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Paper

High-speed Optical Imaging of Lightning and Sparks: Some Recent Results

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This review covers selected results of recent observations of natural lightning and laboratory sparks performed using high-speed video cameras at the Lightning Observatory in Gainesville (LOG), Florida, and at the high-voltage research facility in Istra, Russia, respectively. The most important results include (a) the first high-speed video images of bidirectional leader that made contact with the ground and produced a return stroke, (b) the first speed profile of positive leader that developed in the channel of preceding negative stroke, (c) discovery of unusual plasma formations that coexist with "normal" discharges inside the artificially-charged cloud, and (d) the first two-frame record of the connection between negative and positive leaders after the common streamer zone has been formed.

Keywords: lightning, laboratory sparks, high-speed video cameras

1. Observations of Natural Lightning in Gainesville, Florida

1.1 Overview of the Lightning Observatory in Gainesville (LOG), Florida The LOG has been established in 2004 and is currently located on the roof of the five-story New Engineering Building on the campus of the University of Florida. The LOG includes a glass cupola providing over a 180° unobstructed view of the horizon. The cupola houses optical instrumentation, computers, and digitizing oscilloscopes, while the sensors are located on the roof, outside the cupola. An overview of LOG is shown in Fig. 1(a) and a photograph of the cupola is shown in Fig. 1(b). Sensors currently used at LOG include electric field (E) antennas, electric field derivative (dE/dt) antennas, magnetic field derivative (dB/dt) antennas, and an x-ray detector. Signals from the sensors are transmitted to digitizing oscilloscopes installed in the LOG cupola using fiber optic links.

A total of four optical systems are presently installed at

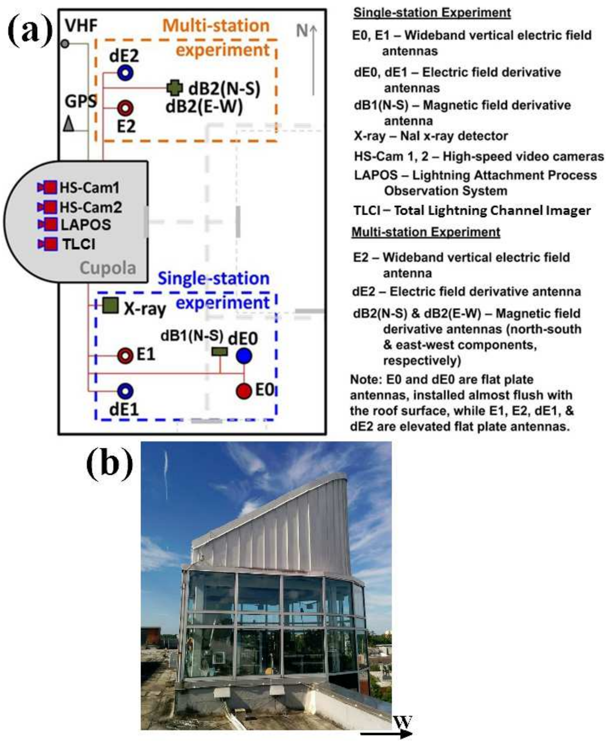

Fig. 1. (a) Overview of LOG and (b) Photograph of the cupola

LOG, including two high-speed video cameras, Phantom V310 and Megaspeed HHC-X2, the Total-Sky Lightning Channel Imager (TLCI), installed at LOG as part of collaboration with the Chinese Academy of Meteorological Sciences, and the photoelectric Lightning Attachment Process Observation System (LAPOS), installed at LOG as part of

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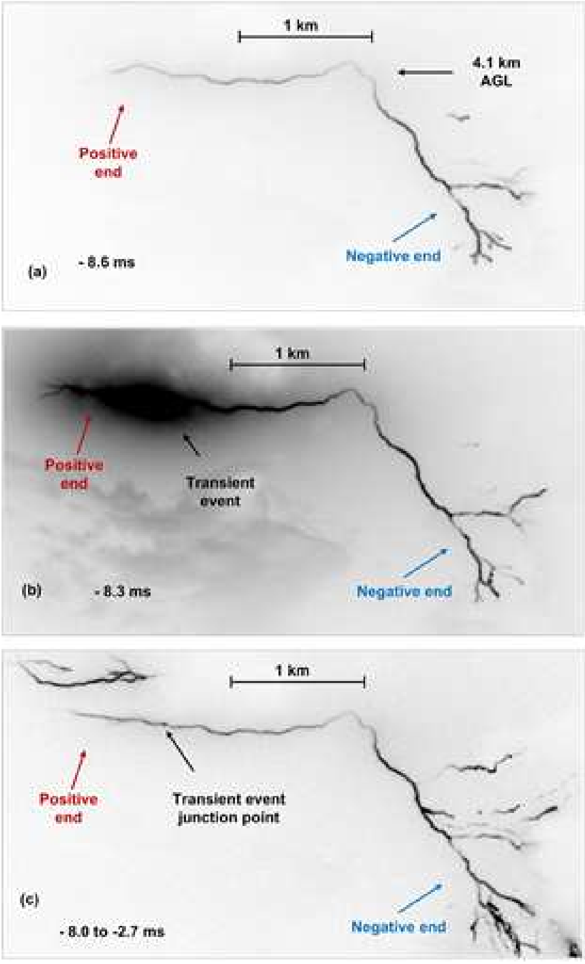

Fig. 2. Transient event at the positive end of lightning bidirectional leader: (a) frame at −8.6 ms, just prior to the transient event, (b) frame at −8.3 ms containing the transient event, during which a 1-km long branch was formed, (c) composite image (from −8.0 to −2.7 ms) showing the transient event junction point. The images were obtained using the Phantom v310 camera. Adapted from Tran and Rakov [1]

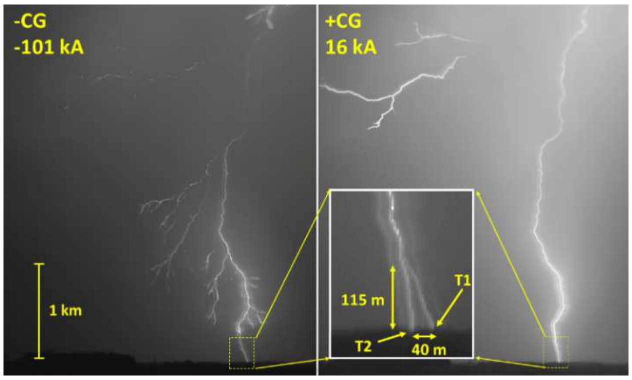

Fig. 3. Composite images of the first, negative stroke (left panel labeled -CG) and second, positive stroke (right panel labeled +CG). The top of the imaged channel was about 3.9 km above ground. The inset shows a magnified composite image of the bottom portions of channels of the first, negative stroke and second, positive stroke. T1 and T2 mark the ground terminations of the first and second strokes, respectively. The images were obtained using the Phantom v310 camera. Adapted from Zhu et al. [2]

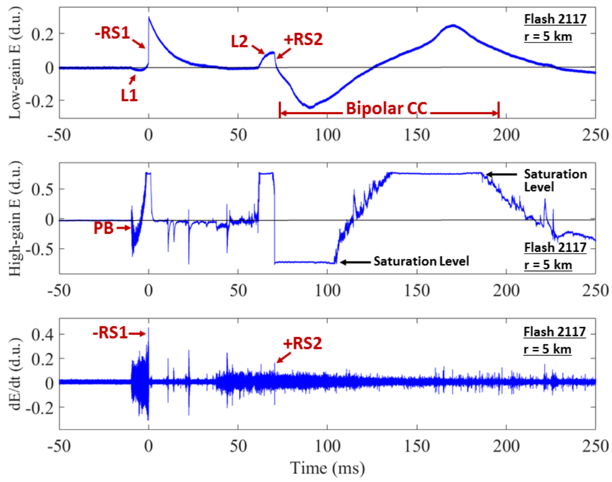

Fig. 4. Simultaneous low-gain electric field, high-gain electric field, and dE/dt records of the initial part of the bipolar flash, including the preliminary breakdown (PB), the first and the second leader (L)/return stroke (RS) sequences and bipolar continuing current (CC). Duration of the latter was estimated from the Phantom camera record. Atmospheric electricity sign convention is used. Adapted from Zhu et al. [2]

collaboration with Gifu University, Japan. The Phanton V310 has a maximum framing rate of 500,000 fps. The maximum framing rate of Megaspeed HHC-X2 is 1,000 fps. The TLCI operates at 40 fps. The sampling rate of LAPOS is 10 MHz (100-ns sampling interval).

1.2 Bidirectional Leader Makes Contact with the Ground and Produces a Return Stroke Tran and Rakov [1] have optically observed a lightning bidirectional leader, one end of which contacted ground and produced a 36-kA return stroke. The bidirectional leader developed during the late stage of a cloud discharge and appeared to be initiated in a decayed (not luminous for at least 43 ms) channel of that cloud discharge. The leader extended bidirectionally in virgin air for at least 12 ms with both ends branching. After turning toward ground, its negative end exhibited features characteristic of preliminary breakdown and stepped leader of first negative cloud-to-ground strokes, while the positive end most of the time appeared to be inactive or showed intermittent channel luminosity enhancements. The development of positive end involved a very bright process (transient event) that caused abrupt creation of 1-km long, relatively straight branch, forked at its far end (see Fig. 2(b)). The bidirectional leader connected, via its positive end, to another bidirectional leader (floating channel) to form a larger bidirectional leader, whose negative end attached to the ground.

1.3 Subsequent Positive Stroke Develops in the Channel of Preceding Negative Stroke Zhu et al. [2] have obtained simultaneous high-speed optical images and electric field signatures of highly unusual four-stroke cloud-to-ground lightning flash. This flash was bipolar and exhibited two types of polarity reversal (in the same channel to ground) associated with the first two strokes separated by 70 ms. Optical images and electric field records of those two strokes are shown in Fig. 3 and Fig. 4, respectively. The first, negative

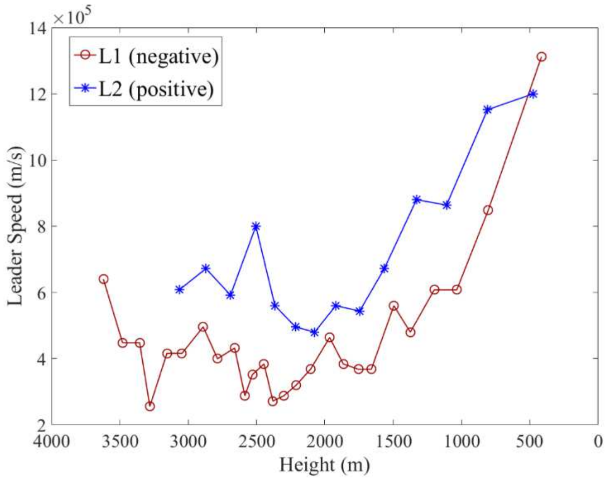

Fig. 5. The frame-to-frame 2-D speeds of the negative stepped leader (L1) and the following positive leader (L2) versus height of the leader tip above ground. Both leaders developed in the same channel and significantly accelerated below 2 km above ground

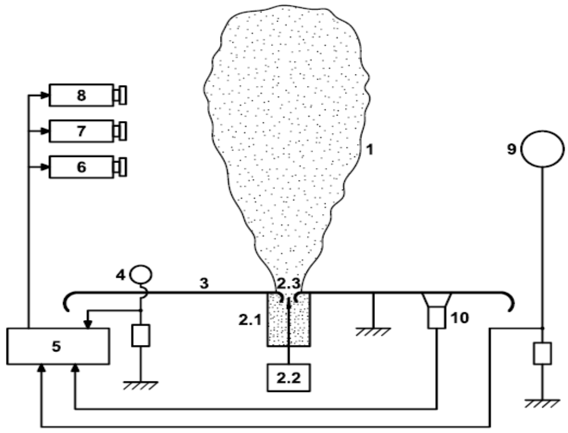

Fig. 6. Experimental setup to produce artificial clouds: 1 = cloud of charged water droplets, 2.1 = steam generator, 2.2 = high-voltage source with corona-producing sharp point, 2.3 = nozzle, 3 = grounded metal plane, 4 = 5-cm grounded sphere equipped with current-measuring shunt, 6 = visible range high-speed framing camera (4Picos), 7 = infrared high-speed framing camera (FLIR), 8 = still camera, 9 = 50-cm sphere for monitoring variations of cloud charge, and 10 = electric field mill (fluxmeter). Not shown in this figure are photomultipliers that were used for triggering the cameras in the case of positively charged cloud. In the case of negatively charged cloud, the cameras were mostly triggered by signals from the current-measuring shunt

stroke whose NLDN-reported peak current was −101 kA was followed by a second, positive stroke whose NLDN-reported peak current was 16 kA. The latter contained 130-ms long bipolar continuing current.

Two-dimensional speed versus height profiles for the negative stepped leader of the first stroke and, for the first time, for the positive leader in the previously conditioned, first-stroke channel were examined (see Fig. 5) and average speeds were found to be 4.7×10^5 m/s and 7.2×10^5 m/s, respectively. The speeds of both the negative and positive leaders increased as they approached the ground.

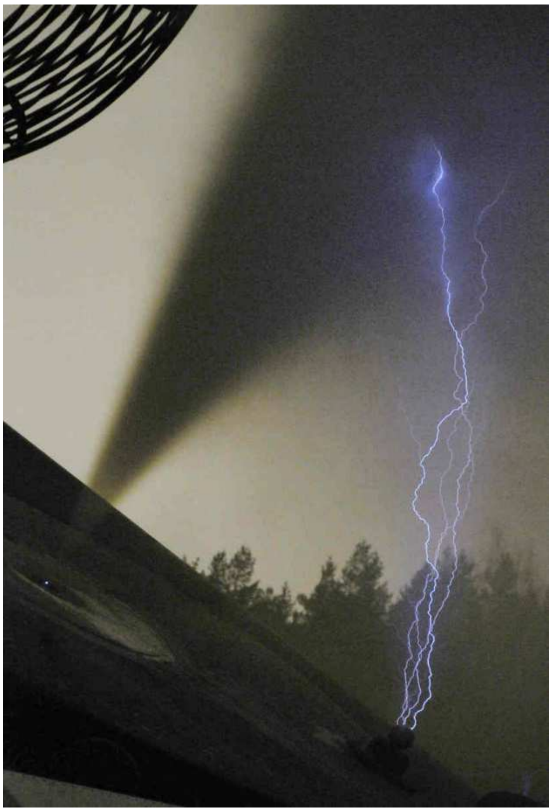

Fig. 7. Still picture (visible range; 5-s exposure) of negatively charged cloud (slanted jet-like, dark formation) and four upward positive discharges, about 1.5 m in length, triggered from the grounded sphere. Adapted from Kostinskiy et al. [3]

2. Observations of Long Sparks in Istra, Russia

2.1 Overview of the High-voltage Research Center in Istra (HVRCI), Russia The HVRCI has two main installations: (1) a 6-MV impulse generator and (2) a generator of artificially-charged clouds of water droplets. Only the second one is discussed here. The experimental setup for producing artificial clouds is shown in Fig. 6. It includes a steam generator, a high-voltage (20 kV) source with corona-producing sharp point, and a 5-cm grounded sphere equipped with a current-measuring shunt. More details are found in Fig. 6. The artificially-charged clouds can produce sparks about 1.5 m in length (see Fig. 7).

Optical images shown in this paper were obtained using the infrared high-speed framing camera FLIR SC7700M and the visible-range 4Picos camera. The infrared camera had a resolution of 640×512 pixels and operated with exposure time of 6.7 ms. The 4Picos can produce two frames separated by 500 ns or more, with 1360×1024 pixels each. It has a built-in image intensifier. The exposure time for each of the 4Picos frames could be set in the range from 0.2 ns to 80 s.

2.2 Infrared Images of In-cloud Discharges Presented in this section (also in Section 2.3) are some results of the recent studies of “electrodeless” electric discharges generated by artificially charged clouds of water droplets in Istra.

Kostinskiy et al. [3], using a high-speed infrared camera, have observed a new class of discharges, which they referred to as unusual plasma formations (UPFs), inside the cloud.

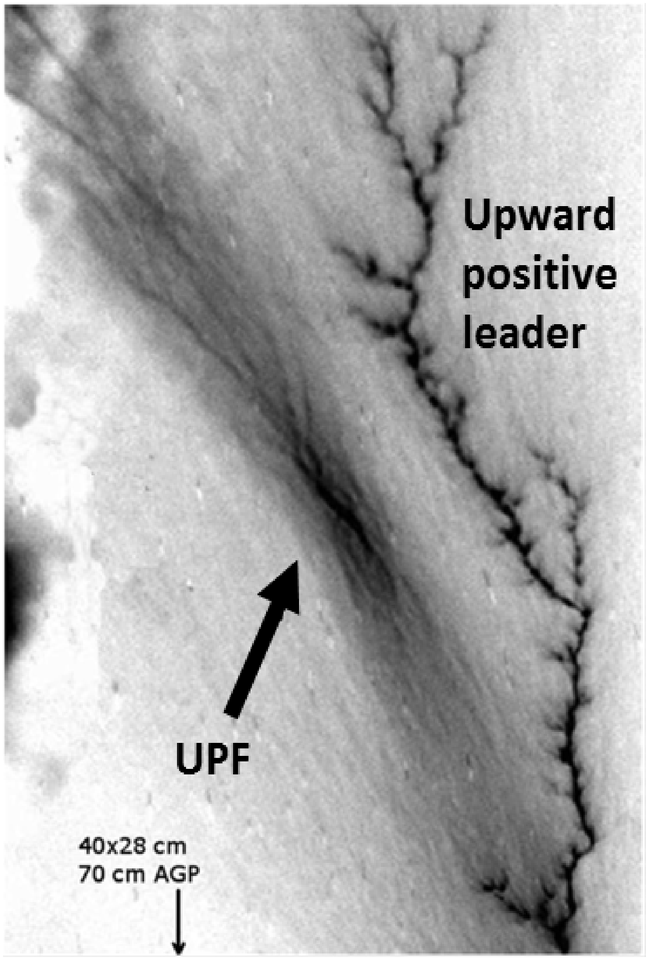

Fig. 8. Infrared image (negative) obtained with 6.7-ms exposure that shows the upper part of the branched upward positive leader and UPF, both inside the cloud. The brightest part of UPF is 3–4 cm long. The two appear to be distinct discharge processes which interact, via their streamer zones, in the lower part of the image. The image was obtained using a FLIR SC7700M camera. AGP stands for above the grounded plane. Adapted from Kostinskiy et al. [3]

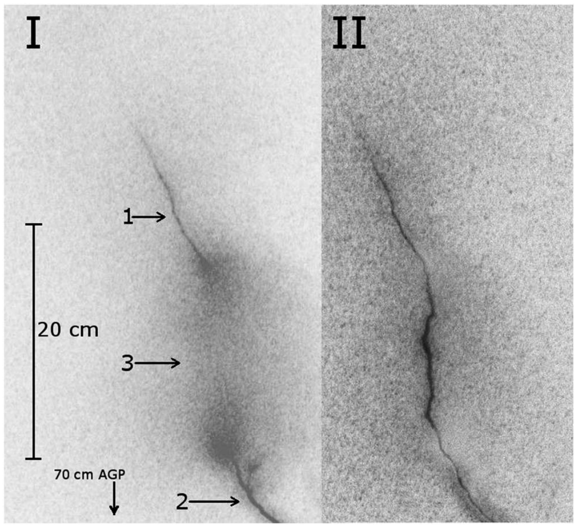

Fig. 9. Two 4Picos frames showing the breakthrough phase (I) and later stage of return-stroke-like process (II) of a negative discharge to ground generated by the cloud of artificially charged water droplets. The exposure time for each frame is 100 ns, and the time interval between frames is 2 μs (see trace 4 in Fig. 10). Labeled are the downward negative leader 1, upward positive leader 2, and the common streamer zone 3. Image (II) was considerably fainter than image (I) and was contrast enhanced more than image (I), to improve its visualization. AGP stands for "above the grounded plane." Adapted from Kostinskiy et al. [4]

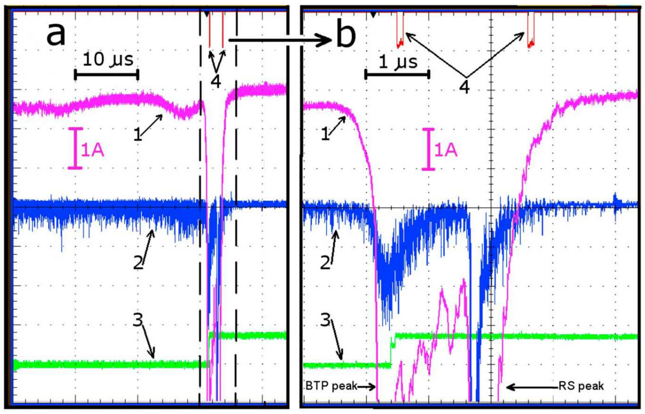

Fig. 10. Records of current 1 and light intensity 2 corresponding to the two 4Picos frames shown in Fig. 9. Also shown are the camera trigger signal 3 and exposure times of the two frames 4. All records are shown on two time scales: (a) 10 μs per division and (b) 1 μs per division. Vertical broken lines in Fig. 10(a) indicate the overall time interval shown in Fig. 10(b). BTP and RS stand for the "breakthrough phase" and "return-stroke-like process", respectively

UPF temperature was inferred to be close to that of leaders observed in the same experiments, while the channel morphology was distinctly different from that of leaders. An example of UPF is shown in Fig. 8.

UPFs appear to be manifestations of collective processes building, essentially from scratch, a complex hierarchical network of interacting channels at different stages of development. They should commonly occur in thunderclouds and might give insights on the missing link in the still poorly understood lightning initiation mechanism.

2.3 Breakthrough Phase of the Attachment Process in Sparks Kostinskiy et al. [4] obtained detailed optical images of the attachment process (the transition from leader to return stroke, which occurs in both sparks and lightning) in its final, breakthrough phase, which is one of the most poorly understood lightning processes. 4Picos images and the associated currents for two events are presented in Figs. 9–12.

Significant leader branching inside the common streamer zone (see Fig. 11) was documented for the first time. Positive and negative leader speeds inside the common streamer zone (just before their collision) were measured and found to be similar. Higher leader speeds were generally associated with higher leader currents (see Table 1).

3. Summary

The main results presented in this paper can be summarized as follows.

(1) The first high-speed video images of bidirectional leader that made contact with the ground and produced a

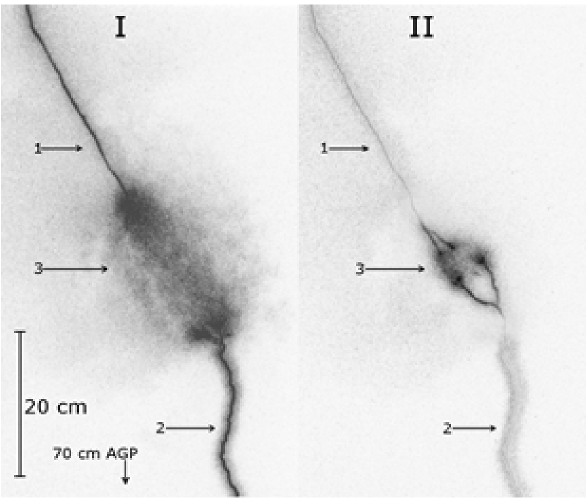

Fig. 11. Two frames both showing the breakthrough phase of a negative discharge to ground generated by the cloud of negatively-charged water droplets. The exposure time for frame (I) is 100 ns and for frame (II) it is 50 ns. The time interval between frames is 2 μs. Labeled are the electrodeless, downward negative leader 1, upward positive leader 2, and the common streamer zone 3. The frames were obtained using a 4Picos visible-range camera with image enhancement (optical gain = 5×10^3). AGP stands for above the grounded plane. Adapted from Kostinskiy et al. [(4)]

Table 1. Comparison of measured leader speeds in the common streamer zone with those estimated from measured currents and the empirical formula of Andreev et al. [(5)]

Reference	Measured current range, A	Measured speed, m/s	Calculated speed range, m/s
Figs. 9 and 10, Frame 1 to RS onset	5.7 to 7.8 (decreasing)	8.5 x 10^4	6.0 x 10^4 to 7.4 x 10^4
Figs. 11 and 12, Frame 1 to frame 2	3.2 to >8 (mostly decreasing)	5.2 x 10^4 to 5.5 x 10^4	4.1 x 10^4 to >7.6 x 10^4
Figs. 11 and 12, Frame 2 to RS onset	3.4 to 4 (increasing)	5.1 x 10^4 to 5.5 x 10^4	4.3 x 10^4 to 4.8 x 10^4

The formula of Andreev et al. [(5)] is given by $v_L = 1.88 \times I_L^{0.67}$, where I_L is the leader current in amperes, and v_L is the leader speed in cm/μs.

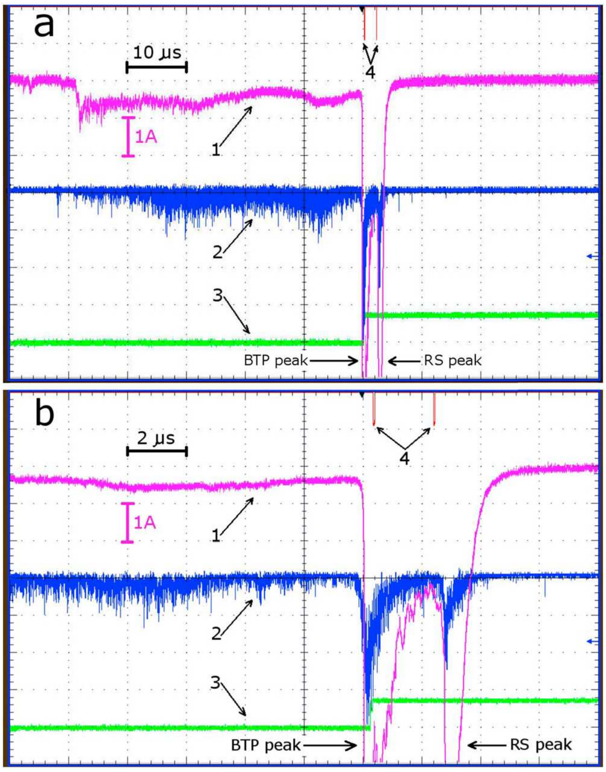

Fig. 12. Records of current 1 and light intensity 2 corresponding to the two 4Picos frames shown in Fig. 11. Also shown are the camera trigger signal 3 and exposure times of the two frames 4. All records are shown on two time scales: (a) 10 μs per division and (b) 2 μs per division. BTP and RS stand for the breakthrough phase and return-stroke-like process, respectively

return stroke.

(2) The first speed profile of positive leader that developed in the channel of preceding negative stroke.

(3) Discovery of unusual plasma formations that coexist with "normal" discharges inside the artificially-charged cloud.

(4) The first two-frame record of the connection between negative and positive leaders after the common streamer zone has been formed.

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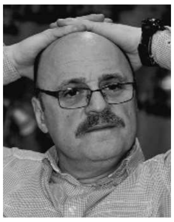

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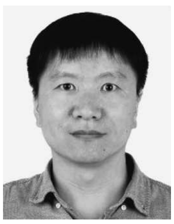

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