Runaway electrons and x-rays from a corona discharge in atmospheric pressure air

Tao Shao$^{1,3,4}$, V F Tarasenko$^{2,4}$, Cheng Zhang$^{1,3}$, D V Rybka$^{2}$, I D Kostyrya$^{2}$, A V Kozyrev$^{2}$, Ping Yan$^{1,3,4}$ and V Yu Kozhevnikov$^{2}$

$^1$ Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China
$^2$ Institute of High Current Electronics of the Siberian Branch of the Russian Academy of Science, Tomsk 634055, Russia
$^3$ Key Laboratory of Power Electronics and Electric Drive, Chinese Academy of Sciences, Beijing 100190, China
E-mail: st@mail.iee.ac.cn, VFT@loi.hcei.tsc.ru and pingyan@mail.iee.ac.cn

New Journal of Physics 13 (2011) 113035 (20pp)
Received 16 June 2011
Published 25 November 2011
Online at http://www.njp.org/
doi:10.1088/1367-2630/13/11/113035

Abstract. The characteristics of a corona discharge in atmospheric pressure air are studied using pulsed power generators that produce voltage pulses of different durations, polarities and shapes. The characteristics are measured in the single pulse, batch, and repetitively pulsed modes. It is shown that no matter what the voltage pulse polarity is, a corona discharge starts developing as a conical diffuse discharge near the electrode tip with a voltage rate of increase of $\sim 10^{15}$ V s$^{-1}$ across an electrode of small curvature radius. With lower voltage rate of increase ($\sim 10^{13}$ V s$^{-1}$ or lower), one or several diffuse jets develop from this electrode. The diameter of the jets at their front is less than 1 mm and depends on many factors (voltage pulse amplitude and increase, inter-electrode gap width, pulse repetition rate, etc). It is found that at long voltage pulse durations, the radiation spectrum of the corona discharge changes, and the bands and lines of the material of the electrode appear in the UV region at 200–300 nm. It is demonstrated that a runaway electron beam in a corona discharge is generated and detected at a distance several times greater than the brightly glowing plasma region of the corona discharge. It is shown that x-rays are generated from a corona discharge at high pulse repetition rates of up to 1 kHz.

4 Authors to whom any correspondence should be addressed.
1. Introduction

In recent years, research on atmospheric discharges has yielded important results (Dwyer et al., 2005, 2009, Pasko 2007, Østgaard et al. 2008, Roussel-Dupré et al. 2008, Gurevich et al. 2009, Hazelton et al. 2009, Milikh and Roussel-Dupré 2010, Raizer et al. 2010, Smith et al. 2010 and references cited therein). It was confirmed that some atmospheric discharges produce x-rays and that the generation of runaway electrons occurs with high-power microwave pulses and high-energy particle flows. It was demonstrated that lightning develops with large contributions from runaway electron avalanches initiated in low electric fields due to high-energy particles from space (Gurevich et al. 2009). However, many questions concerning physical processes in lightning remain unclear.

Laboratory experiments on the breakdown of large gaps in an inhomogeneous electric field allow the simulation of lightning and explanation of some of its mechanisms (Bazelyan and Raizer 2001, Pasko 2007, Dwyer et al. 2008, Nguyen et al. 2008, Rahman et al. 2008, March and Montanyà 2010, Chanrion and Neubert 2010 and references therein). The breakdown of large gaps is largely associated with runaway electrons and x-rays. So, in recent works (Dwyer et al. 2008, Nguyen et al. 2008, Rahman et al. 2008, March and Montanyà 2010), x-rays were detected before the main stage of gap breakdown during the rise time or within the plateau of microsecond pulses, which can be compared with the generation of x-rays in a pulsed corona discharge. The x-rays were detected at both polarities of an electrode of small curvature radius (Dwyer et al. 2008). X-rays were also detected in the repetitive pulsed mode at a pulse repetition frequency of up to 1 kHz (Shao et al. 2011a). In air breakdown, the generation of runaway electrons, as a certain critical electric field is approached, produces x-rays. The possibility of an increase in electron energy and of an electron transition to the runaway mode in atmospheric discharges was predicted by Wilson (1925). X-rays from a corona discharge were detected for the first time by Bosamykin et al. (1980), who reported on the generation of microsecond x-ray pulses in this type of discharge. In these experiments, a needle cathode and a planar anode were used. The voltage pulse amplitude reached 280 kV at a pulse rise time of 100 ns. X-rays were obtained by Kostyrya et al. (2006) in a nanosecond corona discharge. The critical field for a particular gas and pressure depends on the initial electron energy (Gurevich et al. 2001, Yakovlenko 2007). However, until now, the role of x-rays in the development of discharges in large gaps and in lightning remains unclear. More specifically, no data are available on the properties of the electron beam responsible for x-rays.

The objective of the present work is to study the corona discharge in an inhomogeneous electric field, including the conditions for the generation of x-rays and runaway electrons, and...
Table 1. Technical specifications of the generators used in the experiments.

| Parameters                        | Specification |
|-----------------------------------|---------------|
| Generator 1                       | Generator 2   | Generator 3 | Generator 4 |
| Max. output voltage (kV)          | 250           | 300         | 300         | 10          |
| Rise time (ns)                    | 4000 000, 2000| 15          | 0.5         | 200         |
| Pulse width at half peak (ns)     | 10 000 000, 2000| 30–40     | 2           | 1.5         |
| Pulse repetition frequency (kHz)  | 0.05, 289     | 1           | 0.001       | 100         |

Table 1 presents typical technical parameters of the generators used in the experiments.

2. Instrumentation

All experiments were performed for an inhomogeneous electric field in the gap filled with atmospheric pressure air without preionization of the gap from an additional source. Four pulse generators were used in the experiments. The generators were connected to discharge gaps in which one electrode had a small curvature radius and the other grounded electrode was placed at various distances from the high-voltage electrode. The voltage pulse polarity, duration and shape were varied. Thus, the use of different generators and different modes of their operation, along with different inter-electrode gap spacings and cathode designs, allowed us to obtain various forms of discharge: a corona discharge, a diffuse discharge that ends at the opposite electrode and a spark discharge. The initiation of a corona discharge was ensured by increasing the inter-electrode gap spacing, all other things being equal. In this work, greatest attention is paid to the corona discharge whose development resembles the development of a leader in lightning (Bazelyan and Raizer 2001).

Table 1 presents typical technical parameters of the generators used in the experiments.

High-voltage pulse generator 1 was based on a Tesla transformer. The generator produced voltage pulses consisting of individual trains of 10 ms duration that operated at a pulse repetition rate of 50 Hz. Each train was a sinusoidal signal with an oscillation frequency of 289 kHz. The maximum voltage rate of increase across the gap was $\sim 10^{11} \text{ V s}^{-1}$. The high-voltage pulses were applied to a vertically arranged cylindrical Al electrode of diameter 3.6 mm with a pointed tip of 0.3 mm curvature radius. A thin oxide film on the Al electrode on generator 1 did not affect the corona discharge ignition and the discharge current level. With a gap of 40 cm and larger, a corona discharge in atmospheric pressure air was ignited from the pointed tip. With inter-electrode gap spacings smaller than the above value, diffuse jets could bridge the gap and the corona discharge transformed into a low-current spark. The spark current was limited by the generator impedance and was not greater than 10 A. The voltage pulse amplitude and signal...
shape in the primary and secondary circuits of the high-voltage pulse transformer were measured using resistive voltage dividers. Figure 1 shows voltage pulses in the secondary circuit of the pulse transformer during the formation of a corona discharge and a central portion of a pulse train. It was observed that the voltage across the corona-forming electrode reversed polarity within about 2 µs. The maximum difference between the positive and negative voltage peaks in the train reached 250 kV.

Pulse generator 2 was a solid-state generator of repetitive nanosecond pulses (Zhang et al 2010, Shao et al 2011a, 2011c). The generator’s repetition rate was adjustable from single shot operation to 1 kHz and could be controlled by a trigger modulator. The output voltage pulse can be up to 300 kV with a rise time of 15 ns and a full-width at half-maximum (FWHM) of 30–40 ns. The maximum voltage rate of rise time across the gap was ∼$10^{13}$ V s$^{-1}$. Two cathodes were used on generator 2. One was a Cu tip of 15 mm with a curvature radius of 0.5 mm, and the other cathode was a cylinder with a diameter of 12 mm. The cylinder is made of Cu foil of 1 mm thickness. The electrodes were arranged parallel to the ground surface. The grounded anode was a Cu metal plate of 80 mm diameter. The discharge gap was variable between 3 and 20 cm.

The design of a generator 3 is shown in figure 2. Voltage pulses to the discharge gap were applied from an ARINA x-ray unit (Mesyats 2004). The generator produced voltage pulses of amplitude up to 300 kV. With a matched load, the FWHM of the voltage pulse was 2 ns and the voltage pulse rise time was about 0.5 ns. The maximum voltage rate of increase across the gap was ∼$10^{15}$ V s$^{-1}$. An insulator 2, with 16 cm outer diameter, was located at the generator output. Because of this, no complete surface breakdown along the insulator was observed even with an 8 cm gap between the cathode placed at the insulator output and the anode. Cylindrical chamber 3 was connected to the generator and was a coaxial air transmission line of impedance 190 Ω. The line had inner conductor 4, which ended in a tubular cathode 5, and the outer diameter of the

Figure 1. Waveforms of the voltage at the output of generator 1 for different oscilloscope sweeps: 20 ms div$^{-1}$ (1), 2 µs div$^{-1}$ (2) and 4 ms div$^{-1}$ (3). The vertical scale is 156 kV div$^{-1}$.
inner conductor 4 was 7 mm. The cathode was a brass tube with a wall thickness of 0.3 mm and an outer diameter of 7 mm. The inter-electrode gap spacing could be varied from 10 to 80 mm. The design of the discharge chamber made it possible to initiate a corona discharge between the inner and outer cylinders of the coaxial line. A diffuse discharge between electrodes 5 and 7 and a decrease in voltage oscillation in the coaxial line led to a corona discharge. The outer cylinder of the line was made of Cu foil of 200 $\mu$m thickness and 160 mm inner diameter. The length of the line from the insulator to the opposite face was 30 cm. The line was terminated by a flat Cu plate 6. The center of the Cu plate was a hole of 40 mm diameter covered with AlBe foil of 50 $\mu$m thickness, which was the anode 7. This allowed us to use a collector 8 to measure the electron beam from the discharge between the edge of the cathode 5 and the AlBe foil anode 7. The cylindrical side wall of the chamber (line) had the window 9 of 25 cm length and 5 cm width covered either with Al foil of 15 $\mu$m thickness or with Cu foil of 200 $\mu$m thickness. The beam current downstream of the rectangular window covered with Al foil was measured using a collector 10. The x-rays were measured using a dosimeter 11.

A high-voltage pulse generator 4 produced two negative and two positive voltage pulses in the repetitively pulsed mode. The polarity of the 'double' pulses following one another with a 2 $\mu$s delay reversed every 5 $\mu$s. The duration of an individual pulse of each polarity was 1.5 $\mu$s and its amplitude was 10 kV. The voltage pulse rise time and decay time were 200 ns, and the maximum voltage rate of increase across the gap was $\sim 0.5 \times 10^{11}$ V s$^{-1}$. The pulse repetition rate of the double pulses was 100 kHz. The pulses were applied in batches of 10 ms duration with a time interval of 1 and 10 ms between batches. The cathode was a needle of 0.5 mm diameter arranged in the vertical direction. The planar anode was placed 30 mm away from the cathode.

The voltage pulses were measured using resistive voltage dividers and the discharge current was measured using current shunts. The runaway electron beam current was measured using collectors that had a receiving region of diameter between 20 and 5 mm. The time resolution of the collectors was not worse than 100 ps (Tarasenko et al 2008a, Tarasenko 2011). The time dependence of the voltage, discharge current beam current, and x-rays from the gap...
was recorded using a TDS-3034 oscilloscope (0.3 GHz, 2.5 GS s\(^{-1}\)) on generators 1 and 4, a DPO70604 oscilloscope (6 GHz, 25 GS s\(^{-1}\)) on generator 3 and a WR204Xi LeCroy oscilloscope (2 GHz, 10 GS s\(^{-1}\)) on generator 2. The discharge radiation spectrum was recorded using an EPP2000-C25 StellarNet spectrometer and a HR4000 Ocean Optics spectrometer with known spectral sensitivities in relative units. The x-rays from the gap on generator 2 were detected using a joint system including a photomultiplier tube (PMT) with a NaI scintillator and a multi-channel analyzer. The measurement procedure is described by Zhang et al. (2010). The x-rays from the gap on generator 3 were measured using an Arrow-Tech dosimeter (Model 138). Images of the integrated pattern of the discharge glow were obtained through the grid (anode) or the window (perpendicular to the longitudinal gap axis) using Sony A100 and Canon 500D cameras.

3. Observations

All four generators allowed us to obtain a corona discharge, a diffuse discharge in the form of a cone or individual jets bridging the gap and a spark by varying the inter-electrode gap spacing. The discharge form on each generator depended on the pulse repetition rate, the number of pulses in a batch and cathode design. Note that early in each voltage pulse, a spark discharge started developing as a corona discharge and transformed into a diffuse discharge. After this, the discharge was constricted. In the single pulse mode and with low pulse repetition rates, the stage of the corona discharge was normally longer than that in the repetitively pulsed mode. In the repetitively pulsed mode, the transition to a spark could occur within the first pulse applied to the gap (with small gap spacings) as well as within several successive pulses. Below is a description of the characteristics of a pulsed corona discharge whose development reflects the development of lightning.

Images of different discharge modes are shown in figures 3, 4, 6–8, 10 and 13 and are discussed in the subsequent sections. A brief comparison of the main measurements on various generators is presented in table 2. During this testing, we investigated the effect of parameters of the generator voltage pulse on the shape and optical radiation spectrum of a corona discharge, and studied the generation of runaway electron beams and x-rays. The data on the generation of runaway electron beams and x-rays in diffuse discharges bridging the gap are reported in Kostyrya et al. (2006, 2010), Tarasenko et al. (2008a, 2008b, 2010, 2011) and Lomaev.
Table 2. Comparison of the experimental measurements and results.

| Parameters                     | Specification                                      |
|--------------------------------|----------------------------------------------------|
| Discharge characteristic       | Generator 1: Corona with long plasma filaments     |
|                                | Generator 2: Corona                                 |
|                                | Generator 3: Corona and diffuse discharge           |
|                                | Generator 4: Corona                                 |
| X-ray measurement              | No                                                 |
| Runaway electron measurement   | No                                                 |
| Spectra of light emission      | The N2+ system and bands of material of the electrode |
|                                | The N2+ system                                      |
|                                | The N2+ system                                      |

et al (2009). The amplitudes of the runaway electron beam current and x-ray doses achieved during this testing are the highest among those that we have managed to attain so far in discharges in atmospheric pressure air.

On generator 1 with inter-electrode gap spacings greater than 40 cm, a corona discharge was formed, and integrated images of the discharge glow in 1 pulse and in 50 pulses are presented in figure 3. Generator 1 produced pulse trains of 10 ms duration with a pulse repetition rate of 50 Hz. Each train was a sinusoidal signal of both polarities with an oscillation frequency of 289 kHz. As a pulse (a train) is applied to the gap, one or several diffuse filaments (plasma jets) of up to 40 cm in length are formed. The color of the diffuse filament differs along its length during the formation and decay stages. As the voltage is increased, the diffuse filament shows a violet glow at its beginning and end remote from the electrode. A thin diffuse filament consisting of jets running from its center is observed rather than the white diffuse filament shown in figure 3(a). The diameter of the plasma jets at their front is less than 1 mm. In the near-electrode region, the diffuse filaments gradually turn white as their lengths increase. As the voltage across the gap drops, the filaments become smeared and turn white along their entire length. The highest radiation brightness is observed at the electrode, due to the increase in discharge current density near the electrode and to the dynamics in the cathode.

Figure 4 shows the dynamics of the formation and decay of the corona discharge. A fast camera (HiSpec 1, Fastec Imaging Company, USA) was used to capture the discharge images. The duration for each frame was 1 ms, and the time interval between adjacent shots was 2 ms. The images were taken from one voltage pulse. As the voltage across the gap increases, the corona discharge plasma diffuses and glows predominantly in the violet portion of the spectrum, and the lengths of the jets (filaments) increase (figures 4(a) and (b)). The violet color of the diffuse filament was recorded using a Sony A100 camera (figure 3(b)). The voltage amplitude at this point is understood as the difference in amplitude between positive and negative peaks of the sinusoid voltage pulse (figure 1, oscilloscope trace 2). As the voltage pulse amplitude is decreased, the filament gradually turns white and starts bending (figure 3(a)) and its length decreases (figures 4(c)–(e)).

Spectral analysis of the plasma radiation on generator 1 shows that most of the radiation at 200–600 nm is attributed to the N2+ system of nitrogen, and a wide continuum with a maximum
Figure 4. Dynamics of the glow of the corona discharge in a single pulse. Each frame was taken in 1 ms; the frames delay (a–e) is 2 ms. The delay time between the onset of the glow near the pointed electrode and the onset of the glow on frame (a) is 2 ms too. An image of the gap with a ruler in centimeters is shown in (f). Generator 1. Camera: Fastec-HiSpec 1 (a–e) and Sony A100 (f).

Intensity of 200–300 nm, which are much narrower bands (figures 5(a) and (b)—black curve). Also figure 5(b) shows the vertical lines that correspond to the position of the N2+ (green lines), N4+ (red lines) and the Lyman–Birge–Hopfield (LBH; blue lines) bands of nitrogen. It is found that a broad continuum of 200–300 nm can be attributed only to the N2+ system. A reference book (Pears and Gaydon 1941) is used for the identification of the molecular spectra. It is found that the bands and lines in the near electrode area are determined by the electrode material. Note that the bright glow in the visible spectral range (white radiation) on spectrograms has low intensity and is referred to as the continuum radiation. The appearance of bands and lines of electrode material with a large intensity is due to the long pulse duration of generator 1. With shorter pulses on the other three generators, N4+ bands and LBH bands in a diffuse corona discharge escaped detection. An attempt to detect x-rays from the corona discharge with a scintillator and a PMT on generator 1 failed. The data on the scintillator and PMT are given by Shao et al (2011b). During the experiments, the scintillator was placed 50 cm away from the corona-forming electrode and was wrapped with black paper with 100 µm thickness. Upstream of the scintillator a brass grid was placed to decrease electromagnetic noise. Note that this x-ray measuring system displayed high sensitivity. The oscilloscope constantly detected pulses from the PMT due to the luminescence of the scintillator under cosmic rays. The frequency and pauses between the detected pulses changed over time. Moreover, the joint system, consisting of the scintillator and PMT, detected x-ray pulses from the discharge in atmospheric pressure air on the nanosecond generator with a voltage pulse amplitude of 12.5 kV in the incident wave (Shao et al 2011b).
Figure 5. Radiation spectra of the corona discharge on generator 1 (a, b) and generator 4 (c). Spectra in (a, c) were measured by EPP 2000-C StellarNet spectrometer; Black spectra in (b) were measured by HR 4000 Ocean Optics spectrometer. Positions of LBH bands (blue lines), N4+ bands (red lines) and the beginning of N2+ bands (green lines) are shown in (b).

On generator 2 with point and tubular cathodes, a corona discharge was ignited across a wide range of experimental conditions (figure 6). The size of the glowing plasma region depends on the distance to the anode, voltage pulse amplitude and pulse repetition rate (figure 7). As is known, the corona size decreases with increasing distance to the anode and increases with greater voltage amplitude and pulse repetition rate. The considerable decrease in voltage pulse duration to about 100 ns (pulse base) on generator 2 compared to 10 ms (pulse base) on generator 1 changed the color of the corona discharge and its spectrum. The plasma radiation was violet with the more intense bands belonging to the N2+ system (Lomaev et al 2009, Shao et al 2011b).

The development of the corona discharge on generator 2 is illustrated in figure 8. The figure shows images of the discharge in the first 1, 5, 10 and 50 pulses at a pulse repetition frequency of 1 kHz. In the first single pulse, the size of the glowing plasma region fixed by the camera is small (not larger than 1 cm). The superposition of several pulses increases the glow intensity and the size of the emitting region. The plasma jet diameter depends on the number of pulses. In the first pulses, the plasma jet diameter is normally less than 1 mm. However, in the repetitively pulsed mode the lateral dimensions of the jets increase and overlap. At a pulse repetition rate of 1 kHz with a large number of pulses (1000 or higher) and an 8 cm gap spacing in the steady-state mode, the plasma can reach the anode and the corona discharge transforms into a diffuse discharge. The discharge current thus increases and the plasma glow is detected across the entire gap.

New Journal of Physics 13 (2011) 113035 (http://www.njp.org/)
Figure 6. Corona discharge images (applied voltage: $-120$ kV; gap: 18 cm). Upper images: the point–plane gap; lower images: the tube-plane gap; (a) and (c) are superimposed 50 pulses; (b) and (d) are superimposed 5 pulses. Generator 2. Camera: Canon 500D.

As in Shao et al. (2011c), the study of x-rays from the corona discharge on generator 2 using the scintillator and PMT made it possible to detect x-rays from the anode. The x-ray intensity decreased as the inter-electrode gap spacing increased (figure 9(a)), and was dependent on the anode material (see figure 3(b) in Shao et al. (2011c)). Oscilloscope traces of the discharge current and voltage for the conditions in figure 9(a) are shown in figure 9(b). It is seen that the amplitude of the corona discharge current under these conditions is less than 20 A and decreases with increasing inter-electrode gap spacing. Under these conditions, the voltage pulse is almost unchanged under variation of the inter-electrode gap spacing.

On generator 3 with inter-electrode gap spacings of 10–70 mm, a diffuse discharge is formed between the cathode and the wall of the chamber (a brightly glowing region on the left of figure 10, which was taken through the side window). The radiation intensity of the diffuse discharge between the cathode 5 and the foil anode 7 increased with decreasing the inter-electrode gap spacing (figure 2), and the volume occupied by the dense discharge plasma decreased. Figure 10 also shows short diffuse jets in the form of cones from the inner conductor of the coaxial line. The lengths of the jets increase with increasing gap spacing. The diameter of the inner conductor of the line was 7 mm, as before. With a gap spacing of 50–60 mm, the resistance of the discharge plasma was close to the resistance of the coaxial line. As a result, the voltage pulse energy from the ARINA generator was absorbed mainly by the plasma of the diffuse discharge. The rise time of the discharge current pulse was not longer than 0.5 ns, and its amplitude in the first nanosecond was about 3.5 kA (figure 11(a)). This made it possible to determine the voltage amplitude of the incident wave. The voltage across the inner conductor of the coaxial line at the inter-electrode gap of 50 mm was 300 kV. The corona discharge consisted

New Journal of Physics 13 (2011) 113035 (http://www.njp.org/)
Figure 7. Corona discharge images under different gaps (applied voltage: $-120$ kV, 1 kHz). The discharge length from 10–20 cm gaps is 6.5 cm (10 cm), 5 cm (12 cm), 4 cm (14 cm), 2.5 cm (16 cm), 2 cm (18 cm) and 2 cm (20 cm). Generator 2. Camera: Canon 500D.

of diffuse jets that were rather uniformly distributed over the conductor 4. The length of the diffuse jets was less than 45 mm and decreased with decreasing inter-electrode gap spacing. In addition to the diffuse jets, a weak gas glow was observed throughout the entire volume of the coaxial line. Note that the diffuse jets in the corona discharge were similar in appearance for different generators (see figures 6–8, 10 and 13), except for their shape and size. With a large voltage rate of rise time across the electrode of a small curvature radius of about $10^{15}$ V s$^{-1}$, the
diffuse jets were conical with a spherical head. With a relatively low increase of the voltage of about $10^{11}$ V s$^{-1}$, the diffuse jets were nearly cylindrical.

The highest amplitude of the runaway electron beam current on the collector with a receiving part of 20 mm diameter was detected through the window at the chamber face with an inter-electrode gap spacing of 20–30 mm. The beam current density was above 0.5 A cm$^{-2}$. As already noted, with these gap lengths a ‘dense’ diffuse discharge was formed in the gap. This mode corresponds to the generation of a supershort avalanche electron beam (SAEB) and is described in Tarasenko et al (2008, 2008b, 2010), Kostyrya et al (2010), Tarasenko (2011). An oscilloscope trace of the beam current is shown in figure 11(b).

The measurements also show that the runaway electron beam is detected not only from the face of the discharge chamber, but also downstream of the window on the side wall of the coaxial line. The beam current pulse from the corona discharge is shown in figure 11(c). The electron energy in the beam was above 50 keV, and this allowed detection of the electron beam downstream of two Al foils, each 15 µm thick. The beam current density from the corona discharge was two orders of magnitude lower than that in the SAEB mode downstream of the window at the face of the discharge chamber. The beam current amplitude from the corona discharge measured through the side window with the use of the displaced collector 10 is shown in figure 12. With a 50 mm inter-electrode gap, the maximum amplitude of the beam current detected from the corona discharge was seen 10 cm away from the chamber face.

A previous study (Tarasenko et al 2008b) demonstrated that in a diffuse discharge with small distance to the side wall of a gas diode, an electron beam was generated at an angle larger than $2\pi$. In these experiments, the beam current was measured at large distances from the diffuse discharge. Therefore, the oscilloscope trace in figure 11(c) was obtained 18 cm away from the chamber face.
Figure 9. (a) X-ray counts versus gap; (b) the applied voltage and current of the corona discharge of the tube–plane gap spacing. Generator 2.

Figure 10. Image of the discharge glow taken through the side window with five superimposed pulses. The image width is 35 cm. Generator 3. Camera: Sony A100.
Figure 11. Waveform of the discharge current in the short-circuit mode (a), electron beam current from collector 8 in figure 2 downstream of the window at the chamber face (b) and electron beam current from collector 10 downstream of the side window (c) for a 50 mm gap spacing and a generator voltage of \(\sim 300\) kV. The diameter of the collector receiving part is 20 mm. Generator 3.
was detected at a large distance from the bright glow of the corona discharge. Moreover, it was found that the FWHM of the beam current pulse from the corona discharge was small (not more than 100 ps when measured by the collector with a receiving area of 20 mm diameter). During the generation of an SAEB in diffuse discharges, the beam current pulse duration is limited by the dense plasma front that bridges the gap moving from the cathode of a small curvature radius (Tarasenko 2011 and references cited therein). In the corona discharge, the dense plasma front had no time to reach the anode during the generation of the runaway electron beam. Hence, while there exists a mechanism for the initiation of a short current pulse of the runaway electron beam in the near-cathode region, the mechanism remains unclear. The mechanism will be studied in our future work.

The intensity and energy of x-ray quanta from the gas diode depended on the form of the discharge and on the position of the dosimeter. The greatest intensity of x-rays was detected during the generation of an SAEB. With a 30 mm inter-electrode gap spacing where the dosimeter was placed at the face of the discharge chamber, the x-ray dose downstream of the Cu foil of 20 µm thickness was 0.1 m Rad in a pulse. With an optimum gas diode design and a generator similar to the Arina generator with a tubular cathode of 6 mm diameter, the x-ray dose was 0.6 m Rad (Tarasenko et al 2010). In the measurements of x-rays from the corona discharge, the x-ray dose as well as the beam current density decreased by several orders of magnitude. As observed, the most intense optical bands from the plasma of the diffuse and corona discharges belonged to the N2+ system (Lomaev et al 2009, Shao et al 2011b).

Using generator 4, a corona discharge was also formed. The decrease in gap voltage and operation in the batch mode at a 10 ms interval made it possible to detect a corona discharge in the form of a single diffuse jet with a diameter not greater than 0.2 mm in the repetitively pulsed mode (figure 13(a)). As the interval between the pulse batches decreased, a second diffuse jet
Figure 13. Images taken of the corona discharge in atmospheric pressure air on generator 4. The interval between the pulse batches is 10 (a) and 1 ms (b). The duration of the batch is about 10 ms and the amplitude of pulses in the batch is 10 kV. Camera: Sony A100.

appeared and the diameter of both jets increased (figure 13(b)). The radiation spectra of the corona discharge were dominated by the N2+ bands under these conditions (figure 5(c)).

4. Discussion

The chief problem in determining the mechanism by which lightning develops is associated with the propagation of a leader in a breakdown of large gaps. It is also necessary to explain why the leader propagates in a jump-like manner when it is negative and moves gradually when it is positive (Bazelyan and Raizer 2001). We believe that this is attributed to the energy of runaway electrons and to the mode of their generation. This paper presented the results of a study of the corona discharge, and we assume that the conditions for the formation of the corona discharge can be similar to those for the propagation of a leader in a breakdown of large gaps. Therefore, the experimental result on the corona discharge presented in this paper will be useful in understanding the physical mechanisms of leader discharge and the resultant radiation of runaway electrons and x-rays on large-gap discharges in inhomogeneous electric fields. Generally, the rise time of lightning pulses observed in nature is about a microsecond or sub-microsecond. It is known that the head of a leader discharge during lightning has a very high electric field, and some studies suggest that the resultant radiation of runaway electrons and x-rays dominates the development of the leader discharge. According to data on lightning and simulated experiments (Gurevich and Zybin 2001, Nguyen et al 2008, Dwyer et al 2008, Tardiveau et al 2009), direct measurement of runaway electrons is difficult and x-rays can be detected as evidence of runaway electrons. A simulation result shows that the critical electric field for electron runaway is rather high in a gap with a homogeneous electric field, and the reduced electric field can be 10 kV cm$^{-1}$ torr$^{-1}$ in atmospheric-pressure nitrogen (Tarasenko and Yakovlenko 2004). Other data on laboratory discharges also show that the critical reduced electric field for producing runaway electrons in air or nitrogen is 350–590 V cm$^{-1}$ torr$^{-1}$.
Regardless of the difference of the critical electric field for producing runaway electrons, it can be found that runaway electrons are produced in a high electric field that can be generally obtained by fast-rise-time pulses in laboratory discharges. In our case of point-to-plane electrode geometry, although the mean electric field is not high, electric field amplification is characterized by micro- and macro-irregularities of the electrode of small curvature radius (Mesyats (2006), Tarasenko et al (2008a), Shao et al (2011a)). Therefore, the partial electric field near the point electrode is still very high and provides possible conditions for runaway electrons. In laboratory experiments we need to use very fast pulse voltage to generate high partial electric fields. As shown in tables 1 and 2, the use of different generators and different modes of their operation along with different inter-electrode gap spacings and cathode designs allowed us to measure characteristic parameters and obtain various types of discharges. The rise times of the output voltage pulses from the generators used ranges from 4 ms to 0.5 ns. These provide a convenient condition to study the corona discharge for understanding large-gap leader discharges and lightning.

In a corona discharge with negative polarity of the electrode of a small curvature radius, we detected short pulses of the runaway electron beam. Relatively short x-ray pulses were also detected in a breakdown of large gaps in Dwyer et al (2008), Nguyen et al (2008), Rahman et al (2008), March and Montanyà (2010). We suppose that as the leader propagates, an excess negative charge is periodically accumulated in its head and the electric field strength increases. Once a critical field is approached, a short runaway electron beam is generated that leads to the preionization of air ahead of the leader and to its jump-like behavior. The electric field strength in the region of the leader head thus decreases and the motion of the leader slows down. This cycle is periodically repeated. With this mechanism of the generation of runaway electrons, their energy can be comparatively high. X-ray pulses from the gap were detected in Dwyer et al (2008), Nguyen et al (2008), Rahman et al (2008) and March and Montanyà (2010) and in our experiments on generators 2 and 3. Moreover, pulses of a runaway electron beam current were detected in experiments using generator 3.

With positive polarity of the electrode of small curvature radius, an excess positive charge is present in the leader head and the electrons near the leader head turn to the runaway mode. On their deceleration, x-ray quanta are generated. However, the energies of x-ray quanta and runaway electrons with positive polarity of the electrode or the leader (as follows from Kostyrya et al 2006, Tarasenko et al 2008a) are lower than those found with negative polarity. This ensures a more uniform (in time) preionization of the gas by x-rays and gradual propagation of the leader.

In experiments, x-rays from a corona discharge were detected only using generators 2 and 3. Evidence of x-rays in experiments on generators 1 and 4 can be the diffuse form of a corona discharge with violet color and the spectrum of the N2+ system. Note that during the voltage pulse rise time on generator 1, the corona discharge also consists of diffuse violet jets (figure 3(c)). Only diffuse violet jets are observed on generator 4 (figure 13).

The formation of diffuse discharges at increased pressures requires preionization of the gap. When the gap is broken down by diffuse jets, preionization ahead of the jet front is also required (Yakovlenko 2007). The experiments suggest that a decrease in voltage pulse amplitude or an increase in voltage pulse rise time and duration do not affect the diffuse form of a corona discharge and the spectrum of optical radiation from the discharge across a wide range of experimental conditions. Using these data as the foundation, we assume that generators 1 and 4
produce runaway electrons with smaller energy and ensure, together with x-rays, preionization near the electrode of small curvature radius and at the front of the diffuse jets.

5. Conclusion

The studies described in this paper demonstrate that runaway electrons and x-rays play an important role in the development of a corona discharge in atmospheric pressure air. In the corona discharge, runaway electrons were detected away from the bright glow of the discharge plasma. It is shown that the FWHM of the pulse of the runaway electron beam for a short rise time and quasi-constant gap voltage is not longer than 100 ps. Based on the data obtained, it can be assumed that a major contributor to the propagation of the leader after its formation are runaway electrons and x-rays produced due to the processes occurring in the leader itself.

Acknowledgments

The work on generators 1, 3 and 4 was supported in part by Russian State Contract No. 02.740.11.0562. The work on generator 2 was supported by the National Natural Science Foundation of China under contracts 11076026 and 50707032 and the Opening Project of State Key Laboratory of Polymer Materials Engineering in Sichuan University under contract no. KF201103.

References

Bazelyan E M and Raizer Yu P 2001 Lightning Physics and Lightning Protection (Moscow: Fizmatlit Fismat) (in Russian) p 320
Bosamykin V S, Karelin V I, Pavlovskii A I and Repin P B 1980 X-rays microsecond duration phase forming spark channels Sov. Tech. Phys. Lett. 6 3383–85
Chanrion O and Neubert T 2010 Production of runaway electrons by negative streamer discharges J. Geophys. Res. 115 A00E32
Dwyer J R et al 2005 X-ray bursts associated with leader steps in cloud-to-ground lightning Geophys. Res. Lett. 32 L01803
Dwyer J R, Saleh Z, Rassoul H K, Concha D, Rahman M, Cooray V, Jerauld J, Uman M A and Rakov V A 2008 A study of X-ray emission from laboratory sparks in air at atmospheric pressure J. Geophys. Res. 113 D23207
Dwyer J R, Uman M A and Rassul H K 2009 Remote measurements of thundercloud electrostatic fields J. Geophys. Res. 114 D09208
Gurevich A V and Zybin K P 2001 Runaway breakdown and electric discharges in thunderstorms Phys.—Usp. 44 1119–40
Gurevich A V, Karashtin A N, Ryabov V A, Chubenko A P and Shchepetov S V 2009 Effect of cosmic rays and runaway breakdown on lightning discharges Phys.—Usp. 52 735–45
Hazelton B J, Greifenstette B W, Smith D M, Dwyer J R, Shao X M, Cummer S A, Chronis T, Lay E H and Holzworth R H 2009 Spectral dependence of terrestrial gamma-ray flashes on source distance Geophys. Res. Lett. 36 L01108
Korolev Y D and Mesyats G A 1991 Physics of Pulse Breakdown in Gases (Moscow: Nauka) p 224
Kostyrya I D, Tarasenko V F, Tkachev A N and Yakovenko S I 2006 X-ray radiation due to nanosecond volume discharges in air at atmospheric pressure Tech. Phys. 51 356–61
Kostyrya I D, Bakht E Kh and Tarasenko V F 2010 An efficient cathode for generating an supershort avalanche electron beams in air at atmospheric pressure Instrum. Exp. Tech. 53 545–8

New Journal of Physics 13 (2011) 113035 (http://www.njp.org/)
Lomaev M I, Rybka D V, Corokin D A, Tarasenko V F and Krivonogova K Yu 2009 Radiative characteristics of nitrogen upon excitation by volume discharge initiated by runaway electron beam Opt. Spectrosc. 107 33–40

March V and Montanyà J 2010 Influence of the voltage-time derivative in X-ray emission from laboratory sparks Geophys. Res. Lett. 37 L19801

Mesyats G A 2004 Pulsed Power (Moscow: Nauka) p 704

Mesyats G A 2006 Similarity laws for pulsed gas discharges Phys.—Usp. 49 1045–65

Milikh G and Roussel-Dupré R 2010 Runaway breakdown and electrical discharges in thunderstorms J. Geophys. Res. 115 A00E60

Nguyen C V, van Deursen A P J and Elbert U M 2008 Multiple x-ray bursts from long discharges in air J. Phys. D: Appl. Phys. 41 234012

Østgaard N, Gjesteland T, Stadsnes J, Connell P H and Carlson B 2008 Production altitude and time delays of the terrestrial gamma flashes: revisiting the Burst and Transient Source Experiment spectra J. Geophys. Res. 113 A02307

Pai D Z, Lacoste D A and Laux C O 2010 Nanosecond repetitively pulsed discharges in air at atmospheric pressure—the spark regime Plasma Sources Sci. Technol. 19 065015

Pasko V 2007 Red sprite discharges in the atmosphere at high altitude: the molecular physics and the similarity with laboratory discharges Plasma Sources Sci. Technol. 16 S13

Pears R W B and Gaydon A G 1941 The Identification of Molecular Spectra (London: Chapman and Hall) p 240

Rahman M, Cooray V, Ahmad N A, Nyberg J, Rakov V A and Sharma S 2008 X-rays from 80-cm long sparks in air Geophys. Res. Lett. 35 L06805

Raizer Yu P, Milikh G M and Shneider M N 2010 Streamer and leader-like processes in the upper atmosphere: models of red sprites and blue jets J. Geophys. Res. 115 A00E42

Roussel-Dupré R, Colman J J, Symbalisty E, Sentman D and Pasko V P 2008 Physical processes related to discharges in planetary atmospheres Space Sci. Rev. 137 51–82

Shao T, Zhang C, Niu Z, Yan P, Tarasenko V F, Bakht E Kh, Burachenko A G and Shut’ko Y V 2011a Diffuse discharge, runaway electron, and x-ray in atmospheric pressure air in an inhomogeneous electrical field in repetitive pulsed modes Appl. Phys. Lett. 98 021503

Shao T, Zhang C, Niu Z, Yan P, Tarasenko V, Bakht E Kh, Kostyrya Igor D and Shut’ko Yu V 2011b Runaway electron preionized diffuse discharges in atmospheric pressure air with a point-to-plane gap in repetitive pulsed mode J. Appl. Phys. 109 083306

Shao T, Tarasenko V F, Zhang C, Kostyrya I D, Jiang H, Xu R, Rybka D V and Yan P 2011c Generation of runaway electrons and x-rays in repetitive nanosecond pulse corona discharge in atmospheric pressure air Appl. Phys. Express 4 066001

Smith D M, Hazleton B J, Grefenstette B W, Dwyer J R, Holzworth R H and Lay E H 2010 Terrestrial gamma ray flashes correlated to storm phase and tropopause height J. Geophys. Res. 115 A00E49

Tarasenko V F and Yakovlenko S I 2004 The electron runaway mechanism in dense gases and the production of high-power subnanosecond electron beams Phys.—Usp. 47 887–905

Tarasenko V F, Bakht E H, Burachenko A G, Kostyrya I D, Lomaev M I and Rybka D V 2008a Generation of supershort avalanche electron beams and formation of diffuse discharges in different gases at high pressure Plasma Devices Oper. 16 267–98

Tarasenko V F, Bakht E H, Burachenko A G, Kostyrya I D, Lomaev M I and Rybka D V 2008b Supershort avalanche electron beam generation in gases Laser Part. Beams 26 605–17

Tarasenko V F, Bakht E Kh, Burachenko A G, Kostyrya I D, Lomaev M I and Rybka D V 2010 Supershort avalanche electron beams and x-rays in atmospheric-pressure air IEEE Trans. Plasma Sci. 38 741–50

Tarasenko V F 2011 Parameters of a supershort avalanche electron beam generated in atmospheric-pressure air Plasma Phys. Rep. 37 409–21
Tardiveau P, Moreau N, Bentaleb S, Postel C and Pasquiers S 2009 Diffuse mode and diffuse-to-filamentary
transition in a high pressure nanosecond scale corona discharge under high voltage J. Phys. D: Appl. Phys. 42 175202

Wilson C T R 1925 The acceleration of b-particles in strong electric fields such as those of thunderclouds Proc. Cambridge Phil. Soc. 22 534–8

Yakovlenko S I 2007 Beams of runaway electrons and discharges in dense gases, based on a wave of multiplication of background electrons Proc. Prokhorov General Inst. vol 63 (Moscow: Nauka) (in Russian) p 186

Zhang C, Shao T, Yu Y, Niu Z, Yan P and Zhou Y 2010 Detection of x-ray emission in a nanosecond discharge in air at atmospheric pressure Rev. Sci. Instrum. 81 123501