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Production of X-rays in Air Gaps Stressed by Switching Impulse Voltages

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***Abstract*— We present for the first time detection of X-rays from laboratory sparks created in air at atmospheric pressure by applying an impulse voltage with slow rise time. It is in full analogy with the detection of X-rays from lightning stepped and dart leaders.**

Keywords-X-rays; Laboratory sparks; Switching impulse; Lightning; Leaders

I. Introduction

Elevated X-ray fluxes in the energy range from 3 to above 110 keV were detected by an instrumented aircraft flying through thunderstorms [1, 2]. 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 [3]. 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 in [4, 5], respectively. Dwyer et al. [6] observed X-ray bursts, with energies up to a few hundred keV, produced by individual steps by natural-lightning stepped leaders.

However, Dwyer et al. [7] first 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 [8]. Later many experiments were conducted [9-17] in laboratory. March and Montanyà [12] reported that HV pulses with rapid rise time tend to produce more X-rays. But so far nobody has addressed the slow rate of rise similar to the lightning leaders. Since X-ray bursts from laboratory sparks were detected only from air gaps stressed by the lightning impulse similar to the return strokes and the mechanism of X-ray generation by laboratory sparks remains still uncertain, a further study of this phenomenon is an order. In this paper, we present results of an independent experiment where an air gap stressed by switching impulse voltage produced X-rays.

II. Experimental Setup

During the approach of a stepped leader a slow rates of voltage rise may occur in structures, systems, or equipment's which are exposed to lightning. These slow rates of rise are simulated in the laboratory and are used in lightning tests by the so-called "switching impulse voltage". The experiments reported here were conducted using a Marx impulse voltage generator (Haefely Test AG, SGSA 1000-50, maximum charging voltage: 1 MV, maximum energy: 50 kJ) where the generator was configured to deliver the switching impulse voltage (250/2500 µs). The experiments were performed over a period of three weeks during Spring 2007 at the High-Voltage Laboratory at Uppsala University, Sweden and the results for experiments using a standard lightning impulse were already published in [11]. For most of the present experiments, the gap length was approximately 35 cm, although other lengths were studied. In addition to measuring x-rays, we recorded the voltage across the gap and the discharge current flowing to the ground electrode. 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 "rogowski coil" (Pearson model 411, maximum peak current 5 kA, risetime 20 ns, bandwidth 20 MHz).

The basic configuration of the experiment is shown in Figures 1 and 2. The X rays were measured by three instruments that were temporarily removed from the Thunderstorm Energetic Radiation Array (TERA) located at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. These instruments have a history of successfully measuring X-ray emission in the electromagnetically noisy environment near both rocket triggered lightning and natural cloud-to-ground lightning [7]. Each instrument contains two detectors: Instruments 1 and 2

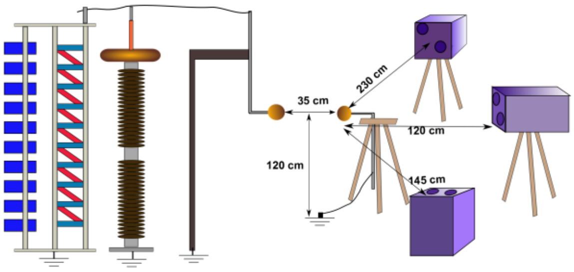

Figure 1. Experimental setup, horizontal gap.

each contain two 7.6 cm x 7.6 cm cylindrical NaI(Tl)/Photomultiplier tube (PMT) detectors. Instrument 3 contains one NaI(Tl)/PMT detector and one plastic scintillator (36 cm x 25 cm x 1 cm), the latter having a faster time response than the NaI scintillators. The NaI detectors were manufactured by Saint Gobain (3M3 series). The NaI scintillators were mounted to the PMTs and placed inside light-tight aluminum housings with m-metal shields. The NaI/PMTs were then mounted on Ortec photomultiplier tube bases (model 296), which contained internal HV supplies and divider chains. In addition, the NaI/PMT detectors, which are designed to be light-tight, were wrapped in black electrical tape and in aluminum tape and were checked for light leaks with a bright strobe light before placing the detectors inside the 0.32-cm-thick aluminum boxes. The plastic scintillator/PMT detector was manufactured by mounting a 5.08-cm-diameter PMT to a light guide attached to the end of the scintillator. The assembly was then made light tight by wrapping it in black plastic.

The aluminum boxes and their lids were both welded on eight seams. The lids slid over the bottom of the boxes like a shoe box with a 15-cm overlap between the top and the bottom. The lids were secured tightly with four strong latches that compressed an RF gasket made of copper braid. The inside of the boxes were painted black to absorb any light that might enter through the gaskets. The instruments were powered by internal 12-V batteries. Opticomm FM, analog fiber optic links were used to transmit the signals from the PMT anodes directly to the data acquisition system located in a separate, shielded room. As a result, the detectors were very well shielded from RF noise and light leaks. The aluminum box lids allowed X rays with energies down to about 30 keV to enter from all directions. Two of the NaI detectors were mounted inside 0.32-cm-thick lead tubes that extended 4.5 cm above the top of the scintillators. The lead also extended 41 cm below the scintillator, completely covering the PMT and the base.

Signals from all six detectors plus a measurement of the electrical current were recorded simultaneously by a Yokogawa 750 ScopeCorder, with 12 bit resolution and a sampling rate of 10 megasamples per second. The scope was usually trigged by the current pulse, and data were recorded for a length of 2 ms with 1 ms of pretrigger sampling. Two channels from Instrument 3 were split off and were recorded along with the current in a Lecroy Wavepro 7100A that sampled at 250 megasamples per second with 8 bit resolution, with a total record length of 1 ms and 0.5 ms of pretrigger sampling. In addition, voltages and current were recorded separately with an 8 ns time resolution.

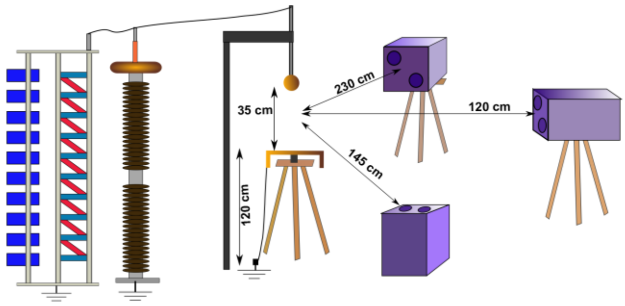

Figure 2. Experimental setup, vertical gap.

III. OBSERVATIONS

Experiments were performed with different configurations. In the first series of measurements a sphere to sphere horizontal air gap of 35 cm length was used. The gap was situated about 120 cm above ground as can be seen in Fig.1. The positions of the detectors are also shown. The charging voltage of negative polarity was set to 800 kV. The breakdown voltage was around 530 kV. About 15 shots were applied. In 11 cases out of these 15 shots X-rays were detected in one or several of the detectors.

For the same electrode configuration as described above and gap length another series of measurements were conducted but with a vertical gap instead. Again about 15 shots were applied and now in 8 cases of 15 X-rays were recorded in one or more detectors. The charging voltage of negative polarity was set to 800 kV. The breakdown voltage was around 528 kV.

Then the electrode configuration was changed to rod-to-plane as can be seen in Fig. 2. In this configuration the gap lengths were 35 and 46 cm. Out of 15 applied shots only in one case X-rays were detected. The charging voltage of negative polarity was set to 800 kV. The breakdown voltage was around 470 and 540 kV respectively.

It seems that X-ray radiation is very much directed from the discharge channel. Moreover, it depends on the electrode shapes and gap configuration. A typical X-ray record is shown in Figure 3 where signals from all 6 detectors are shown together with the voltage and current measurements. A close look reveals that X-rays are appearing as soon as the current at the grounded electrode starts increasing. A corresponding voltage drop is observed on the measured voltage waveform. It indicates that X-rays are created either at the streamer/leader tip almost reached at the opposite electrode or at the meeting point of countering streamer/leader heads a bit away from the opposite electrode.

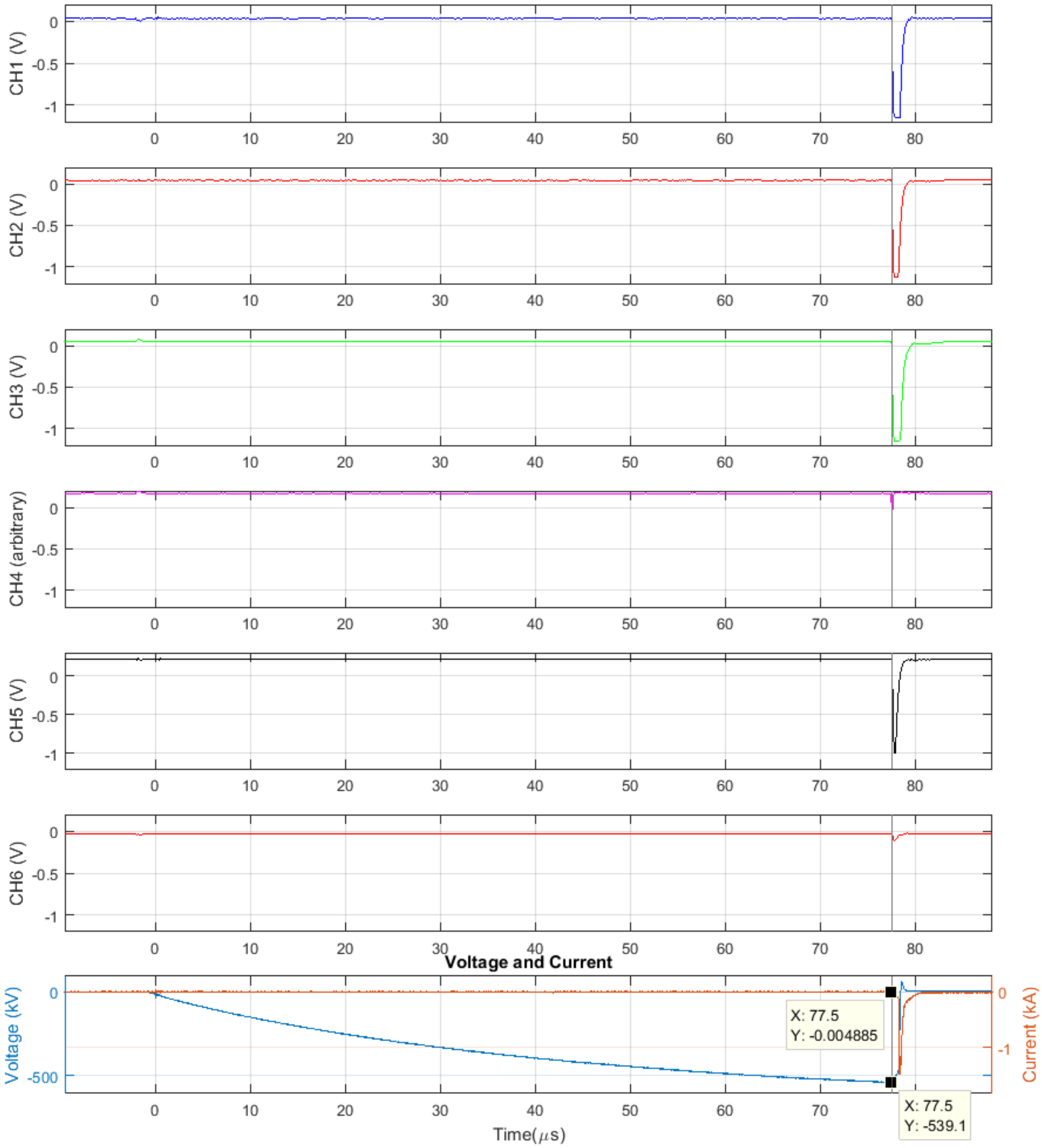

Figure 3. X-rays signals from 6 detectors placed in 3 boxes together with measured voltage and current waveforms.

IV. CONCLUSIONS

This experiment shows that the X-ray radiation seems to be directional and depends on the electrode configuration. X-rays from air gaps stressed by pulses with slow rise time are reported for the first time and X-rays seem to appear before the complete breakdown during the final jump (attachment process).

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