diagram

Fig. 12. Copper wire fuse and Pearson´s Coil at the batteries system terminal

4) Measurement System

Fig. 13 presents an overview about the current generator and the measuring system. The current was measured with a current shunt of 5.4 mΩ inserted in the electrical circuit. The current waveform was recorded by a digital measuring system called High Volt MIAS. The measuring system was located in a shielded cabin to order to avoid electromagnetic disturbances.

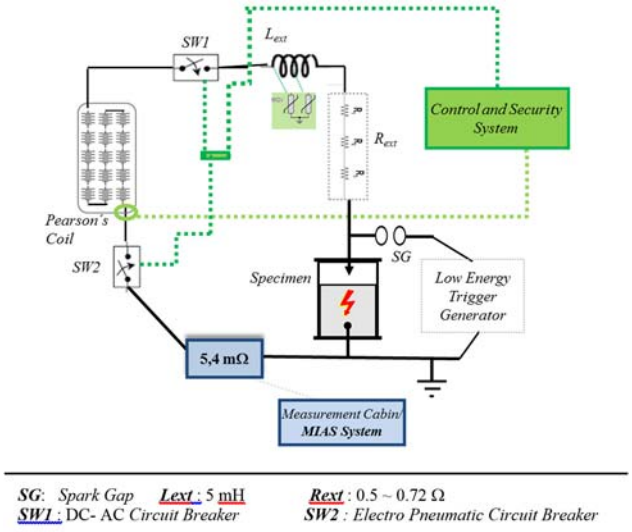


Fig. 13. Current generator and the measuring system

IV. Results and Conclusions

A. RLC-Circuit with High Current Generator

With the first setup, consisting of a high current generator with RLC-circuit, we could generate mostly LIVS. The aim of these tests was to define the set up to be used during the experiments. Therefore, only natural "Laacher See" ash was used. Adjusting the impulse with appropriate elements, we were able to produce fulgurite (see Fig. 6(a)) with unidirectional current waveforms showing an exponential decay (Fig. 6(b)).

B. DC Source with Trigger-Pulse

With this setup we were able to create a good variety of fulgurites and LIVS. The results are currently being analyzed at the LMU for their chemical and morphological characteristics. However, some important aspects and effects of the phenomena involved could be realized or confirmed during the experiments:

- With the "Laacher See" ash, a material collected at a natural site, we could produce LIVS and fulgurites very similar to the ones found in nature.
- Longer impulse duration has resulted in larger fulgurites.
- Most fulgurites produced with "Laacher See" ash or industrial glass fibers are branched and thin. They occur as aggregates, with spherules attached.
- Both fulgurites and LIVS are often covered with pristine material.
- Quartz sand and "Laacher See" ash were the most efficient material for producing fulgurites.
- Industrial glass fiber was the most efficient material for producing LIVS.
- Olivine was the material with considerable longer thermal reaction, no matter with or without air circulation.
- Due to the longer thermal reaction of the Olivine, it was possible to realize that tubular fulgurites could be formed and then collapsed into themselves, turning into a compact form (Fig. 14). A faster cooling may happen very often in nature, what would avoid such collapsing.
- Tests made with less sand but air circulation, promoted a longer thermal reaction inside the tube, even with argon replacing the atmospheric air. This behavior is explained by the charges proximity promoted by the air circulation, generating sparks in a very similar way to volcanic lightning effects in nature.

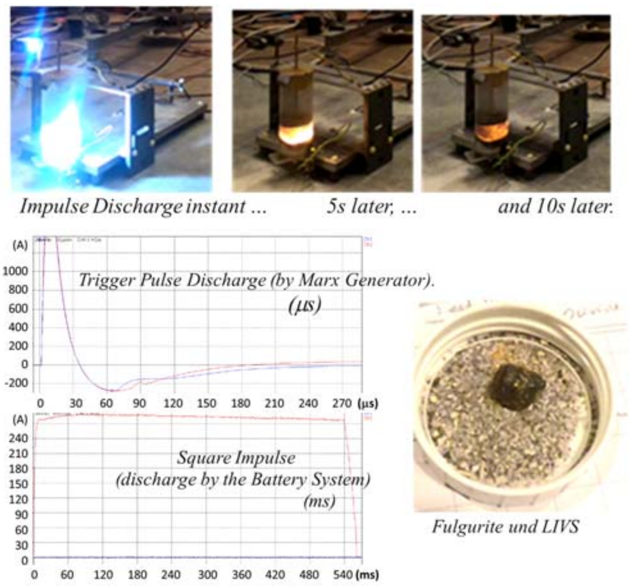


Fig. 14. Test with Olivine

References

[1] C. Cimarelli et alli, "Micro- and nano-CT textural analysis of an experimental volcanic fulgurite", Proccedings of the Conference: EGU General Assembly, January, 2017.

[2] B J Saikia et alli, "Fourier–transform infrared spectroscopic characterization of naturally occurring glassy fulgurites", Indian Academy of Sciences, Mater. Sci., Vol. 31, No. 2, pp. 155–158. April 2008.

[3] M. A. Pasek1, M. Hurst , "A Fossilized Energy Distribution of Lightning", Nat. Sci. Rep. 6, 30586, 2016.

[4] Rakov, V.A. "Lightning makes glass", Proceedings of the 29th Annual Conference of the Glass Art Society, Tampa, FL, USA, pp. 45-50, 1999.