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# Observations of X-rays from Laboratory Sparks in Air at Atmospheric Pressure under Negative Switching Impulse Voltages

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**Abstract:** We present observations of X-rays from laboratory sparks created in the air at atmospheric pressure by applying an impulse voltage with long (250 μs) rise-time. X-ray production in 35 and 46 cm gaps for three different electrode configurations was studied. The results demonstrate, for the first time, the production of X-rays in gaps subjected to switching impulses. The low rate of rise of the voltage in switching impulses does not significantly reduce the production of X-rays. Additionally, the timing of the X-ray occurrence suggests the possibility that the mechanism of X-ray production by sparks is related to the collision of streamers of opposite polarity.

**Keywords:** X-rays; high energy radiation; laboratory sparks; switching impulse

## 1. Introduction

In 2001, Moore et al. [1] recorded energetic radiation pulses in excess of 1 MeV, associated with approaching stepped-leaders in natural cloud-to-ground negative lightning strikes. The radiation began about 1–2 ms before and continued until the onset of the first return stroke. Later in 2003 and 2004, Dwyer et al. [2,3] reported the first observation of energetic radiation during the dart and dart-stepped leader phase of rocket-triggered lightning. The energetic radiation in this case usually started a few tens of microseconds before the return stroke and always got terminated very close to the time of the return stroke or at the beginning of the return stroke. X-rays with energies extending up to a few hundred keV were also detected within about 1 ms prior to the first return stroke, during the stepped-leader phase of negative natural lightning strokes [4]. These works were followed by detailed studies of the properties of this energetic radiation [5–7]. Yoshida et al. [8] successfully recorded the bursts of high energy electrons with energies in excess of 100 keV from lightning discharges during Japanese winter thunderstorms. Furthermore, their observations suggested that not only negative leaders, but also positive leaders of natural lightning could cause an increase in the count rate of their NaI (Tl) scintillation detector.

These successful on-ground observations of penetrating emissions in association with lightning discharges and their analysis broadened the new field of high energy atmospheric physics. Wilson [9] first described runaway electrons and predicted the production of high energy radiation from thunderstorms. However, the detailed mechanism behind this radiation that is likely to involve runaway electrons breakdown [10] is still under discussion.

The potential difference between the lower boundary of the main negative charge region and ground is in the range of 50–500 MV when its height above the ground level is assumed to be 5 km [11]. The lightning current flowing after the attachment process may reach peak values of about 100 kA. In contrast, electrical discharges in the air at atmospheric pressure created in laboratories may involve potentials of only a few MV and peak currents of about a few kA in a meter-long spark channel. Interestingly, in 2005, X-ray bursts in the range of 30–150 keV were observed in the air from 5 cm to 2 m long high-voltage laboratory sparks of both polarities [12]. In that experiment, the peak of the measured impulse voltage across the gap was about 1.5 MV. It has generally been believed that electrical discharges in air occur via a conventional breakdown which involves only low-energy electrons having energies of, at the most, a few tens of eV [13]. It has also been suggested that breakdown and discharges in dense gases can develop in a mode with high-energy runaway electrons and even are governed by runaway electrons [10]. However, as of today, there is no evidence that the runaway breakdown is a necessary feature of lightning leaders [7]. The results of the experimental studies conducted at Uppsala University on X-ray production in laboratory discharges were presented by Rahman et al. [14,15]. These studies were followed by many experimental studies investigating different electrical and geometrical parameters and characteristics of high-energy radiation from laboratory sparks [16–25].

To simulate the effects of lightning, and the effects of transients created during switching operations in power systems, impulse voltage waveforms of different shapes are used in the laboratory. The so-called “standard lightning impulse” waveform (rise time of the impulse: 1.2 μs, time to half-peak-value: 50 μs) having a medium rate of rise, was originally derived from the measurements of lightning-induced over-voltages on power transmission lines. On the other hand, in order to simulate the breakdown effects of switching over-voltages in power systems, the so-called “standard switching impulse” (rise time of the impulse: 250 μs, time to half-peak-value: 2500 μs) was used. In all previous studies on X-ray generation by laboratory sparks [12,14–23], the “standard lightning impulse” or other voltage impulses with rise times similar to that of the “standard lightning impulse” were used.

In a recent study, March and Montanyà [18] found that shorter voltage rise times tended to produce more X-ray emissions with higher energies than longer voltage rise times. The rise times of the applied voltage impulses in their experiments were 0.66, 1, and 2 μs. The rate of rise of the voltage in “standard switching impulses” is more than 100 times lower than that in “standard lightning impulses”. Thus, one may infer that in gaps subjected to switching impulses, X-ray production can be significantly reduced or did not occur at all. Further, if it does occur, it could be associated with a different process. In this paper, we present results of an independent experiment demonstrating that decimeter-scale sparks in air gaps stressed by switching impulse voltages do produce X-rays.

## 2. Experiments

In 2007, during the months of May and June, a joint experimental campaign was carried out between the Florida Institute of Technology (FIT), the University of Florida (UF), and the Uppsala University (UU). In that campaign, a series of experiments were conducted at the High-Voltage Laboratory of Uppsala University, to study X-ray emissions from long sparks in air. A Marx impulse voltage generator (Haefely Test AG, SGSA 1000–50) was used to create the long sparks. The experiments were performed in the air at atmospheric pressure using two different impulse voltages waveforms. The first was a standard lightning impulse (1.2/50 μs) and the results for experiments using the standard lightning impulse were already published [17]. The second was a “standard switching impulse” voltage, and we shall report on experiments using the “standard switching impulse” in this paper. In the latter case, the generator was configured to deliver the "standard switching impulse" voltage (250/2500 μs). Since switching impulses are less controllable in the laboratory, for the present experiments, two short gaps, 35 and 46 cm, were used. Negative impulse voltages were applied to the high voltage electrode for different electrode configurations, with the other electrode being grounded. The breakdown voltage for negative polarity is much higher compared to the positive, and that is why the negative polarity was studied first. Experiments with positive polarity were also planned, but due to the time constraints could not be carried out. The charging voltage was set to 800 kV for all measurements. In the series of experiments with lightning impulses, it was found that two 12-cm-diameter spherical electrodes produced the most intense bursts of X-rays among all electrode configurations used [17]. Furthermore, it was found that emissions from horizontal and vertical sparks (gaps) differed in terms of both amplitude and time of appearance. These observations motivated us to use horizontal and vertical air gaps with big spherical electrodes. Different electrode configurations used in these experiments were (1) a sphere-to-sphere horizontal air gap of 35 cm length with both electrodes being about 120 cm above the ground, (2) a sphere-to-sphere vertical air gap of 35 cm length with the high voltage electrode suspended above the grounded electrode, and (3) a rod-to-plane vertical air gap of 35 and 46 cm lengths with the high voltage electrode suspended above the grounded electrode. The spherical electrodes were copper with chromium coating. The rod had a diameter of 1 cm and was made of brass. The basic configurations of the experiments are shown in Figures 1 and 2. The rest of the experimental set-up and all instruments were the same as those described in Reference [17], but for the sake of completeness, we list them here briefly.

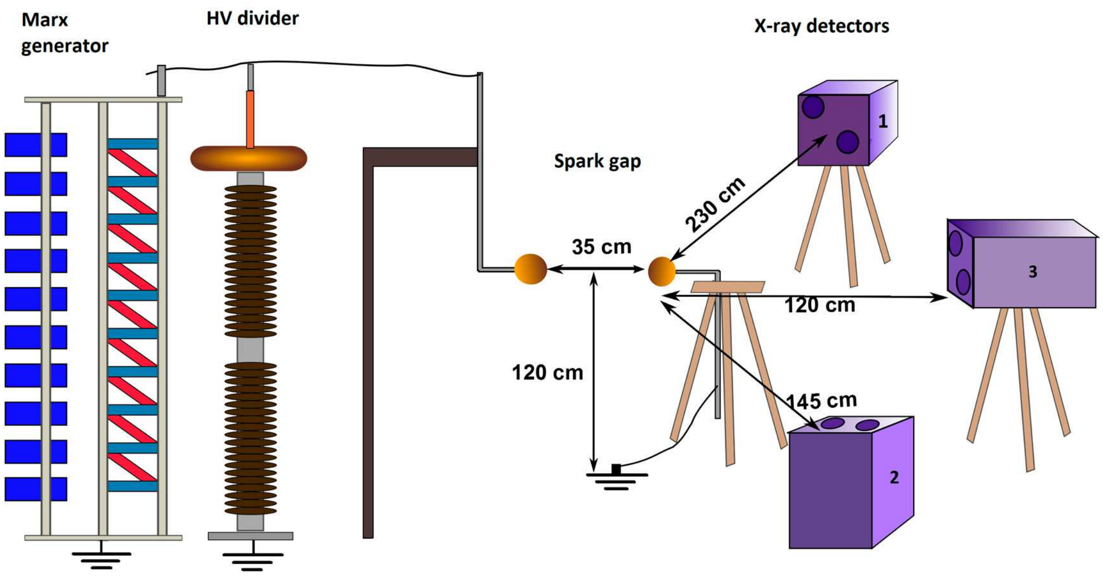


**Figure 1.** Schematic diagram of the experimental setup, showing the approximate arrangement, from left to right, of the Marx generator, high-voltage divider, sphere-to-sphere horizontal air gap of 35 cm length, and three X-ray instruments. The distances of the X-ray instruments to the grounded electrode are shown. The circles on the X-ray instrument boxes show the locations of detectors inside the boxes.

X-rays, the voltage between the electrodes, and the breakdown current at the grounded electrode were measured. A capacitive impulse voltage divider (Haefely CS 1000-670) was used to measure the voltage. The current was measured using a current transformer (Pearson model 411, maximum peak current 5 kA, rise time 20 ns, bandwidth 20 MHz).

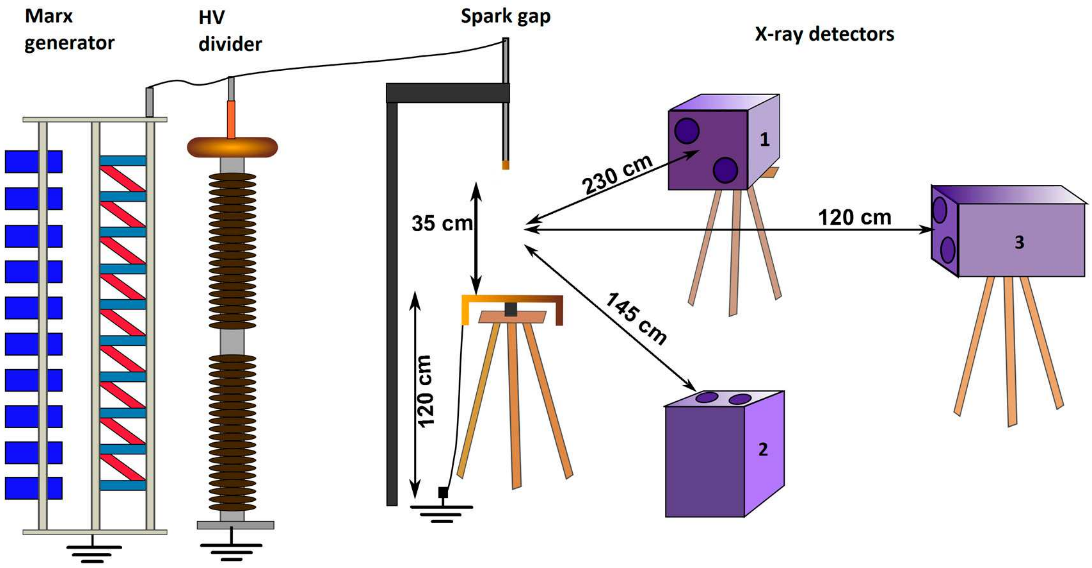


**Figure 2.** Same as Figure 1, but for a rod-to-plane vertical air gap of 35 cm length (the plane is grounded). The distances of the X-ray instruments to the middle point of the vertical air gap are shown.

Three instruments called instruments (boxes) 1, 2, and 3 (see Figures 1 and 2) measured the X-ray emissions. Each instrument contained two detectors: Instrument 1 consisted of one NaI (Tl)/ Photomultiplier tube (PMT) detector and one plastic scintillator (36 cm × 25 cm × 1 cm). Instruments 2 and 3 each contained two 7.6 cm × 7.6 cm cylindrical NaI (Tl)/ PMT detectors. The thickness of the aluminum boxes (instruments) was 0.32 cm, which allowed X-rays having energies above about 30 keV to enter from all directions.

The breakdown current and the signals from all six detectors were recorded simultaneously by a Yokogawa 750 ScopeCorder with 12-bit resolution and a sampling rate of 10 mega-samples per second. The scope was usually triggered by the current pulse, and data were recorded for 2 ms with 1 ms of pre-trigger sampling. Moreover, the voltages across the gap and the breakdown currents were recorded separately with an 8-ns time resolution. The average temperature and relative humidity of air during the experiments were measured using a Vaisala temperature and humidity indicator of type HPI31 and were 26 °C and 36%, respectively.

## 3. Results

As mentioned above, three different series of experiments were performed with different electrode configurations. In the first series of measurements a sphere to sphere horizontal air gap of 35 cm length was used, where the gap was situated at about 120 cm above the ground level, as seen in Figure 1. A total of 15 negative "standard switching impulse" voltages were applied. In 11 cases out of these 15, X-rays were detected by at least one detector. The average breakdown voltage was around 530 kV for this series. A typical X-ray record is shown in Figure 3 where signals from all 6 detectors are shown together with the voltage and the current measurements. Signals in CH1 and CH2 are from the detectors in the box situated on a wooden stool, 120 cm behind the grounded electrode. CH1 shows signal from an unshielded detector, whereas CH2 shows a signal from the collimated detector. Both are saturated. Signals in CH3 and CH4 are from the detectors in the box situated on a wooden stool 230 cm away from the grounded electrode. CH3 shows a signal from an unshielded detector, whereas CH4 shows a signal from a plastic detector. The CH3 signal is also saturated. Signals in CH5 and CH6 are from the detectors in the box situated on the floor, 145 cm away from the grounded electrode. CH5 shows a signal from an unshielded detector, whereas CH6 shows a signal from a detector with a lead cap. Figure 4 shows the same signals as in Figure 3 but on an expanded time scale. The peak voltage and the peak current were about 540 kV and 1.4 kA, respectively. As seen in Figure 4, the X-rays appear at about 77 µs after the application of the switching impulse voltage, but on average 0.74 µs before the final breakdown. Moreover, at the time of the appearance of the X-ray signals, the voltage started decreasing and the corresponding current signal started increasing, with multiple oscillations occurring on the current signal. The applied switching impulse voltage was initially increasing in the same way as in the case of an open circuit voltage waveform. However, at around 77 µs, the voltage started collapsing with the current slightly increasing. Within about 0.74 µs from this instant of time, the complete breakdown took place. The total deposited X-ray energy varied from 180 keV up to the saturation level of 6 MeV.

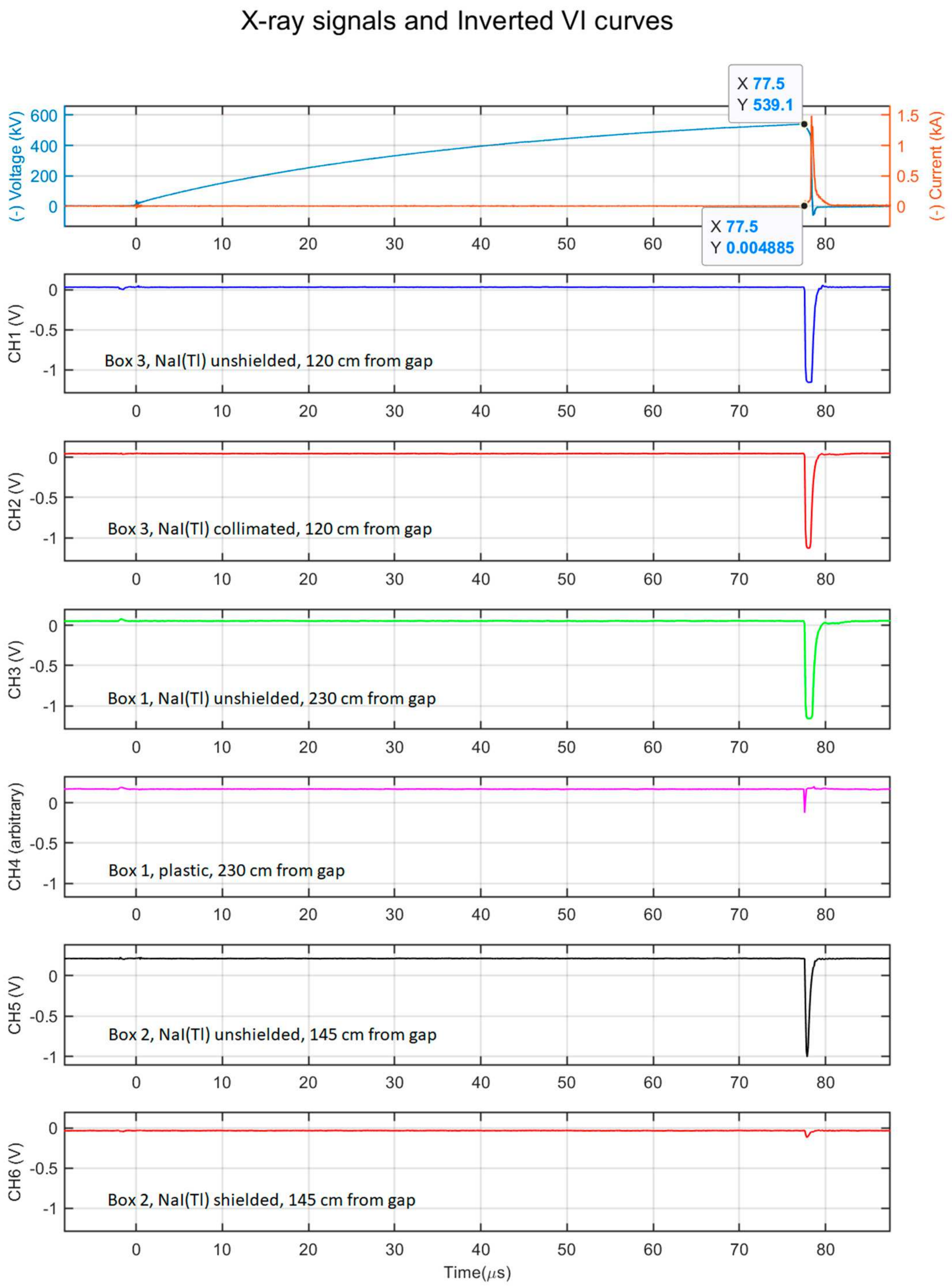


**Figure 3.** X-rays signals from all 6 detectors placed in 3 boxes together with the magnitude of the measured voltage and current waveforms.

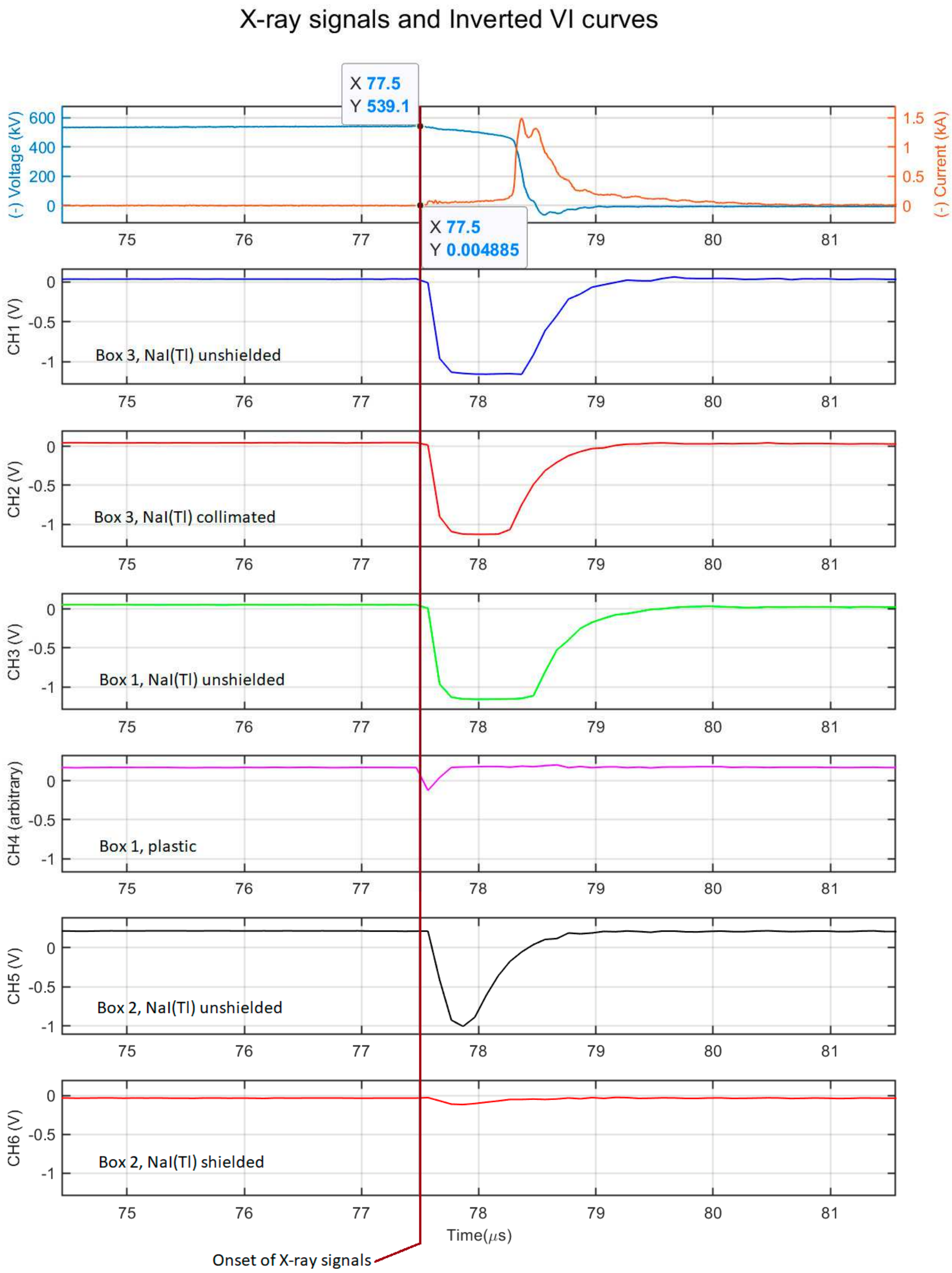


**Figure 4.** Same as Figure 3 but on an expanded time scale. The vertical line passing through all 7 panels represents the onset of the X-ray signals. At that time, a small current is seen at the grounded electrode and the voltage has just started to collapse. The X-ray emission occurred on average 0.74 µs prior to the final breakdown.

For the same electrode configuration (sphere-to-sphere) and gap length (35 cm) as described above, the second series of measurements was conducted, but with a vertical gap with the high voltage electrode suspended above the grounded electrode. The grounded spherical electrode was placed on a wooden stool about 120 cm above the floor of the High-Voltage Laboratory. Again, 15 negative "standard switching impulse" voltages were applied, and in 8 cases of the 15, the X-rays were recorded by one or more detectors. The breakdown voltage was around 528 kV for this series. The total deposited energy varied from 150 keV up to the saturation level. All observations were similar to those obtained for the case of the horizontal gap described above.

Later, in the third series of measurements, the electrode configuration was changed to rod-to-plane, as seen in Figure 2. In this configuration, the gap lengths were 35 and 46 cm. The breakdown voltage was around 470 and 540 kV, respectively. Seven impulses were applied to the 35 cm long gap, and eight impulses were applied to the 46-cm long gap. Out of 15 applied switching impulse voltages, only in one case (35 cm gap) were X-rays detected by three detectors with the energies varying from 120 keV to 490 keV. The X-rays occurred even in this rod-to-plane configuration about the same time after the application of the impulse voltage.

As the characteristic response of the detectors to X-rays was known, any possible noise electromagnetically induced could easily be distinguished. Besides, the X-ray signals observed during these experiments were relatively large signals. Also, the recorded X-ray signals were different from those of typical optical emissions produced by such sparks. That is why a false signal due to an optical emission could be ruled out. The background counts in the detectors were typically about 100 counts/second. Therefore, the probability that even a single count occurred within 79 μs of the impulse voltage duration is extremely small. Moreover, all the X-rays always appeared in connection with the discharge almost at the same place, simultaneously on several detectors, except in one case where one single X-ray signal appeared (CH1) in the first measurement series at around 50 μs after the application of the impulse voltage and about 27 μs before the complete breakdown.

## 4. Discussion

The goal of this experiment was to study the X-ray production by laboratory sparks in gaps subjected to voltage impulses having a low rate of rise compared to previous studies of spark-generated X-rays. The "standard switching impulse" voltage with a rise time of 250 μs was used in this study. Note that this voltage is the output voltage (open circuit voltage) of the generator which was applied across the spark gap. As the spark gap breaks down, the measured voltage has a different wave-shape with different rise time and duration, as seen in Figures 3 and 4. The results confirm, for the first time, the production of X-rays in gaps that are stressed by switching impulses. The X-ray energies obtained using switching impulses were comparable to those observed in experiments with "standard lightning impulses". Thus, the rate of rise of the voltage impulse does not have a significant influence on the production of X-rays, at least within the studied range of values. It is important to mention here that there is a significant difference in the breakdown mechanism of gaps while using "standard lightning impulse" and "standard switching impulse" voltage. In the case of "standard lightning impulses", the breakdown is mediated by streamers propagating from the high-voltage electrode to the grounded one, whereas in "standard switching impulse" voltages, it is mediated by a combination of leaders and streamers. However, the results available in the literature show that in gaps shorter than about 1 m, the leaders do not play a significant role in the breakdown mechanism in the case of switching impulses [26]. Since the maximum gap length used in the present study was 46 cm, one can assume that the breakdown was primarily mediated by streamers, so the breakdown mechanism is expected to be the same in both cases.

A close look reveals that X-rays appear as soon as the current at the grounded electrode begins to increase. A corresponding voltage drop is observed in the measured voltage waveform. It indicates that X-rays are produced either at the streamer/leader tip when it almost reached the opposite electrode or, more likely, at the meeting point of the colliding streamer/leader heads at some distance from the opposite electrode. Therefore, the mechanism proposed by Cooray et al. in Reference [27], that the opposite polarity streamer collisions produce the X-rays, is probably valid for switching impulses.

Regarding the difference between the emissions from horizontal and vertical sparks (gaps) in terms of both amplitude and time of appearance observed in Reference [17], in this experiment we also see a difference (Horizontal gap: 11 cases of X-ray observation out of 15 discharges, minimum energy about 180 keV vs. Vertical gap: 8 of 15 discharges, and 150 keV). Even though the observations are the same, it is difficult to point out one single physical explanation for this. Two possible reasons for this observation are mentioned here. First, the field of view of the X-ray detectors in relation to the orientation of the spark discharge is changed. This could be an indication of a favorable direction of radiation of the produced X-rays in the discharge. Second, the electric field configurations between the electrodes and in their vicinity are different in these two cases. In the case of the horizontal gap, the presence of the grounded floor of the high-voltage laboratory seems to favor the X-ray production. One can think of a slightly increased non-uniformity of the electric field in this case cause this difference. One might be able to resolve the apparent differences by performing additional controlled laboratory experiments with better arrangements for the X-ray sensors set up and for the geometry constraints on the background electric field.

The third series of experiments where a rod-to-plane electrode configuration was used did not produce detectable X-rays as efficiently as the other two series of experiments. One possible explanation for this observation could be that in the rod-to-plane gap counter corona/streamer/leader initiation from the plane electrode and its further propagation is less likely compared to the rod-to-rod or sphere-to-sphere gap. The electric field around the plane electrode is more uniform than the electric field around the spherical electrode in the case of the sphere-to-sphere gap, and the electric field strength is also much lower around the plane electrode.

## 5. Conclusions

X-rays from air gaps stressed by impulses with long (250 μs) rise time are reported for the first time. The X-rays apparently occurred before the complete breakdown, during the final jump process. The results indicate that X-ray emissions are taking place just before the breakdown, suggesting that the mechanism of X-ray production is related to the collision of streamers of opposite polarity.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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