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X rays from 80-cm long sparks in air

Mahbubur Rahman,[1] Vernon Cooray,[1] Noor Azlinda Ahmad,[1] Johan Nyberg,[2] Vladimir A. Rakov,[3] and Sriram Sharma[4]

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[1] New data on X-ray production by laboratory sparks in air are reported. The total deposited energy ranged from about 30 keV to a few MeV. X-ray signals were observed both before and during the collapse of voltage across the gap. The earlier signal is likely associated with processes involving runaway electron breakdown in streamer tips and the later signal with the attachment (final jump) process.
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1. Introduction

[2] Elevated X-ray fluxes in the energy range from 3 to above 110 keV were detected by an instrumented aircraft flying through thunderstorms [*Parks et al.*, 1981; *McCarthy and Parks*, 1985]. The elevated X-ray activity preceded some lightning flashes by at least several seconds and ceased immediately and coincidently with the lightning. These observations were supported by balloon-borne measurements of *Eack et al.* [1996]. Radiation with energies in excess of 1 MeV associated with lightning stepped-leader (started 1 to 2 ms before the return stroke and continued until its onset) and that with energies 30–250 keV during the dart (dart-stepped) leader phase of rocket-triggered lightning were reported by *Moore et al.* [2001] and *Dwyer et al.* [2004], respectively. *Dwyer et al.* [2005a] observed X-ray bursts, with energies up to a few hundred keV, produced by individual steps by natural-lightning stepped leaders. Observation of X-rays was reported from pulsed atmospheric pressure spark discharges in helium at Princeton-Pennsylvania Accelerator [*Frankel et al.*, 1966]. This was a result of their investigation to solve the problem of detecting charged particle paths using two spark chambers in series. X-ray radiation was observed and analyzed in many studies during late 1960s and 1970s from nanosecond-scale high-voltage electrical discharges in mm-long gaps in different gases at different pressures. For example, *Stankevich and Kalinin* [1968], *Tarasova and Khudyakova* [1970], *Tarasova et al.* [1974] and *Babich et al.* [1975] performed experimental studies in air at atmospheric pressures. In these studies, a voltage impulse with about 1 ns rise time and tens of ns pulse duration was applied to a 0.4–85 mm long air gap confined by rod or sphere to plane electrodes. The amplitudes of the voltage pulses were between 46 and 180 kV, and the resultant X-rays had an estimated average energy of 4–20 keV. A laboratory study conducted by *Noggle et al.* [1968] failed to detect any X-rays from electrical discharges in air. However, *Dwyer et al.* [2005b] recently observed X-ray bursts (in the ~30 to 150 keV range) from high-voltage laboratory sparks (positive and negative; 5 cm–2 m in length) in air. The existence of high energy radiation from lightning and especially from laboratory discharges raise questions as to the possible mechanism behind this radiation. This mechanism is likely to involve runway electron breakdown [*Gurevich et al.*, 1992]. Since X-ray bursts from long (about a meter-long as opposed to mm-long discharges mentioned previously) laboratory sparks were detected only for a limited number (seven) of events of each polarity at one high-voltage facility and the mechanism of X-ray generation by laboratory sparks remains uncertain, a further study of this phenomenon is an order. In this paper, we present results of an independent experiment conducted at a different high-voltage facility and using different instrumentation to confirm (or refute) the production of X-rays by long laboratory discharges.

2. Experiment

[3] The experiment was conducted at the high-voltage laboratory of Uppsala University, Sweden. A spark was created in air at atmospheric pressure applying a standard lightning impulse voltage (the so-called *1.2/50 impulse*; front time: 1.2 μs, time to half-value: 50 μs) to an 80-cm long rod-to-hemisphere air gap. A negative impulse voltage was applied to the rod, which was made of brass and had a diameter of 10 mm. At the tip of the rod there was a screw of diameter 6 mm. The hemispherical (3-cm radius) copper electrode with tungsten coating was grounded. The voltage impulse was generated by using a Marx impulse voltage generator (Haefely Test AG, SGSA 1000-50, maximum charging voltage: 1 MV, maximum energy: 50 kJ). In this experiment, the generator was charged to 1 MV with negative polarity. When voltage across the gap reached the breakdown value, a spark bridged the gap causing a voltage collapse. The voltage across the gap, the current in the spark, the visible optical radiation from the spark, and the emission of X-rays (if any) produced by the spark were measured. A capacitive impulse voltage divider (Haefely CS 1000-670) was used to measure the voltage across the gap. The current was measured at the grounded electrode using a current transformer (Pearson model 411, maximum

[1]Ångström Laboratory, Division for Electricity and Lightning Research, Department of Engineering Sciences, Uppsala University, Uppsala, Sweden.
[2]Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden.
[3]Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida, USA.
[4]Atmospheric Physics and Lightning Research Group, Department of Physics, University of Colombo, Colombo, Sri Lanka.

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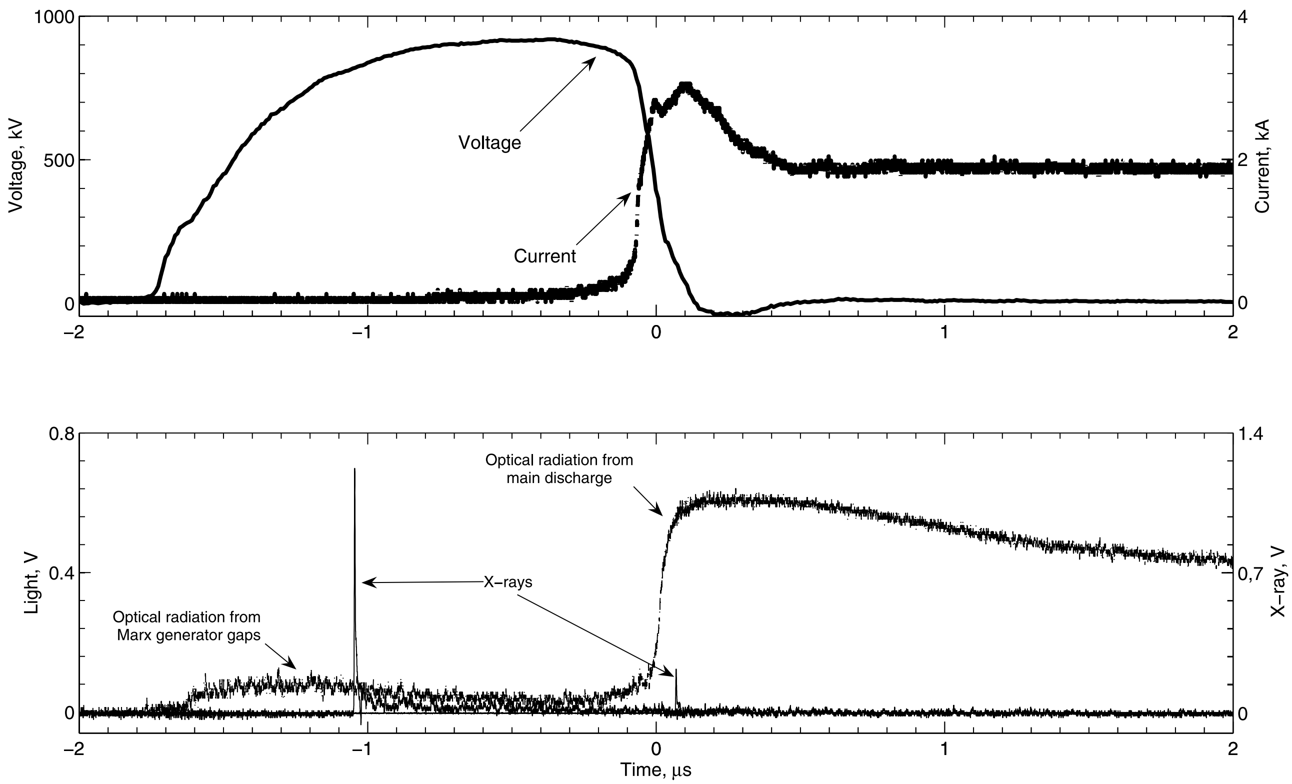

Figure 1. Measured voltage across the 80-cm long air gap at atmospheric pressure, current through the gap, optical radiation from the discharge, and the X-ray signal, each as a function of time. Note that the measured voltage across the gap exhibits rapid decrease (collapse) due to electrical breakdown, while the applied voltage was a 1.2/50 μs impulse.

peak current 5 kA, rise time 20 ns, upper frequency response 20 MHz). Optical radiation emitted from the discharge channel was measured with a photomultiplier tube, PMT (Hamamatsu R1477, 28 mm size, rise-time 2.2 ns, spectral sensitivity 185–900 nm) to which the optical radiation was transmitted by means of a fiber-optic cable. The spectral sensitivity for the entire system was between 300 and 850 nm. The emission of X-rays was detected via the scintillation light produced in a barium fluoride (BaF_2) crystal scintillator, which had a shape of frustum of a right cone (front diameter: 2.2 cm, rear diameter: 4 cm, and length: 4 cm). The scintillator was attached to a 51 mm PMT (Photonis XP2020/URQ, rise-time 1.4 ns, spectral sensitivity 200–550 nm). The crystal was wrapped in lead of thickness 0.5 cm to make the scintillator directed towards the air gap. The PMT was enclosed by a μ-metal shield. The whole detector system consisting of the scintillator, PMT, and electronics, was sealed in a black polyethylene bag and put in a steel (thickness 1 mm) box having a square opening (window) of 100 × 100 mm. The steel box was placed on a wooden table located inside an ungrounded galvanized-steel (thickness 1 mm) cabinet having a rectangular window of 75 × 160 mm, which was covered by 15 μm thick aluminum foil and a layer of about 15 μm thick black polyethylene. Thus, the X-ray detector completely covered by black polyethylene inside a metal box was looking through two windows: the open window in the metal box and the window covered by aluminum foil and polyethylene in the metal cabinet. The ungrounded, light-tight, and electromagnetically sealed metal cabinet was placed about 1 m away from the spark gap so that the center of the crystal was a few centimeters below the high-voltage rod electrode. The current, optical signal, and the output (anode signal) of the X-ray detector were recorded on a digital oscilloscope (Lecroy Wavepro 7100A) placed inside the metal cabinet. The oscilloscope was triggered by the current signal. Data were recorded for 1 ms with 0.5 ms pre-trigger. The X-ray detector, optical measuring system, and oscilloscope were powered by batteries placed inside the metal cabinet. The data acquisition system for the voltage measurement (capacitive voltage divider connected to a computer via a 20 m long cable, upper frequency response: 30 MHz, rise-time: 3.5 ns) and the control system of the Marx generator were situated inside the shielded control room of the high-voltage laboratory. The temperature and relative humidity of air during the experiments were measured using a Vaisala temperature and humidity indicator of type HPI31 and were 16–25°C and 30–66%, respectively.

3. Results and Discussions

[4] A total of 83 negative voltage impulses were applied across the gap and in 49 cases (59% of the events) X-ray signals were detected. In 23 cases, the X-ray signal

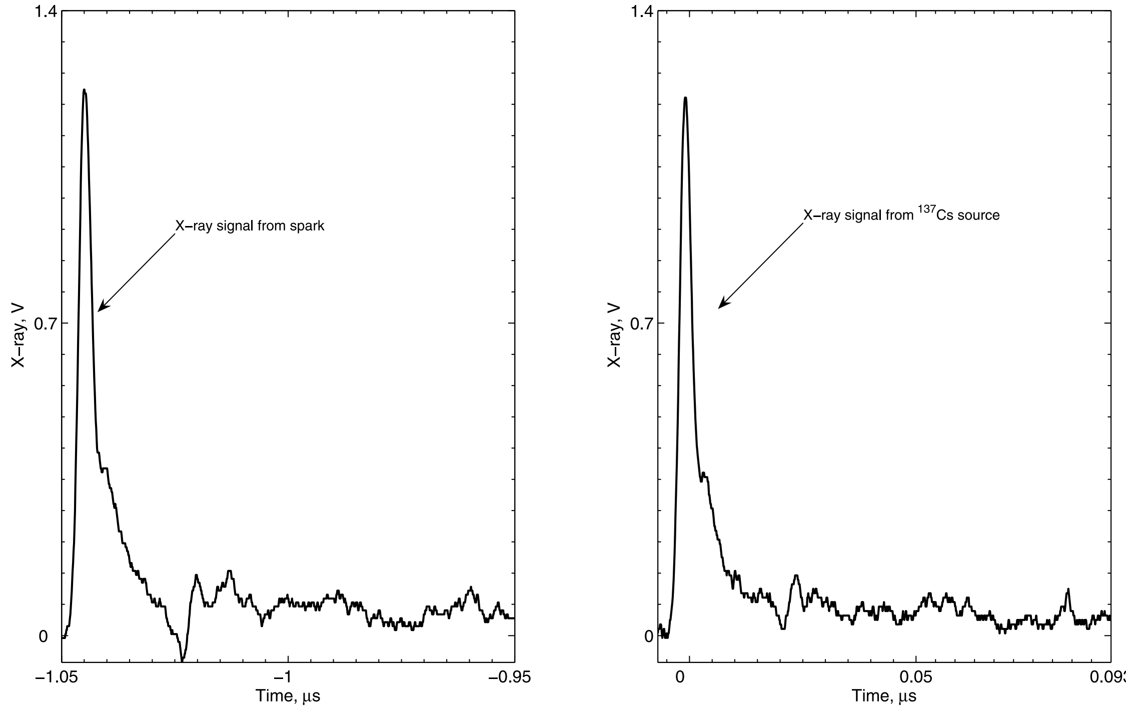

Figure 2. X-ray signals (right) from a ^{137}Cs radioactive source placed on the aluminum/polyethylene-covered-window of the metal cabinet and (left) from spark.

appeared only before the collapse of the applied voltage across the gap and about 1 μs prior to onset of the main discharge current, in 22 cases, it appeared only around the main discharge current peak, and in 4 cases both before and during the collapse of voltage across the gap (see Figure 1). A rough estimation of total deposited energy in the crystal was carried out based on measured signals from three X-ray sources, ^{137}Cs, ^{60}Co, and ^{241}Am. The lowest total deposited energy was around 30 keV. The amplitude and the width of the detected X-ray signals were different for different events, and some signals were saturated. The average total deposited energy of the 31 unsaturated signals was calculated to be around 170 keV. The total deposited energy in the case of saturated signals was of the order of a few MeV. The detected X-ray signal is consistent with the response of the BaF_2 detector to a signal from a ^{137}Cs radioactive source placed on the aluminum/polyethylene-covered-window of the metal cabinet (see Figure 2). Further, a comparison to the X-ray and optical signals shows clearly that the first recorded X-ray signal, which appears before the collapse of the applied voltage across the gap, is associated with the pre-discharge activity in the gap. The second recorded X-ray signal appears during the collapse of the applied voltage across the gap. As noted earlier, there were 4 cases out of 49 when the X-ray signals appeared both before and during the collapse of voltage across the gap. Note the broad peak in the optical signal prior to the collapse of voltage across the gap is due to radiation from the Marx generator gaps that are used for switching of the capacitors in the generator from parallel to series configuration. The breakdown voltage of the 80-cm air gap varied between 898 and 938 kV with average value of 925 kV. An extensive electromagnetic noise study shows that the only time when noise is coupled to the system inside the metal cabinet is related to the discharges in the Marx generator gaps prior to formation of spark in the main gap and the maximum noise amplitudes were relatively small, a couple of mV compared to the X-ray signal amplitudes varying from tens of mV to more than 8 V. No X-rays were detected from sparks with positive voltage impulse applied to the rod for the same gap geometry, although in this case the breakdown voltage was considerably lower than that corresponding to the negative voltages.

[5] The results presented in this paper show clearly that in laboratory sparks bursts of X-rays are emitted before the rapid increase in the current and another one during the rapid increase in the current, around the current peak. Let us consider the breakdown mechanism for long gaps. In general, the processes that take place in a long gap before the final breakdown include the negative streamers, negative leader, positive streamers and positive leader [*Les Renardières Group*, 1977, 1981; *Gallimberti et al.*, 2002; *Cooray*, 2003]. The relative contribution of each of these four processes to the final breakdown process depends on the polarity and shape of the applied voltage, gap geometry, and gap length. In the case of rod plane gaps of length of the order of 1 m or more stressed by switching impulses (250/2500 μs) the breakdown process is facilitated by a leader traveling from the high voltage electrode to grounded one. The leader has a streamer system at its tip. The so-called

final jump (attachment process) begins when the streamer system of the leader reaches the grounded electrode. In the case of rod-rod gaps, as the leader propagates towards the grounded rod, a leader of opposite polarity is usually initiated from the latter and the final jump condition is reached when the streamer systems of the two leaders come in contact with each other. In the case of lightning impulses (1.2/50 μs), the breakdown process is controlled solely by the streamer discharges. In the case of rod-plane gaps, the streamers initiated from the high-voltage electrode travel towards the grounded plane and the final jump condition is reached when the streamers make contact with the grounded plane. In the case of lightning impulses, the streamers moving away from the high-voltage electrode could be met by streamers of opposite polarity initiated from the grounded rod. Therefore, the breakdown voltage of a long gap for lightning impulses is approximately equal to the potential gradient of the streamer channels multiplied by the gap length. In the case of switching impulses, the leader channels (whose potential gradient is lower than for streamer channels) partially bridge the gap, and, as a result, the voltage necessary for breakdown is less than that needed in the case of lightning impulses.

[6] In the present experiment, the geometry can be approximated by a rod to rod gap. Since the applied voltage is a lightning impulse, one can rule out the involvement of a leader in the breakdown process. Even if there was a rudimentary leader channel close to the high voltage electrode its length could not be longer than a few centimeters. This is the case because the speed of propagation of laboratory leaders is about 1–5 cm/μs. In the present experiment, the radius of the negative high voltage rod was about 0.5 cm and therefore one can expect the negative streamers to be initiated within a fraction of a microsecond from the application of the voltage impulse. Since the streamers can move with speeds in the range of 2×10^5–10^6 m/s, they have sufficient time to cross the gap in facilitating the breakdown process. There are apparently two possible sources of X-rays in our experiment: developing streamers of either positive or negative polarity and processes associated with the final jump. The first X-ray burst observed in the present experiment takes place when the applied voltage has reached more than 80% of its peak value, so that the streamers had sufficient time to extend over a considerable distance into the gap before the X-ray burst is observed. It is likely that the earlier X-ray signal is associated with the runaway electron breakdown in streamer tips, as suggested by *Moss et al.* [2006], and the later one with the final-jump process. In this respect, it is of interest to study (a) the location of sources of X-ray bursts in the gap using a collimated X-ray detection system and (b) the production of X-rays in gaps stressed by switching impulses.

4. Summary

[7] Production of X-rays by laboratory sparks has been confirmed. It appears that X-rays can be generated both prior and during the main discharge stage, when the gap is bridged and voltage across it collapses. The earlier signal is likely associated with processes involving the runaway electron breakdown in streamer tips and the later signal with the attachment (final jump) process.

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N. A Ahmad, V. Cooray, and M. Rahman, Ångström Laboratory, Division for Electricity and Lightning Research, Department of Engineering Sciences, Uppsala University, Box 534, SE-751 21, Uppsala, Sweden. (mahbubur.rahman@angstrom.uu.se)

J. Nyberg, Department of Physics and Astronomy, Uppsala University, Box 535, SE-751 21 Uppsala, Sweden.

V. A. Rakov, Department of Electrical and Computer Engineering, University of Florida, P.O. Box 116130, Gainesville, FL 32611, USA.

S. Sharma, Atmospheric Physics and Lightning Research Group, Department of Physics, University of Colombo, Colombo 03, Sri Lanka.