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Generation and Contribution of Runaway Electrons in Long-Gap Discharges in Air
長ギャップ気中放電における逃走電子の発生と役割

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Strong hard x-ray bursts were observed from high-voltage-impulse discharges in air with positive polarity and maximal voltages from 0.5 MV to 0.9 MV just before the air breakdown. From the absorption measurements of x-rays, the maximal energies of runaway electrons are estimated to be close to the applied potentials. We propose that the sources of electron runaway are localized at the negative polarity electrodes even if this electrode is grounded.

1. Introduction

Interest on the effect of electron runaway in the atmosphere has been growing in the last decade mostly due to strong x-rays observed by satellites and ground detectors associated with thunderstorms [1,2]. The observation of hard x-rays and γ-rays in conventional high-voltage discharges in laboratory [3] has also been reported. However, so far, the physics of formation of runaway electrons in air and their acceleration is not clear. The laser filament plasma (LFP) [4], produced by ultrashort laser pulses, can be an excellent tool to investigate discharge physics including the electron runaway, because it can produce space charges instantaneously to control the initiation of atmospheric ionization precisely. Here, we report the effects of electron runaway in high-voltage-impulse discharges in air via detecting of hard x-ray spectra and correlations between x-ray bursts and discharge parameters.

2. Experimental Setup

Brass balls of 250 mm diameter were used as the high-voltage electrode (HVE) and the grounded electrode with a gap length of 0.45 m. Positive impulse voltage, which reached its maximum at ~ 0.6 μs, was applied on HVE. The charging voltage (CV) applied at the impulse generator was set from 650 kV to 950 kV. Ti:sapphire laser pulses with 70 fs duration and 90 mJ energy were focused by a concave mirror of 10 m focal length, placed at the distance of ~10 m from the electrodes. Cylindrical detectors each composed of a NaI (Tl) scintillator (ϕ50 mm × 16 mm) and a photomultiplier tube (PMT) were used for measuring x-rays from sparks. The detectors, installed in an aluminum box, were placed at about 3 m from electrodes perpendicularly to the laser axis, at the almost same height as that of the top surface of the grounded electrode. Images of discharges were taken by a still camera with an ultraviolet lens and a filter.

3. Results and Discussion

Typical waveforms of voltage, current and PMT signal for discharges are shown in Fig. 1. The x-ray bursts, which should originate from the Bremsstrahlung radiation generated by runaway electrons, always occur before the breakdown synchronized with the beginning of the dark current (a small current before breakdown). Since, in this setup, the electric field strength near the grounded electrode is estimated to be smaller than 10 kV/cm, streamers resulting in the dark current can propagate only from the HVE. In this set-up, more than 50% of all discharges were accompanied with x-ray bursts. X-ray bursts were observed starting at almost the same voltage even when CV increases. However, the amplitude of the x-rays considerably changes with CV amplitude. The change in CV from 650 kV to 950 kV resulted in a ~10-fold increase in the energy of the x-rays. We attribute this dependence to the rate of voltage growth.

To evaluate the spectrum of x-rays, we used the absorption technique [3] at CV=750 kV: x-rays were detected with a Pb or Al shield in front of the detector with shield thickness being varied from 0 to 10 mm. The depletion of the signals with the attenuator thickness is shown in Fig. 2. The experimental data are fitted with the calculated results using a Monte Carlo-type code (Geant4). In the calculation, we assumed an x-ray energy distribution ~exp($-\varepsilon_x/\varepsilon_{x0}$) with an exponential shape,

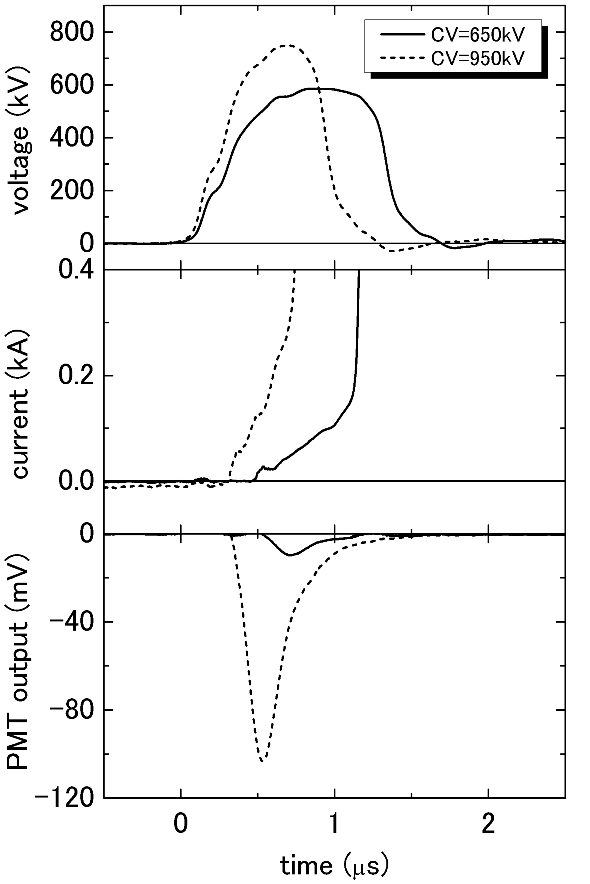

Fig.1. Typical waveforms of voltage, current and PMT signal for discharges at several CV amplitudes.

where ε_x is the x-ray energy and ε_{x0} is a fitting parameter of x-ray energy. The best fitting energy, ε_{x0}, lies in the range of 50-100 keV. On the other hand, we calculated backward x-ray spectra from a massive brass target irradiated by monoenergetic electron beams with different energies. From these results, the electron energy before interaction with the brass is estimated to be approximately 500-700 keV, which is close to the applied potential. These results suggest that the position of the source of runaway electrons should be near the surface of the negatively biased electrode.

LFP, produced by a Ti:sapphire laser pulse in the gap, is a high-conductivity zone with a length of hundreds of mm and a diameter of a few mm. A laser pulse was shot at 0.5 ∓ 0.1 μs before voltage breakdown, which is the time that corresponds to the beginning of an x-ray burst in the case of discharges without the laser irradiation. In the case of CV = 750 kV, the formation of LFP at 5 mm from the HVE stopped the x-ray burst in 100% of the cases. LFP may affect the propagation of avalanches and streamers starting from the HVE [5], which should be important for the generation of runaway electrons.

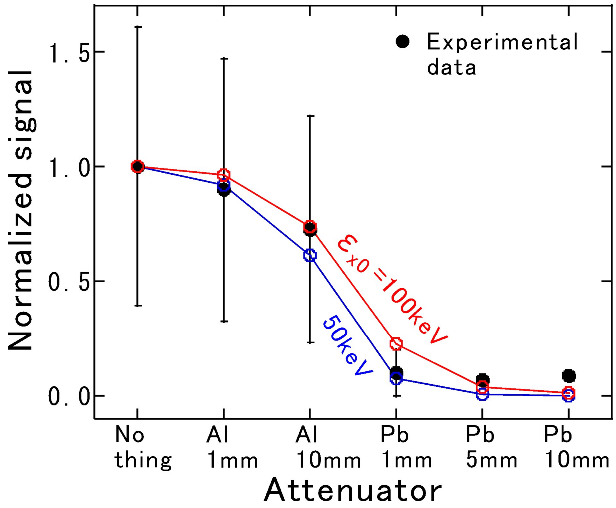

Fig.2. Measured depletion of x-rays after attenuators and calculated curves for several fitting parameters of x-ray energy (ε_{x0}).

From these results, we accept the following scenario for the runaway formation in the case of discharges with positive polarity. A positive streamer propagates from the HVE to the grounded electrode and initiates a weak discharge generating a plasma channel: the small current growth before the x-ray burst is always seen, as shown in Fig. 1. The plasma channel in the vicinity of the grounded electrode is heated, forming a short, pin-shape leader. Such a leader with a considerable number of ~1 keV electrons can be a source of the electron runaway resulting in the x-ray burst from the opposite electrode. When the LFP was ignited, the small dark current decreased, which also supports the above scenario.

4. Conclusions

We have studied the electron runaway process in high-voltage-impulse discharges with positive polarity in air by measurement of the characteristics of x-ray bursts. We have found that sources of electron runaway are localized at the negative polarity electrodes even if this electrode is grounded. These electrons acquire kinetic energies close to the potential difference between the electrodes.

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