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Development of negative discharge in meter-scale STP air gap.

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Abstract

We investigated the development of negative long laboratory discharge powered by a Marx generator of 1 MV in STP air gap of 1.27 meter. We present its evolution with nanosecond-fast photography together with electrical characteristics and x-ray measurement. Negative discharge develops via formation of space stem structures and possesses step-like propagation. As in positive discharge we observe streamer encounters at x-ray time. Difference between positive and negative discharge development and x-ray production is discussed.

1. Introduction

Long laboratory sparks are used as laboratory models for lightning investigation. Although an applicability and scaling procedure are still under discussion, new similarities have been recently discovered [1,2] between long laboratory discharges and natural lightning. About 95% of lightnings bring negative charge to the earth. Negative lightning propagates in steps and emits gamma and x-ray radiation during its propagation. In this work we give an overview of negative laboratory discharge. We show that negative long laboratory discharges also possesses step-like behavior and generate x-rays associated with it.

2. Experimental setup

The setup is similar to described in [1,2] and represented in Figure 1. The 2 MV Marx generator delivers a high-voltage (HV) standard lightning pulse with 1.2/50 μs rise/fall time. The upper voltage limit employed was about 1 - 1.2 MV. The generator voltage was measured by a capacitive high-voltage divider. The electrodes of the spark gap are cones. The tip distance was varied between 1 m and 1.27 m. When the generator is loaded by the air gap, the voltage rise time is about 2 kV/ns. Two Pearson 7427 current probes determined the currents through the HV electrode (cathode) and the grounded electrode (anode). An optical transmission system inside the HV electrode transported the HV current signal. Suitable attenuators and two antiparallel high-speed diodes protect the input of the transmitter. The diodes limit the linear response to 250 A; above this value the transfer is approximately logarithmic. An RG214 cable connected the current probe for the grounded electrode directly to the measuring system. An aluminum disk mounted near each probe minimized the risk of a direct hit by the full 4 kA spark current.

![Figure 1. Schematic of the experimental setup. Two ICCD cameras are located at 3.5-4.5 m distance from the gap. The distance between Marx generator and the spark gap is 8 m. The upper right inset shows the scaled floor plan of the setup.](image-url)
A Picos4 Stanford Optical camera was placed at 4 m distance from the spark gap. The camera contains charge coupled image sensors preceded by a fast switched image intensifier (ICCD). The image intensifier is a micro-channel plate that allows us to adjust the camera sensitivity by varying the applied voltage. The CCD is read out with 12 bit resolution. The camera optical axis was most often directed towards the spark gap centre. Appropriate electromagnetic shielding protected the cameras and their communication cables against electro-magnetic interference. The image intensifier amplification has been set to accommodate the light level and range of a particular experiment. Lens was the Nikon 35 mm F2.8 fixed focus.

Two LaBr₃(Ce⁺) scintillator detectors manufactured by Saint-Gobain were mounted in EMC cabinets and recorded the x-rays. Any interference on their signals due to the discharge initiation can be excluded, since such interference would most likely manifest itself as oscillatory signal, and not mimic a clear scintillator signal. Also, in many discharges only the signal channel noise floor was measured. The scintillators have a fast primary rise/decay time (11/16 ns) and a high light yield of 63 photons/keV, which is 165% of the more common NaI(Tl). The linearity of the detectors tested on ²⁴¹Am, ¹³⁷Cs, ⁶⁰Co and remains perfect up to 2505 keV, which is the total absorbed energy from two gamma quanta of the ⁶⁰Co source in the scintillator. The slight deviation from linearity at higher energies is attributed to saturation of the photomultiplier. The output of the photomultiplier is recorded directly on the oscilloscope without any waveshaping electronics usually employed in photon counting. This allows to distinguish individual pulses even when pile-up occurs within the decay time of the scintillator.

The electrical signal acquisition system consisted of two LeCroy oscilloscopes with 1 GHz bandwidth. The negative edge of the signal from the HV divider triggered the oscilloscopes. One oscilloscope then also triggered the camera. The electrical signal acquisition system consisted of two LeCroy oscilloscopes with 1 GHz bandwidth. The negative edge of the signal from the HV divider triggered the oscilloscopes. One oscilloscope then also triggered the camera. The differences in the delays caused by the instruments and cables were corrected for to within 1 nanosecond accuracy.

### 3. Results

By increasing the camera exposure time from discharge to discharge we receive a time integrated sequence of the discharge development process. Basing on electrical characteristics of each discharge and x-ray measurements we give interpretation to the entire observed phenomena.

#### 3.1 Negative discharge development and space stem.

Figure 2 presents the negative discharge development in a series of time-integrated images. The high-voltage (top) and grounded electrode (bottom) are indicated in the images. The distance between electrodes is 1.27 m between the tips. A faint speckle trace connecting the electrodes is visible in the first six images. It is caused by the huge brightness of the spark that appears after the camera shutter is closed. The electronic shutter is good but not perfect; some light of the arc leaks through the image intensifier even when it is off. But the speckle trace shows the final breakdown path even on pre-breakdown images. During the entire sequence we keep the camera sensitivity constant. The linear color coding scheme to the ICCD output is indicated by the color bar on the right.

The cathode current I HV has an undulating shape. It was shown in [2] that first four waves correspond to four negative streamer bursts. As can be seen in Figure 2, x-rays appear at the moment when picture (f) is taken. Although some preliminary activity near the grounded electrode is already visible, in contrast with positive discharge [1], no streamer coupling between two electrodes yet established. Moreover, as we have shown in [2], the x-rays appear even without a final breakdown in 1.75 meter gap, most of x-rays come from the cathode vicinity, and x-rays are associated with cathode current high-frequency oscillations (see Figure 2 plot, [1] and [2]).

The cathode vicinity in zoom at the x-ray time is shown in Figure 3. For better visibility the camera sensitivity is significantly increased in comparison with Figure 2. Negative streamer leave isolated dots behind during its propagation (Figure 3 (a)). Later, positive streamers originate from the dots. The positive streamers move towards the cathode and undergo encounters with newly originated negative streamers on their way (Figure 3 (b)). The entire structure "negative streamer – dots – positive streamers" called a "space stem" [3]. In large gaps and natural lighting, the space stem can develop into a space leader.

It is understood that many processes happen simultaneously at x-ray time in the cathode vicinity. In our investigation, we are not able to link the single encounter with the single x-ray burst directly. We associate the x-rays with the encounter basing on several experimental facts. First of all, we see encounter at x-ray time in both – positive and negative discharges. Secondly, x-rays come in short (<1 ns) bursts. Only a fast process can generate them. Third, high-frequency oscillations on the cathode current curve are associated with the x-rays. Last but not least, an electric field between two streamer tips has apparently the highest value than anywhere else. When it exceeds certain critical value E cr, the electrons can gain more energy from the electric field then they lose on (mainly) ionization processes. Electrons come into a runaway regime. Later, such electrons undergo Bremsstrahlung and emit part of their energy in x-ray form.
Figure 2. Time-integrated sequence of negative discharge development in 127 cm gap. Each picture shows a different discharge under the same conditions. The shutter always opens at $t = 0.47 \mu s$ (solid line z). The exposure time varies from 25 ns in panel (a) to 1650 ns in panel (o) and indicated at right bottom corner of each picture. The linear color coding scheme for the light intensity is indicated on the right side of the figure. Voltage ($U$), cathode ($I_{HV}$) and anode ($I_{GND}$) current are represented in the bottom plot. X-rays have been synchronously registered by both detectors (D1, D2) at the moment $t = 0.82 \mu s$. The data are those of picture (m).
Figure 3. Cathode vicinity at the x-ray time. Exposure time is 50 ns. Negative streamers (ns) propagate downwards from the high-voltage electrode. They leave isolated dots behind (dots). Positive streamers (ps) originate from the dots, move upwards and undergo collisions (c) with negative streamers.

4. Conclusion

Development process of negative long laboratory discharge has been investigated. In comparison with positive discharge described in [1], negative discharge develops via formation of space-stems and possesses step-like propagation behavior. This might be explained by difference in critical electric field value of positive and negative discharges. Positive and negative streamers propagation speed is about $2\cdot10^6$ m/s in our conditions. A minimum necessary electric field for continuous positive streamer propagation $E_{cr}^+ = 5$ kV/cm; for negative streamer $E_{cr}^- = 12.5$ kV/cm [4]. To keep this field on the fast-growing streamer corona edge we must supply high-voltage with 1 kV/ns rate for positive and 2.5 kV/ns for negative discharge. In our setup the high-voltage rises with about 2 kV/ns rate. That is enough for continuous propagation of positive streamers but causes negative streamers to interrupt. The interrupted negative streamers might, in turn, be re-ignited later if the voltage continuously increase. One should notice that in our explanation we neglect space charge effect and inductance of the high-voltage transmission line. X-rays from positive discharge appear when positive corona from the high-voltage electrode "touch" the grounded electrode and encounter with upward-directed negative counter-streamers [1]. In negative discharge, positive streamers appear near the high-voltage electrode from positive part of bipolar space stems. These positive streamers move towards the high-voltage electrode and undergo encounters with negative streamers newly originated from the high-voltage electrode. So, the x-rays are associated with streamer encounter.

5. Acknowledgments

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6. References


