Development of positive discharge in meter-scale STP air gap

Citation for published version (APA):
Kochkin, P., van Deursen, A. P. J., & Ebert, U. (2014). Development of positive discharge in meter-scale STP air gap. In *Scientific Symposium of International Union of Radio Science (URSI GASS 2014), 17-23 August 2014, Beijing, China*

Document status and date:
Published: 01/01/2014

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 16. Nov. 2023

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

P Kochkin*[1], A P J van Deursen[1], and Ute Ebert[2]

[1]Department of Electrical Engineering, Eindhoven University of Technology, POBox. 513, NL-5600 MB Eindhoven, The Netherlands, p.kochkin@tue.nl

[2]Department of Applied Physics, Eindhoven University of Technology, and Centre for Mathematics and Computer Science (CWI), POBox 94079, NL-1090 GB Amsterdam, The Netherlands, ute.ebert@cwi.nl

Abstract

We investigated the development of positive discharge powered by a Marx generator of 1 MV in STP air gap of 1 meter. We present an evolution of the discharge with nanosecond-fast photography together with its electrical characteristics and x-ray measurements. We found that the x-rays appear at the moment of intense encounters between positive and negative streamers. By increasing the amount of such encounters we increase the amount of x-rays generated by the discharge.

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. It is generally accepted that both phenomena generate bursts of hard radiation during their development. However, the precise mechanism is still far from being understood. This work is dedicated to x-ray emission generated by positive long laboratory sparks. We investigate positive discharge development process from the beginning till the hot spark formation. We pay particular attention to the moment and to the place where most of x-rays are generated. We observed that the x-rays occur when positive and negative streamers meet, as will be demonstrated by the simultaneous measurement of the electrical parameters, x-ray detection and fast photography.

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 largest voltage applied 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 1 m. 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 that the probe was directly hit by the full 4 kA spark.

A Picos4 Stanford Optical camera was placed at 4 m distance from the spark gap. The camera contained charge coupled image sensors preceded by a fast switched image intensifier (ICCD). The image intensifier was a micro-channel plate that allowed us to adjust the camera sensitivity by varying the applied voltage. The CCD was 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 was set to accommodate the light level and range of a particular experiment. Lens was the Nikon 35 mm F2.8 fixed focus.

Two $LaBr_3(Ce^+)$ 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(TI). The linearity of the detectors tested on ^{241}Am, ^{137}Cs, ^{60}Co and remains perfect up to 2505 keV, which is the total absorbed energy from two gamma quanta of the ^{60}Co source in the scintillator. The slight deviation from linearity at higher energies is attributed to saturation of the photomultiplier. The x-rays with energy below 30 keV will be dramatically attenuated by the detector's 0.5 mm aluminum case. The output of the photomultiplier was recorded directly on the oscilloscope without any waveshaping electronics usually employed in photon counting. This allowed to distinguish individual pulses even when pile-up occurred within the decay time of the scintillator.

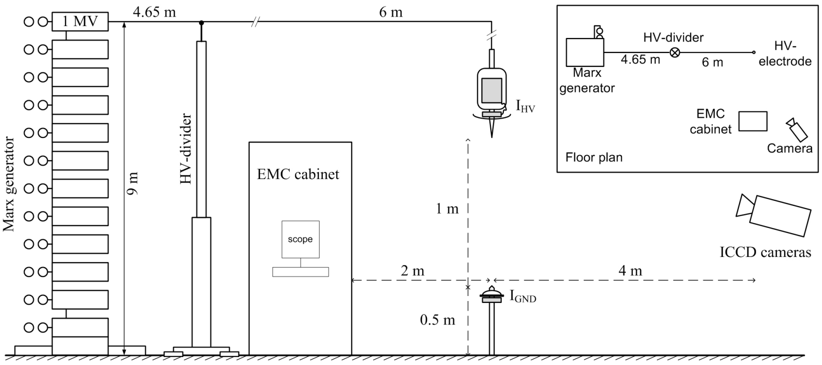

Figure 1. Schematic of the experimental setup. ICCD camera is located at 3.5-4.5 m distance from the gap. The distance between Marx generator and the spark gap is 8 m. The upper right inset shows the scaled floor plan of the setup.

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 got a time integrated sequence of the discharge development process. Together with electrical characteristics of each discharge we give interpretation to the entire observed phenomena.

3.1 Positive discharge development

The growth of positive discharge is shown in Figure 2. Every picture corresponds to a single discharge. We applied a special linear color coding scheme to enhance the faint streamers (showed on the right). The solid vertical line *z* at t=0.36 μs in the bottom panel corresponds to the shutter opening time. Dotted vertical lines *a-o* correspond to the shutter closing times for the corresponding pictures. Thus, a single picture is time-integrated from the starting time *z* until a camera closing time between 60 (picture *a*) to 1000 (picture *o*) nanoseconds later. Fast moving luminous streamers heads appear as streaks whose lengths correspond to their propagation lengths within the exposure time. The electrical signals corresponding to picture *l* are represented at the bottom plot: the voltage waveform U, the currents at the high voltage and at the grounded electrode and the x-ray signal. On the time axis t = 0 corresponds to the start of the voltage waveform. The pictures of the discharge development show a large similarity from discharge to discharge. There is also no significant difference in electrical characteristics. It means that one record represents most of the important steps in the process and can be used to describe the phenomena.

Positive discharge development starts with a formation of streamer corona near the high-voltage electrode. The corona extends with the speed $2 \cdot 10^6$ m/s downward bringing a part of the high-voltage potential to the grounded electrode. It causes negative counter-streamers from the grounded electrode jump up towards the positive streamers. When they interconnect, the first conductive channel appears between two electrodes. Ohmic heating of the channel creates a hot ark. X-rays have been never observed before the anode current. It means that positive streamers by themselves do not generate any detectable x-ray in our setup. All the x-rays are also accompanied by high-frequency oscillations of the cathode current. So, the negative streamers play an important role in x-ray production. The chance to observe any background signal that might mimic an X-ray from the gap is equal to 1 to 4×10^4 in our laboratory.

Since the x-rays appear in short bursts (1 ns or less) allow us to exclude negative streamer *propagation* from possible generation mechanisms due to its relatively long time (about 50 ns). The probable mechanism that is responsible for x-ray production is streamer encounter. When two streamers of opposite polarities approach each other an electric field between their tips dramatically increases. When it exceeds certain critical value E_{cr} [3], 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.

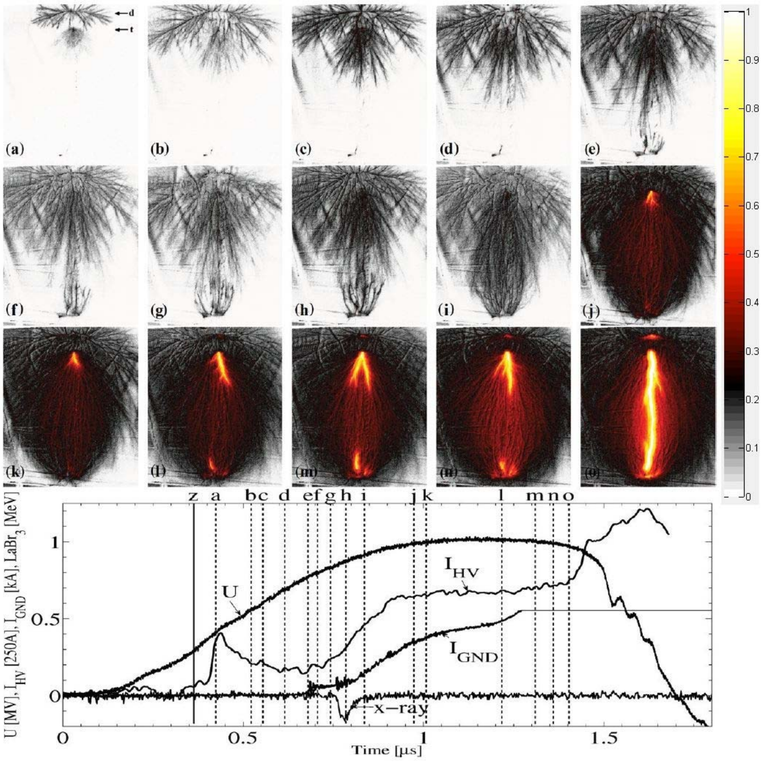

Figure 2. Detailed development of the discharge in consecutive time steps. Each picture corresponds to a single discharge. Gap distance is 1 m. The shutter always opens at t = 0.36 µs (solid line *z*). The exposure time varies from 60 (picture *a*) to 1000 (picture *o*) nanoseconds. The jitter with respect to the generator voltage and current is of the order of 0.04 µs. X-rays, voltage, cathode and anode currents are represented in the bottom plot. The data are those of picture *l*. The moment of X-rays detection coincides with the connection between downward positive streamers and upward negative counter-streamers as shown in pictures *e - h*.

3.2 X-ray registration rate

In order to confirm our suggestion we build an alternative grounded electrode. It contains of 75 sharp spikes (Figure 3 (a)). The amount of negative streamers and consequently encounters should dramatically increase with it. Image of the electrode taken at the x-ray most intense moment with 50 ns exposure time is shown in Figure 3 (b). With the new electrode an x-ray registration rate, as expected, increases 10 times in comparison with the previous electrode schematically drawn in Figure 1. The amount of high-frequency oscillations also significantly increases.

We have measured the x-ray spectrum and attenuation curves (see details in [1]). The spectrum can be roughly fitted by the exponential law with characteristic x-ray energy about 200 keV. Since the x-rays come in very short bursts (less than our detector 11 ns resolution time) more investigation should be done in the future.

We have not found any significant x-ray source anisotropy. X-ray registration rate follow the inverse square low with distance that assumes isotropic source of constant luminosity.

Experiments with lead collimators around the detectors have shown that 2/3 of the x-ray come from cathode area, where most of encounters happen.

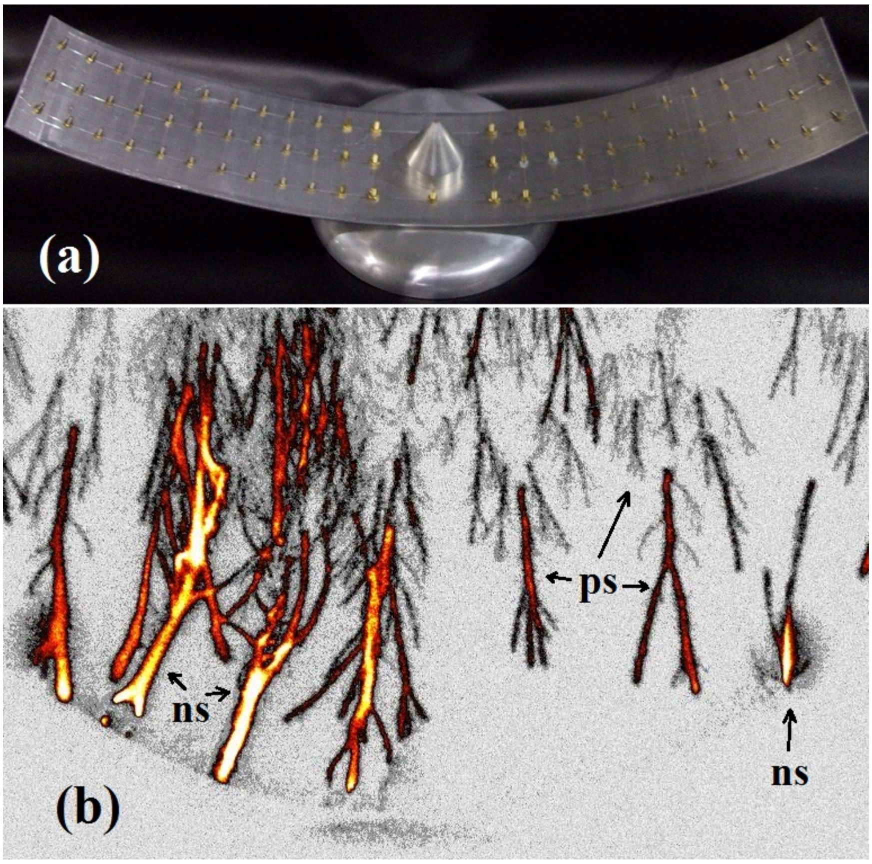

Figure 3. (a) The alternative grounded electrode to increase the amount of negative streamers (ns) and consequently encounters between positive (ps) and negative streamers. (b) Image of the electrode at the x-ray registration moment. Exposure time is 50 ns. The x-ray registration rate increases 10 times with this electrode.

4. Conclusion

We investigated the development of positive laboratory breakdown in particular focusing on its x-ray emission. It was shown that x-rays appear in short bursts at the moment when positive streamers from the high-voltage electrode encounter with negative streamers originated from the grounded electrode. By increasing the amount of negative streamers and such encounters the x-ray intensity also increases. The x-rays from positive long laboratory sparks are associated with streamers encounter.

5. Acknowledgments

This work was supported by the Dutch Technology Foundation STW under project BTP 10757.

6. References

1. P. Kochkin, A. P. J. van Deursen, and U. Ebert, "Experimental study of hard x-rays emitted from metre-scale positive discharges in air," *J. Phys. D Appl. Phys.,* **45**, 2012, 425202

2. P. Kochkin, A. P. J. van Deursen, and U. Ebert, "Experimental study of the spatio-temporal development of meter-scale negative discharge in air," *accepted to J. Phys. D Appl. Phys.,* 2013, arXive:1312.4765

3. C.T.R. Wilson "The electric field of a thunderstorm and some of its effects" *Proceedings of the Royal Society of London* 1925 **37**